DIGESTION AND ABSORPTION OF CARBOHYDRATES, PROTEINS, LIPIDS

Physiology of GIT

Gastrointestinal physiology is the branch of human physiology that addresses the physical function of the gastrointestinal (GI) tract. The function of the GI tract is to process ingested food by mechanical and chemical means, extract nutrients and excrete waste products. The GI tract is composed of the alimentary canal, that runs from the mouth to the anus, as well as the associated glands, chemicals, hormones, and enzymes that assist in digestion. The major processes that occur in the GI tract are: motility, secretion, regulation, digestion and circulation. The proper function and coordination of these processes are vital for maintaining good health by providing for the effective digestion and uptake of nutrients.

Motility: The gastrointestinal tract generates motility using smooth muscle subunits linked by gap junctions. These subunits fire spontaneously in either a tonic or a phasic fashion. Tonic contractions are those contractions that are maintained from several minutes up to hours at a time. These occur in the sphincters of the tract, as well as in the anterior stomach. The other type of contractions, called phasic contractions, consist of brief periods of both relaxation and contraction, occurring in the posterior stomach and the small intestine, and are carried out by the muscularis externa. Motility may be overactive (hypermotility), leading to diarrhea or vomiting, or underactive (hypomotility), leading to constipation or vomiting; either may cause abdominal pain.

Stimulation: The stimulation for these contractions likely originates in modified smooth muscle cells called interstitial cells of Cajal. These cells cause spontaneous cycles of slow wave potentials that can cause action potentials in smooth muscle cells. They are associated with the contractile smooth muscle via gap junctions. These slow wave potentials must reach a threshold level for the action potential to occur, whereupon Ca2+ channels on the smooth muscle open and an action potential occurs. As the contraction is graded based upon how much Ca2+ enters the cell, the longer the duration of slow wave, the more action potentials occur. This, in turn, results in greater contraction force from the smooth muscle. Both amplitude and duration of the slow waves can be modified based upon the presence of neurotransmitters, hormones or other paracrine signaling. The number of slow wave potentials per minute varies based upon the location in the digestive tract. This number ranges from 3 waves/min in the stomach to 12 waves/min in the intestines.

Contraction patterns: The patterns of GI contraction as a whole can be divided into two distinct patterns, peristalsis and segmentation. Occurring between meals, the migrating motor complex is a series of peristaltic wave cycles in distinct phases starting with relaxation, followed by an increasing level of activity to a peak level of peristaltic activity lasting for 5–15 minutes.[5] This

cycle repeats every 1.5–2 hours but is interrupted by food ingestion. The role of this process is likely to clean excess bacteria and food from the digestive system.

Peristalsis: Peristalsis is one of the patterns that occur during and shortly after a meal. The contractions occur in wave patterns traveling down short lengths of the GI tract from one section to the next. The contractions occur directly behind the bolus of food that is in the system, forcing it toward the anus into the next relaxed section of smooth muscle. This relaxed section then contracts, generating smooth forward movement of the bolus at between 2–25 cm per second. This contraction pattern depends upon hormones, paracrine signals, and the autonomic nervous system for proper regulation.

Segmentation: Segmentation also occurs during and shortly after a meal within short lengths in segmented or random patterns along the intestine. This process is carried out by the longitudinal muscles relaxing while circular muscles contract at alternating sections thereby mixing the food. This mixing allows food and digestive enzymes to maintain a uniform composition, as well as to ensure contact with the epithelium for proper absorption.

Secretion: Every day, seven liters of fluid are secreted by the digestive system. This fluid is composed of four primary components: ions, digestive enzymes, mucus, and bile. About half of these fluids are secreted by the salivary glands, pancreas, and liver, which compose the accessory organs and glands of the digestive system. The rest of the fluid is secreted by the GI epithelial cells.

Ions: The largest component of secreted fluids is ions and water, which are first secreted and then reabsorbed along the tract. The ions secreted primarily consist of H^+, K^+, Cl^-, HCO_3^- and Na^+. Water follows the movement of these ions. The GI tract accomplishes this ion pumping using a system of proteins that are capable of active transport, facilitated diffusion and open channel ion movement. The arrangement of these proteins on the apical and basolateral sides of the epithelium determines the net movement of ions and water in the tract.

H^+ and **Cl^-** are secreted by the parietal cells into the lumen of the stomach creating acidic conditions with a low pH of 1. H^+ is pumped into the stomach by exchanging it with K^+. This process also requires ATP as a source of energy; however, Cl^- then follows the positive charge in the H^+ through an open apical channel protein.

HCO_3^- secretion occurs to neutralize the acid secretions that make their way into the duodenum of the small intestine. Most of the HCO_3^- comes from pancreatic acinar cells in the form of $NaHCO_3$ in an aqueous solution.[5] This is the result of the high concentration of both HCO_3^- and Na^+ present in the duct creating an osmotic gradient to which the water follows.[4]

Digestive enzymes: The second vital secretion of the GI tract is that of digestive enzymes that are secreted in the mouth, stomach and intestines. Some of these enzymes are secreted by accessory digestive organs, while others are secreted by the epithelial cells of the stomach and intestine. While some of these enzymes remain embedded in the wall of the GI tract, others are secreted in an inactive proenzyme form.[4] When these proenzymes reach the lumen of the tract, a factor specific to a particular proenzyme will activate it. A prime example of this is pepsin, which is secreted in the stomach by chief cells. Pepsin in its secreted form is inactive (pepsinogen). However, once it reaches the gastric lumen it becomes activated into pepsin by the high H+ concentration, becoming an enzyme vital to digestion. The release of the enzymes is regulated by neural, hormonal, or paracrine signals. However, in general, parasympathetic stimulation increases secretion of all digestive enzymes.

Mucus: Mucus is released in the stomach and intestine, and serves to lubricate and protect the inner mucosa of the tract. It is composed of a specific family of glycoproteins termed mucins and is generally very viscous. Mucus is made by two types of specialized cells termed mucus cells in the stomach and goblet cells in the intestines. Signals for increased mucus release include parasympathetic innervations, immune system response and enteric nervous system messengers.

Bile: Bile is secreted into the duodenum of the small intestine via the common bile duct. It is produced in liver cells and stored in the gall bladder until release during a meal. Bile is formed of three elements: bile salts, bilirubin and cholesterol. Bilirubin is a waste product of the breakdown of hemoglobin. The cholesterol present is secreted with the feces. The bile salt component is an active non-enzymatic substance that facilitates fat absorption by helping it to form an emulsion with water due to its amphoteric nature. These salts are formed in the hepatocytes from bile acids combined with an amino acid. Other compounds such as the waste products of drug degradation are also present in the bile.

Regulation: The digestive system has a complex system of motility and secretion regulation which is vital for proper function. This task is accomplished via a system of long reflexes from the central nervous system (CNS), short reflexes from the enteric nervous system (ENS) and reflexes from GI peptides working in harmony with each other.

Long reflexes: Long reflexes to the digestive system involve a sensory neuron sending information to the brain, which integrates the signal and then sends messages to the digestive system. While in some situations, the sensory information comes from the GI tract itself; in others, information is received from sources other than the GI tract. When the latter situation occurs, these reflexes are called feedforward reflexes. This type of reflex includes reactions to food or danger triggering effects in the GI tract. Emotional responses can also trigger GI

response such as the butterflies in the stomach feeling when nervous. The feedforward and emotional reflexes of the GI tract are considered cephalic reflexes.

Short reflexes: Control of the digestive system is also maintained by ENS, which can be thought of as a digestive brain that can help to regulate motility, secretion and growth. Sensory information from the digestive system can be received, integrated and acted upon by the enteric system alone. When this occurs, the reflex is called a short reflex.[4] Although this may be the case in several situations, the ENS can also work in conjunction with the CNS; vagal afferents from the viscera are received by the medulla, efferents are affected by the vagus nerve. When this occurs, the reflex is called vagovagal reflex. The myenteric plexus and submucosal plexus are both located in the gut wall and receive sensory signals from the lumen of the gut or the CNS.

Gastrointestinal peptides: GI peptides are signal molecules that are released into the blood by the GI cells themselves. They act on a variety of tissues including the brain, digestive accessory organs, and the GI tract. The effects range from excitatory or inhibitory effects on motility and secretion to feelings of satiety or hunger when acting on the brain. These hormones fall into three major categories, the gastrin and secretin families, with the third composed of all the other hormones unlike those in the other two families. Further information on the GI peptides is summarized in the table below.

	Secreted by	Target	Effects on endocrine secretion	Effects on exocrine secretion	Effects on motility	Other effects	Stimulus for release
Gastrin	G Cells in stomach	ECL cells; parietal cells	None	Increases acid secretion, increases mucus growth	Stimulates gastric contraction	None	Peptides and amino acids in lumen; gastrin releasing peptide and ACh in nervous reflexes
Cholecystokinin (CCK)	Endocrine I cells of the small intestine; neurons	Gall bladder, pancreas, gastric smooth muscle	None	Stimulates pancreatic enzyme and HCO3- secretion	Stimulates gallbladder contraction; inhibits stomach emptying	Satiety	Fatty acids and some amino acids

	of the brain and gut						
Secretin	Endocrine S cells of the small intestine	Pancreas, stomach	None	Stimulates pancreatic and hepatic HCO3- secretion; inhibits acid secretion; pancreatic growth	Stimulates gallbladder contraction; Inhibits stomach emptying	None	Acid in small intestine
Gastric inhibitory Peptide	Endocrine K cells of the small intestine	Beta cells of the pancreas	Stimulates pancreatic insulin release	Inhibits acid secretion	None	Satiety and lipid metabolism	Glucose, fatty acid, and amino acids in small intestine
Motilin	Endocrine M cells in small intestine	Smooth muscle of stomach and duodenum	None	None	Stimulates migrating motor complex	Action in brain, stimulates migratory motor complex	Fasting: cyclic release every 1.5–2 hours by neural stimulus
Glucagon-like peptide-1	Endocrine cells in small intestine	Endocrine pancreas	Stimulates insulin release; inhibits glucagon release	Possibly inhibits acid secretion	Slows gastric emptying	Satiety; various CNS functions	Mixed meals of fats and carbohydrates

DIGESTION AND ABSORPTION OF CARBOHYRATES, LIPID, PROTEIN

1. DIGESTION OF CARBOHYDRATES

The term is most common in biochemistry, where it is a synonym of saccharide, a group that includes sugars, starch, and cellulose. The saccharides are divided into four chemical groups: monosaccharides, disaccharides, oligosaccharides, and polysaccharides. Monosaccharides and disaccharides, the smallest (lower molecular weight) carbohydrates, are commonly referred to as sugars. The word saccharide comes from the Greek word σάκχαρον (sákkharon), meaning "sugar". While the scientific nomenclature of carbohydrates is complex, the names of the monosaccharides and disaccharides very often end in the suffix -ose, as in the monosaccharides fructose (fruit sugar) and glucose (starch sugar) and the disaccharides sucrose (cane or beet sugar) and lactose (milk sugar).

Carbohydrates perform numerous roles in living organisms. Polysaccharides serve for the storage of energy (e.g. starch and glycogen) and as structural components (e.g. cellulose in plants and chitin in arthropods). The 5-carbon monosaccharide ribose is an important component of coenzymes (e.g. ATP, FAD and NAD) and the backbone of the genetic molecule known as RNA. The related deoxyribose is a component of DNA. Saccharides and their derivatives include many other important biomolecules that play key roles in the immune system, fertilization, preventing pathogenesis, blood clotting, and development.

Carbohydrates are central to nutrition and are found in a wide variety of natural and processed foods. Starch is a polysaccharide. It is abundant in cereals (wheat, maize, rice), potatoes, and processed food based on cereal flour, such as bread, pizza or pasta. Sugars appear in human diet mainly as table sugar (sucrose, extracted from sugarcane or sugar beets), lactose (abundant in milk), glucose and fructose, both of which occur naturally in honey, many fruits, and some vegetables. Table sugar, milk, or honey are often added to drinks and many prepared foods such as jam, biscuits and cakes.

Cellulose, a polysaccharide found in the cell walls of all plants, is one of the main components of insoluble dietary fiber. Although it is not digestible, insoluble dietary fiber helps to maintain a healthy digestive system by easing defecation. Other polysaccharides contained in dietary fiber include resistant starch and inulin, which feed some bacteria in the microbiota of the large intestine, and are metabolized by these bacteria to yield short-chain fatty acids.

Among carbohydrates, only the monosaccharide forms are absorbed. Hence, all carbohydrates must be digested to glucose, galactose and fructose for absorption to proceed. There are two types of carbohydrates in the human food which need to be digested in the alimentary canal of man. These are:

a) **Disaccharides** like maltose (malt sugar), sucrose (cane sugar), and lactose (milk sugar). Carbohydrate digestion involves the hydrolysis of glycosidic bonds of polymeric and dimeric

carbohyrates to form monosaccharides. The carbohydrate splitting enzymes are called amylolytic or carbohyrolases or glycosidases. Different glycosidases hydrolyse different glycosidic bonds.

b) **Polysaccharides** like starch, glycogen and cellulose.

Digestion of Starch: Starch is a storage polysaccharides of the plants. It is found in the potato tubers; cereals like rice, wheat, etc. and fruits like mango, banana, etc. It is formed of two complex polymeric compounds-α-amylose and amylopectin, both are formed of D-glucose molecules interlinked by α(1 4) glycosidic bonds.

1 **– In Buccal Cavity**: There are three pairs of salivary glands (one pair of each of parotid glands just in front and below the pinna; submaxillary glands below the jaw angle, and sublingual glands below the tongue. There are no infraorbital glands founds in most of the mammals) in the buccal cavity of man (four pairs of salivary glands in rabbit). These salivary glands secrete a slightly acidic secretion called saliva which contains an amylolytic enzyme called salivary amylase or ptyalin or diatase. Composition of saliva is 99.5% water, 0.2% minerals like Cl-, HCO3-CO32- and phosphates of Na+, K+, Ca++, and Mg++; and 0.3% organic compounds like mucin and enzymes, especially salivary amylase. Saliva also contains antibacterial thiocyanate ions. It is an endoamylase and hydrolyses α(1 4) glycosidic bonds of starch into double sugars, maltose and isomaltose and small dextrins called 'limit' dextrins. The ptyalin is most active at pH 6.8 and in the presence of Cl- .

$$\text{Starch} \xrightarrow{\text{Salivary amylase}} \text{Maltose} + \text{Isomaltose} + \text{Dextrin}$$

Some enzymatic digestion of starch occurs in the mouth, due to the action of the enzyme salivary amylase. This enzyme starts to break the long glucose chains of starch into shorter chains, some as small as maltose. (The other carbohydrates in the bread don't undergo any enzymatic digestion in the mouth.), but in catalyzed reactions, that is, facilitated by hydrolytic enzymes, secreted by exocrine pancreas and/or present on the surface of the intestinal mucosal brush border cells (enterocytes).

Starch digestion begins in mouth by salivary alpha-amylase, therefore the rate of mastication and the time of permanence in mouth, however relatively short, are the first factors that affect the interaction between starch and the enzyme and that can improve digestion. Digestion of carbohydrate begins at oral cavity level and then goes on in the next parts of the gastrointestinal tract, particularly in the small intestine

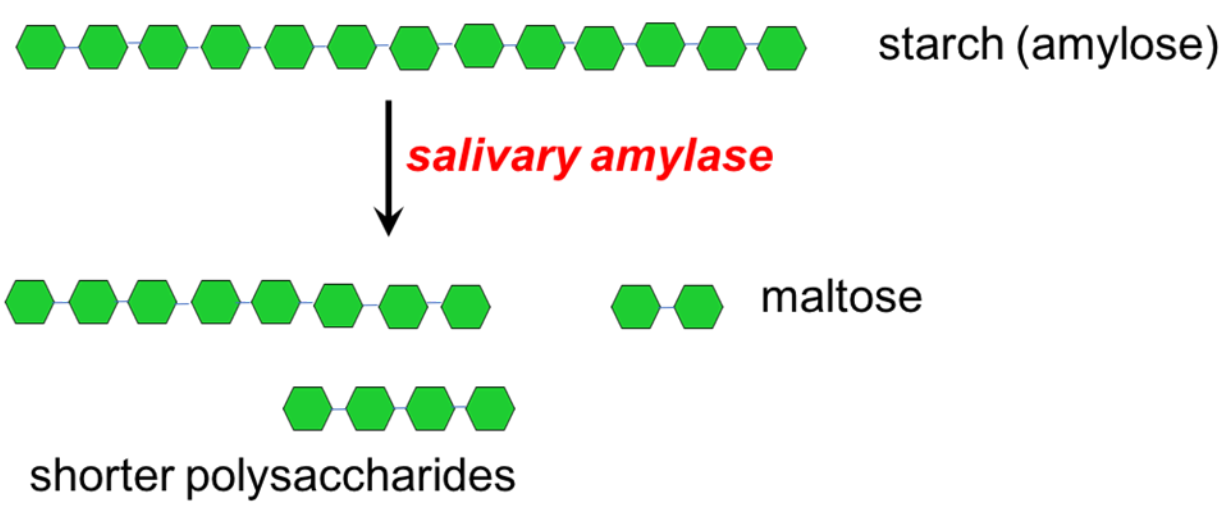


Fig. The enzyme salivary amylase breaks starch into smaller polysaccharides and maltose.

Illustration showing that the enzyme salivary amylase breaks starch into smaller polysaccharides and maltose. The image shows a long chain of starch (shown as green hexagons) that is then broken into shorter lengths, including maltose, by salivary amylase

2 - **Stomach**

Once in the stomach, that essentially acts as a tank, gastric acidity inactivates salivary alpha-amylase, whose optimal pH is about 7, though the presence of starch may partly protects the enzyme from gastric degradation, allowing the passage with meal into the duodenum, where it may support pancreatic alpha-amylase in the digestive process.

The low pH in the stomach inactivates salivary amylase, so it no longer works once it arrives at the stomach. Although there's more mechanical digestion in the stomach, there's little chemical digestion of carbohydrates here.

3 - **Small intestine**

When we pass from the stomach into the small intestine, bicarbonate ion secreted by pancreas (under stimulation of secretin hormone) neutralizes gastric acidity leading pH to about 7, an optimal value for the action of pancreatic enzymes, including alpha-amylase, and intestinal enzymes, and for the residual salivary alpha-amylase. So starch digestion, which occurs mostly in the duodenum, begins again by the action of pancreatic alpha-amylase, secreted in amounts greatly exceeding than the digestive needs (in reply to meals the enzyme is secreted in amounts at least 10 times greater than that needed for optimal starch digestion).

Although pancreatic alpha-amylase acts primarily in the polar milieu of intestinal content, where therefore the most part of the starch digestion occurs, a part adheres to the intestinal mucosa on the brush border surface of enterocytes. It has been proposed that this topographic disposition could be favorable because it would cause the release of the cleavage products of the starch (maltose, maltotriose and alpha-limit dextrins) at the lumen-membrane interface, where the final part of the digestion occurs by the action of brush border enzymes (see below).

Ileum, the final part of the small intestine, is able to digest and absorb carbohydrates, but in a less extend than jejunum and obviously duodenum. In the presence of illness affecting jejunum or of a surgical removal of the upper tract of the small intestine, the ileum can adapt to the new condition and assume an important role in carbohydrate digestion and absorption. Most carbohydrate digestion occurs in the small intestine, thanks to a suite of enzymes. Pancreatic amylase is secreted from the pancreas into the small intestine, and like salivary amylase, it breaks starch down to small oligosaccharides (containing 3 to 10 glucose molecules) and maltose.

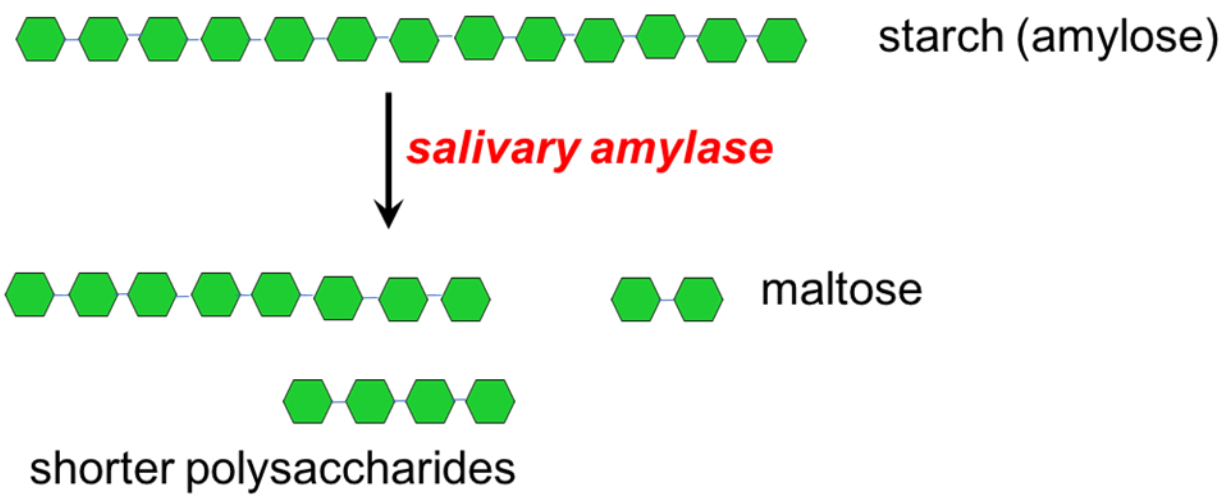


Fig. The enzyme pancreatic amylase breaks starch into smaller polysaccharides and maltose.

Illustration showing that the enzyme pancreatic amylase breaks starch into smaller polysaccharides and maltose. The image shows a long chain of starch (shown as green hexagons) that is then broken into shorter lengths, including maltose, by pancreatic amylase.

The rest of the work of carbohydrate digestion is done by enzymes produced by the enterocytes, the cells lining the small intestine. When it comes to digesting your slice of pizza,

these enzymes will break down the maltase formed in the process of starch digestion, the lactose from the cheese, and the sucrose present in the sauce.

Maltose is digested by maltase, forming 2 glucose molecules

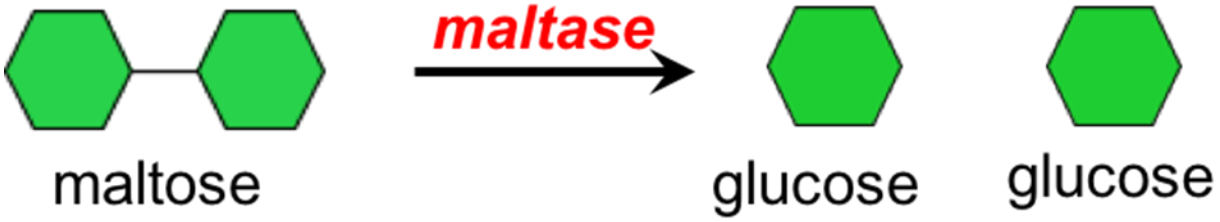


Illustration showing maltose (represented by two green hexagons linked together) being broken into two glucose molecules by the enzyme maltase.

Lactose is digested by lactase, forming glucose and galactose

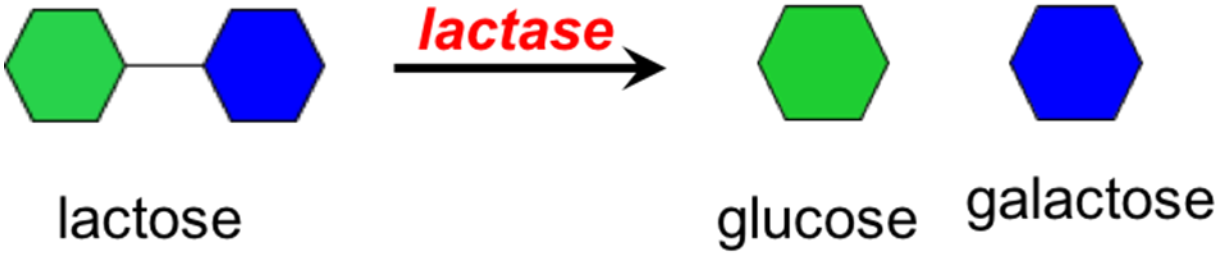


Illustration showing lactose (represented by a green hexagon linked to a blue hexagon) being broken into one glucose molecule and one galactose molecule by the enzyme lactase.

Sucrose is digested by sucrase, forming glucose and fructose

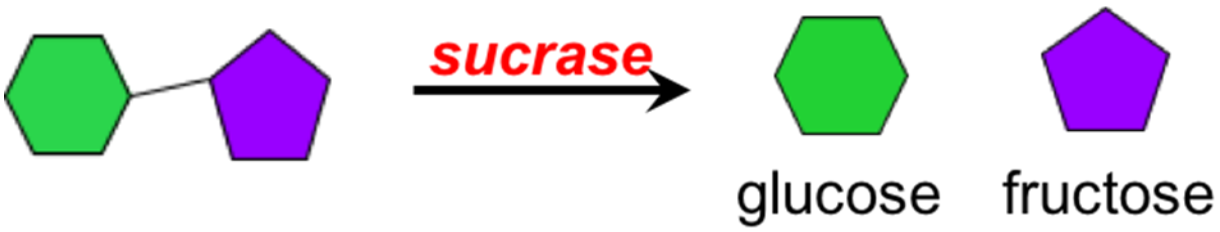


Fig. Action of the enzymes maltase, lactase, and sucrase.

Illustration showing sucrose (represented by a green hexagon linked to a purple pentagon) being broken into one glucose molecule and one fructose molecule by the enzyme sucrase.

(Recall that if a person is lactose intolerant, they don't make enough lactase enzyme to digest lactose adequately. Therefore, lactose passes to the large intestine. There it draws water in by osmosis and is fermented by bacteria, causing symptoms such as flatulence, bloating, and diarrhea.)

Fructose and galactose are converted to glucose in the liver. Once absorbed carbohydrates pass through the liver, glucose is the main form of carbohydrate circulating in the bloodstream.

a-Amylases (salivary and pancreatic) hydrolyze 1,4-glycosidic bonds in starch, yielding maltose, maltotriose, and α-limit dextrins.

Maltase, a-dextrinase, and sucrase in the intestinal brush border then hydrolyze the oligosaccharides to glucose.

Lactase, trehalase, and sucrase degrade their respective disaccharides lactose, trehalose, and sucrose to monosaccharides.

Lactase degrades lactose to glucose and galactose.

Trehalase degrades trehalose to glucose.

Sucrase degrades sucrose to glucose and fructose.

By the end of this process of enzymatic digestion, we're left with three monosaccharides: glucose, fructose, and galactose. These can now be absorbed across the enterocytes of the small intestine and into the bloodstream to be transported to the liver.

Digestion and absorption of carbohydrates in the small intestine are depicted in a very simplified schematic below. (Remember that the inner wall of the small intestine is actually composed of large circular folds, lined with many villi, the surface of which are made up of microvilli. All of this gives the small intestine a huge surface area for absorption.

Monosaccharides are then absorbed into the bloodstream and travel to the liver.

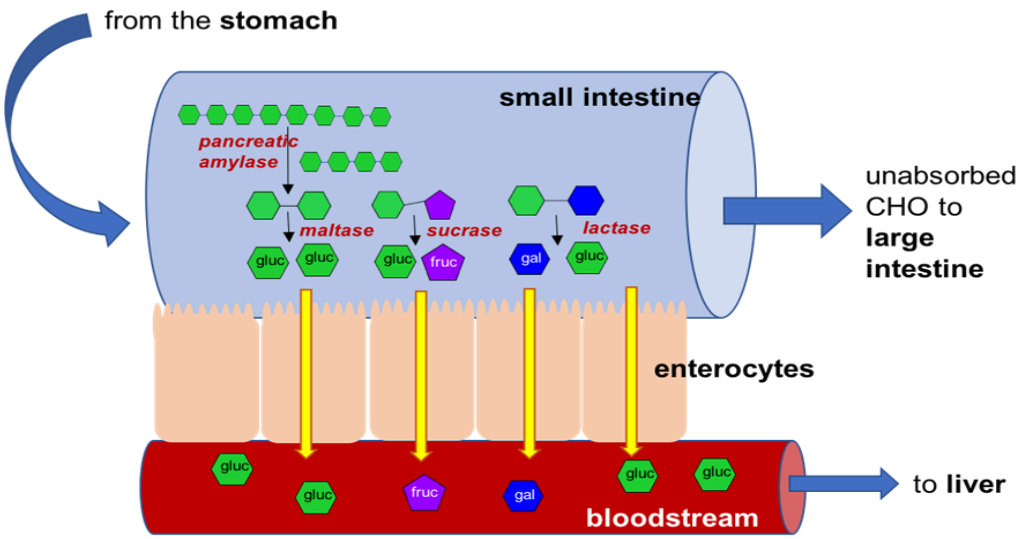


Fig. Digestion and absorption of carbohydrates in the small intestine.

4 - **Large Intestine or Colon**

Any carbohydrates that weren't digested in the small intestine -- mainly fiber -- pass into the large intestine, but there's no enzymatic digestion of these carbohydrates here. Instead, bacteria living in the large intestine, sometimes called our gut microbiota, ferment these carbohydrates to feed themselves. Fermentation causes gas production, and that's why we may experience bloating and flatulence after a particularly fibrous meal. Fermentation also produces short-chain fatty acids, which our large intestine cells can use as an energy source. Over the last decade or so, more and more research has shown that our gut microbiota are incredibly important to our health, playing important roles in the function of our immune response, nutrition, and risk of disease. A diet high in whole food sources of fiber helps to maintain a population of healthy gut microbes.

Digestion of di- and oligosaccharides

The final step of carbohydrate digestion is yielded by enzymes synthesized in enterocytes and localized on the brush border surface of the same cells.

They are glycoproteins with hydrolasic activity that act on the products of the alpha-amylase action, maltose, maltotriose and alpha-limit dextrins, and even more on two other carbohydrates, the disaccharides sucrose and lactose.

The capacity of synthesize these enzymes is acquired during foetal period prior to birth, therefore newborn infants have all these enzymes.

Several glycosidases can act only on alpha-glycosidic bonds that is bonds in which the “bridge” made up by oxygen atom is below the plan individuated by the ring structure of the sugar; so they are called alpha-glycosidases and, in particular:

sucrase;

glucoamylase;

alpha-dextrinase.

It should be noted that glycosidases present in our body can’t act on carbohydrates in which glucose is linked by beta-glycosidic bonds, as e.g. cellulose).

All the alpha-glycosidases present on the brush border surface of enterocytes are specific for the α-(1⟶4) glycosidic bond that links, at the non-reducing end of the chain, the last to the last but one residue of glucose. What differentiates them, and which is at the base of their nomenclature, is the degree of affinity for glycosidic bonds present at the nonreducing end of the saccharidic chain.

It is clear that alpha-glycosidases do not work in a separate manner on substrates because of in every step of the digestive process one or more of them will have an high specificity for the alpha-glycosidic bond currently closest to non-reducing end of the oligosaccharide on duty.

Only the final products of the catalytic activities of alpha-glycosidases, lactase and trehalase, that is glucose, fructose and galactose, will be transported across the intestinal membrane barrier and flowed into the bloodstream to be distributed to liver and then to the several tissues.

Summary of Carbohydrate Digestion: The primary goal of carbohydrate digestion is to break polysaccharides and disaccharides into monosaccharides (glucose, galactose and fructose), which can be absorbed into the bloodstream.

1. After eating, nothing needs to happen in the digestive tract to the monosaccharides in a food like grapes, because they are already small enough to be absorbed as is.

2. Disaccharides in that grape or in a food like milk are broken down (enzymatically digested) in the digestive tract to monosaccharides (glucose, galactose, and fructose).

3. Starch in food is broken down (enzymatically digested) in the digestive tract to glucose molecules.

4. Fiber in food is not enzymatically digested in the digestive tract, because humans don't have enzymes to do this. However, some dietary fiber is fermented in the large intestine by gut microbes.

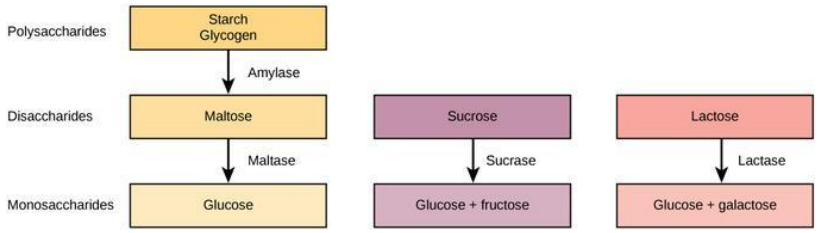


Fig. Digestion of carbohydrates: Digestion of carbohydrates is performed by several enzymes. Starch and glycogen are broken down into glucose by amylase and maltase. Sucrose (table sugar) and lactose (milk sugar) are broken down by sucrase and lactase, respectively.

2. DIGESTION OF PROTEINS

Dietary proteins are a source of amino acids that are utilized for the formation of various cellular substances. Mostly, proteins must be broken down into amino acids for absorption. Digestive products of protein can be absorbed as amino acids, dipeptides, and tripeptides

Proteins are the polymers of amino acids interlinked by peptide bonds formed by the loss of water molecules between adjacent amino acids. The proteins are digested by proteolytic enzymes called **proteases or peptidases**. **The peptidases**, on the basis of their site of action are divided into two categories:

i) **Endopeptidases** are hydrolyse internal peptide bonds and include **pepsin**, **trypsin,** etc.
ii) **Exopeptidases** are hydrolyse terminal peptide bonds and separate individual amino acids. These include **carboxypeptidases** and **aminopeptidases**.

Both endopeptidases enzymes which degrade proteins by hydrolyzing interior peptide bonds and exopeptidases enzyme that hydrolyzes one amino acid at a time from the C-terminus of proteins and peptides are involved in the digestion of proteins.

Digestion takes place in the stomach and the small intestine.

a) **In Buccal cavity**. Saliva has no proteolytic enzyme so no digestion of proteins in the buccal cavity.
b) **In Stomach**. Both mechanical (churning of food, mixing of food with gastric juices) and chemical actions occur on food in the stomach.

Chemical actions in the stomach, food is mixing with gastric juices of the gastric glands secreted by argentaffin cells of pyloric mucosa controlled by gastrin hormone. Gastric juice contains mucus (goblet cells), HCl (oxyntic cells), two proenzymes- prorennin and pepsinogen (peptic or chief cells) and a weak gastric lipase enzyme (peptic cells).

Role of HCl. HCl forms about 0.3% of gastric juices. It helps in-

1. Killing the bacteria in the food.
2. Stopping the action of saliva.
3. Activating the **pepsinogen to pepsin** and **prorennin to rennin**.
4. Providing optimum pH (1.2-1.8 pH) for pepsin
5. Softening of food.

Enzymes Involved

Role of Pepsin: Pepsin is secreted in its zymogen form as pepsinogen by the chief cells of the stomach. Pepsinogen is activated to pepsin by gastric H+. The optimum pH for pepsin is between 1 and 3. **Pepsin** hydrolyzes proteins into **peptones** and **proteoses**. When the pH is >5, pepsin is denatured. Thus, in the intestine, as HCO_3^- is secreted in pancreatic fluids, duodenal pH increases, and pepsin is inactivated.

Protein $\xrightarrow{\text{pepsin}}$ **Peptones and proteoses**

The **proteoses** are the largest fragments of proteins.

Role of Rennin: The proenzyme prorennin is mainly present in infants and is first activatedby HCl in acidic medium to rennin (also called as rennets or chymosin) which is a very strong milk protein coagulating factor (proteinase). It hydrolyses milk soluble protein casein to paracasein. Paracasein is precipitated spontaneously as calcium paracaseinate in the form of curd. This is called curdling of milk.

Prorennin $\xrightarrow{\text{HCl}}$ **Rennin + Inactive dipeptide**

Casein $\xrightarrow{\text{Rennin}}$ **Paracasein (soluble)** $\xrightarrow{\text{calcium ions}}$ **Calcium paracasein (solid curd)**

Calcium paracasein $\xrightarrow{\text{Pepsin}}$ **Peptones + proteoses**

Curdling of milk increases the period of action of pepsin on the milk-proteins especially casein, in the stomach for their proper digestion. Amount of rennin decreases with the age so it is absent in most of adult mammals including man and cow then the curdling of milk is done by pepsin and chymotrypsin.

c) **In intestine:** The food entered in the intestine is semi-digested called chyme, which is mixed with three alkaline juices: **bile** (pH 8.0) from liver; **pancreatic juices** (pH 8.8) from pancreas; and **intestine juices** (pH 8.3) from intestinal glands. These function in alkaline medium.

1. **Bile** has no enzyme so it has no chemical action on proteins.
2. **Pancreatic juices** contain **three alkaline proteoses**:

Pancreatic proteases: The digestion is completed in the small intestine by the action of pancreatic and intestinal juice. The proteases include **trypsin, chymotrypsin, elastase, carboxypeptidase A**, and **carboxypeptidase B**. They are secreted in inactive forms that are activated in the small intestine as follows:

Trypsinogen is activated to trypsin by a brush border enzyme, enterokinase.

Trypsin then converts chymotrypsinogen, proelastase, and procarboxypeptidase A and B to their active forms.

Trypsin is an endoproteolytic enzyme and hydrolyses the peptones and proteoses into peptides by hydrolysing the peptide bonds on C-terminus side of arginine and lysine amino acids. Trypsin is found from protozoans to mammals so is also called universal enzyme.

Peptones and proteoses $\xrightarrow{\text{Trypsin}}$ **Peptides**

Trypsin also activates other proenzymes:

Chymotrypsinogen $\xrightarrow{\text{Trypsin}}$ **Chymotrypsin**

Procarboxypeptidase $\xrightarrow{\text{Trypsin}}$ **Carboxypeptidase**

Chymotrypsin hydrolyses the peptide bonds on C-terminus side of **tyrosine**, **tryptophan** and **phenylalanine amino acids**. It also has the power of clotting milk in alkaline medium.

Peptones and proteoses $\xrightarrow{\text{Chymotrypsin}}$ **Peptides**

Carboxypeptidase: It is an exopeptidase and separates individual amino acids from C-terminus.

3. **Intestinal juices**: These contain two alkaline proteases;

Aminopeptidase (Erepsin) hydrolyses the terminal peptide bond at N-terminus of the peptide chain to release the amino acids one by one.

Dipeptidase hydrolyses the dipeptides to release the amino acids.

Intestinal juice also contain a non-digestive protease enterokinase which activates **trypsinogen to trypsin.**

3. DIGESTION OF LIPID

In biology and biochemistry, a lipid is a macrobiomolecule that is soluble in nonpolar solvents. Non-polar solvents are typically hydrocarbons used to dissolve other naturally occurring hydrocarbon. Lipid molecules that do not (or do not easily) dissolve in water, including fatty acids, waxes, sterols, fat-soluble vitamins (such as vitamins A, D, E, and K), monoglycerides, diglycerides, triglycerides, and phospholipids.

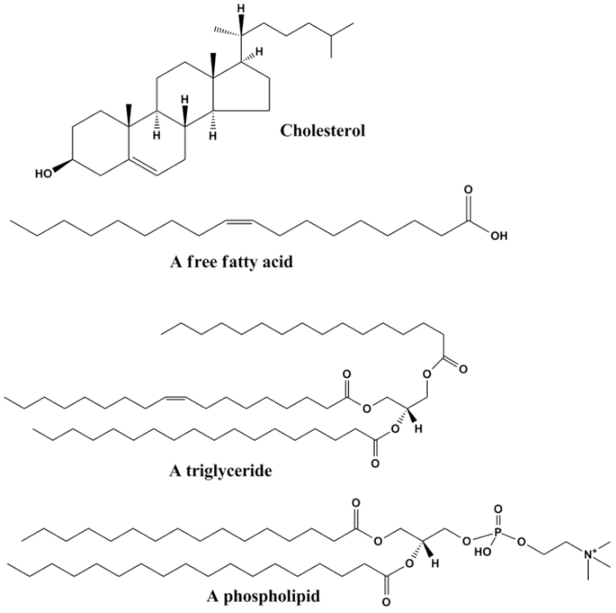


Fig. Structures of some common lipids. At the top are cholesterol[1] and oleic acid.[2] The middle structure is a triglyceride composed of oleoyl, stearoyl, and palmitoyl chains attached to a glycerol backbone. At the bottom is the common phospholipid phosphatidylcholine.

Scientists sometimes define lipids as hydrophobic or amphiphilic small molecules; the amphiphilic nature of some lipids allows them to form structures such as vesicles, multilamellar/unilamellar liposomes, or membranes in an aqueous environment. Biological lipids originate entirely or in part from two distinct types of biochemical subunits or "building-blocks": ketoacyl and isoprene groups. Using this approach, lipids may be divided into eight categories: fatty acids, glycerolipids, glycerophospholipids, sphingolipids, saccharolipids, and polyketides (derived from condensation of ketoacyl subunits); and sterol lipids and prenol lipids (derived from condensation of isoprene subunits).

Fats not being soluble in water by their nature are both difficult to digest and absorb. They do not mix with the stomach or intestinal contents. Almost the entire dietary fat consists of neutral fats **(triglycerides)**. A triglyceride is the combination of three fatty acids molecules

condensed with a molecule of glycerol by ester bonds formed by the loss of water molecules. The enzymes involved in the hydrolysis of fats are esterases. Most important esterase is lipase.

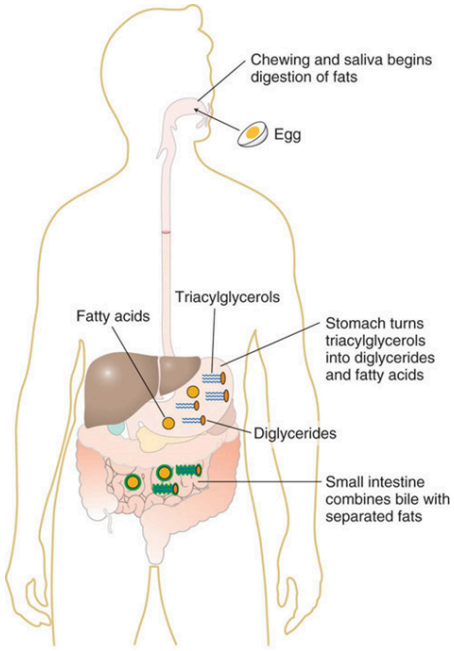


Fig. Lipid Digestion

The first step in lipid digestion is emulsification, which is the transformation of large lipid droplets into much smaller droplets.

The emulsification process increases the surface area of the lipid-exposed to the digestive enzymes by decreasing the droplet size.

Fat digestion started in the stomach and is nearly completed in the small intestine.

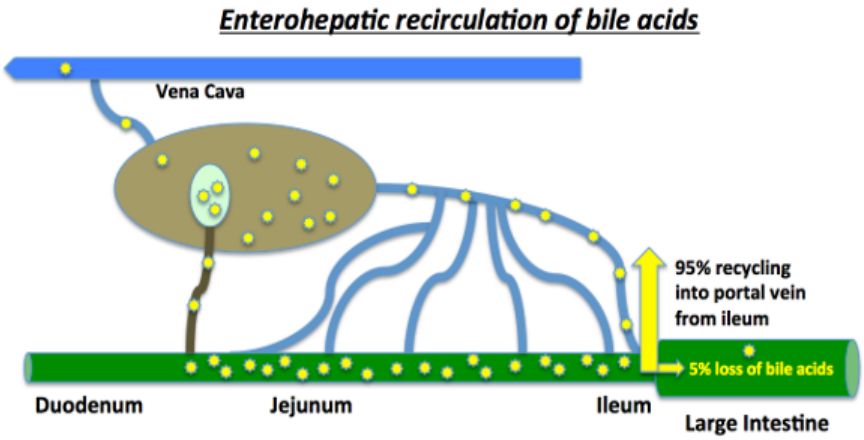
a) **In the Buccal Cavity:** Lingual lipases digest some of the ingested triglycerides to monoglycerides and fatty acids. Saliva has no lipolytic enzyme, so no digestion of fats in the buccal cavity.

b) **In the Stomach:** Gastric juice of gastric glands of stomach has no fat-emulsifying enzyme but has a weak gastric lipase enzyme which hydrolyses a small amount of fats. It is so that gastric lipase has an optimum pH 4.0 to 5.0 and is inactivated by strong acidic conditions. However, most of the ingested lipids are digested in the intestine by pancreatic lipases.

c) **In Small Intestine:**

(1) **Action of Bile.** Bile of liver is an alkaline, yellowish-green and non-enzymatic digestive juices has no chemical action on food. It is formed of water (86%), sodium bicarbonates, bile pigments (green coloured biliverdin and yellow coloured bilirubin),

two bile salts (sodium glycocholate and sodium taurocholate). About 90% of bile salts show enterohepatatic circulation between intestine and liver. These are absorbed in portal blood and carried to liver and reused in bile formation again and again. Bile increases the absorption of fat, it is an important part of the absorption of the fat-soluble substances, such as the vitamins A, D, E, and K. Besides its digestive function, bile serves also as the route of excretion for bilirubin, a byproduct of red blood cells recycled by the liver. Bile salts or bile juice creates an alkaline medium in small intestine for the action of enzymes named; pepsin and trypsin which are used for digestion of protien also bile juice convert big fat molecules into smaller molecules for the action of lypase on fats. Large amounts of bile acids are secreted into the intestine every day, but only relatively small quantities are lost from the body. This is because approximately 95% of the bile acids delivered to the duodenum are absorbed back into blood within the ileum.



Bile acids emulsify lipids in the small intestine, increasing the surface area for digestion. The hydrophobic products of lipid digestion are solubilized in micelles by bile acids. Bile acids are lipid carriers and are able to solubilize many lipids by forming micelles - aggregates of lipids such as fatty acids, cholesterol and monoglycerides - that remain suspended in water. Bile acids are also critical for transport and absorption of the fat soluble vitamens.

(2) **Action of pancreatic lipases (Steapsin**): Pancreatic lipase, also known as pancreatic triacylglycerol lipase or steapsin, is an enzyme secreted from the pancreas. As the primary lipase enzyme that hydrolyzes (breaks down) dietary fat molecules in the human digestive system, it is one of the main digestive enzymes, converting triglyceride substrates like 1 found in ingested oils to monoglycerides 3 and free fatty acids 2a and 2b.

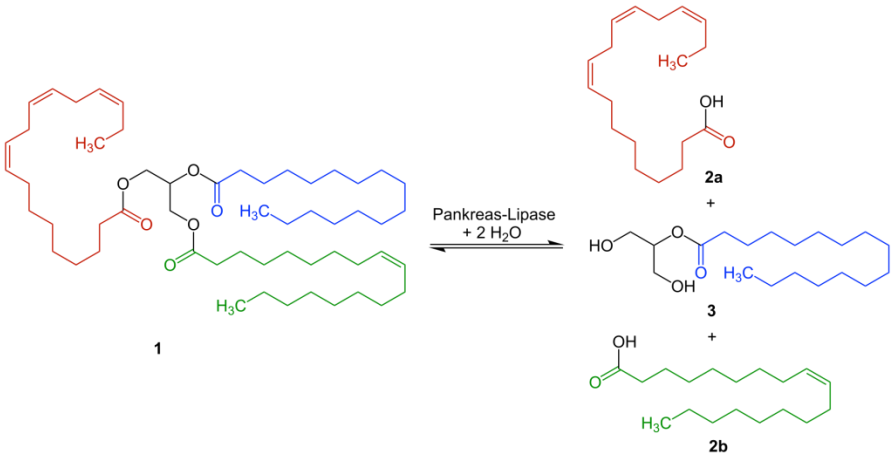


Fig. Hydrolysis of a triglyceride 1

So, the pancreatic lipase hydrolyses the dietary fats and oils into glycerol, fatty acids, monoglyceride and diglyceride. It is so that the fat-digestion is a very slow process which takes about a few hours but is never complete. During, digestion of fats, only 50% fat is completely digested to fatty acids and glycerol while remaining 50% are mono- and di-glycerides.

Emulsified fats —Lipases→ **Fatty acids + Glycerol + Monoglyceride**

The schematic digestion of long chain triglycerides by pancreatic lipases has been shown in above figure.

Pancreatic lipases hydrolyze lipids to fatty acids, monoglycerides, cholesterol, and lysolecithin. The enzymes are pancreatic lipase, cholesterol ester hydrolase, and phospholipase A2.

The role of the colipase in the action of pancreatic lipase.

Colipase is a small protein cofactor needed by pancreatic lipase for efficient dietary lipid hydrolysis. Efficient absorption of dietary fats is dependent on the action of pancreatic triglyceride lipase. Colipase binds to the C-terminal, non-catalytic domain of lipase, thereby stabilising an active conformation and considerably increasing the hydrophobicity of its binding site. Structural studies of the complex and of colipase alone have revealed the functionality of its architecture.

Colipase, abbreviated CLPS, is a protein co-enzyme required for optimal enzyme activity of pancreatic lipase. ... Its function is to prevent the inhibitory effect of bile salts on the lipase-catalyzed intra-duodenal hydrolysis of dietary long-chain triglycerides. In humans, the colipase protein is encoded by the CLPS gene. Colipase is also a family of evolutionarily related proteins.

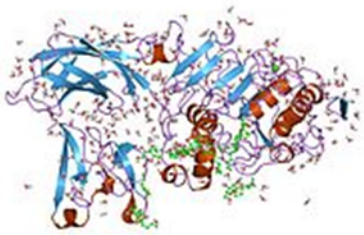


Fig. Structure of the pancreatic lipase-colipase complex inhibited by a C11 alkyl phosphonate.

Symbol	**Colipase**
Pfam	PF01114
InterPro	IPR001981
PROSITE	PDOC00111
SCOP2	1lpb / SCOPe / SUPFAM
CDD	cd00039

Pancreatic juice has also two more lipolytic enzymes: Phospholipase and cholesterol-esterase which hydrolyse the phospholipids and free cholesterol respectively.

(3) **Action of Intestinal juice:** Lipase, any of a group of fat-splitting enzymes found in the blood, gastric juices, pancreatic secretions, intestinal juices, and adipose tissues. Lipases hydrolyze triglycerides (fats) into their component fatty acid and glycerol molecules.

Initial lipase digestion occurs in the lumen (interior) of the small intestine. Bile salts reduce the surface tension of the fat droplets so that the lipases can attack the triglyceride molecules. The fatty acid and glycerol molecules are then taken up into the epithelial cells that line the intestinal wall, where they are resynthesized into triglycerides for transport to muscles and adipose tissues. At these sites lipases in the bloodstream hydrolyze the triglycerides, and the resulting fatty acids and glycerol are taken up by the cells of these tissues. In the adipose tissues triglycerides are re-formed for storage until the energy needs of the animal increase under conditions of stress or exercise. Lipases in the cells of adipose tissues break down the triglycerides so that fatty acids can reenter the bloodstream for transport to energy-requiring tissues.

MECHANISM OF ABSORPTION

The term absorption has been derived from L. absorbere = suck in. When the food is present in the lumen of alimentary canal , it is supposed to be out of body because it has not entered the living tissues of the. These digested food materials must pass on to the body tissue so that these can be used in cellular functions.

It is process by which diffusible nutrients are transferred from the lumen of gut into the blood or lymph by certain physic-chemical processes and active transport.

The absorptive power varies greatly in different regions of the alimentary canal. No appreciable absorption of nutrients occurs through the mucus membrane of buccal cavity and oesophagus except of adrenaline chloride and methyl testosterone. Absorption of only certain drugs occurs in buccal cavity. Very little absorption takes place through the gastric mucosa e.g. of water, alcohol, simple salts, glucose and chlorides. The mucosa of colon and rectum is involved in the absorption of water, glucose and inorganic salts.

So, the principal site of the absorption of digested and diffusible nutrients is the small intestine.

To ensure maximum absorption, small intestine shows following adaptations:

i) Enormously long sized small intestine (6 metres or 20 feet).

ii) Mucosal layer of small intestine is thrown into circular folds which cause a three folds increase in its surface area. These mucosal folds are called folds of Kerckring (also called plicae circulares) and raised into about 4 million finger like projections, called villi, which cause a further ten-folds increase of its surface area (total 30 folds increase). Each villus is about 0.5 to 1 mm long and there are 20-40 villi per mm^2 of intestinal mucosa.

iii) The free surface of each epithelial cell of a villus has electron microscopic evaginations called microvilli (3,000 per intestinal cell) which forms a brush border. These microvilli increase the absorptive surface area by 20 to 30 folds. The villi are numerous in ileum of small intestine.

iv) Each villus is with a lymph capillary called lacteal in the centre which is surrounded by a network of blood capillaries and about 1.4 ltrs of blood flows through this capillary network per minute which is increased by 1-3^{rd} during digestion of food.

v) Absorption is further increased by the movements of villi stimulated by villikinin hormone secreted by the mucosa of small intestine. These movements of villi help to pump lymph into the lacteals of the sub-mucosa.

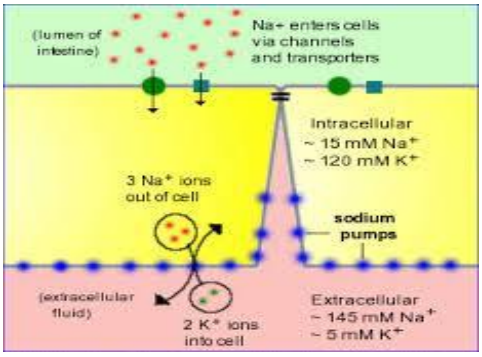


Fig. Absorption in Small Intestine

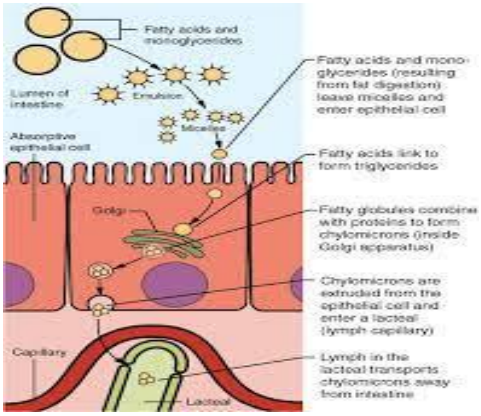


Fig. Chemical digestion and absorption(Unlike amino acids and simple sugars, lipids are transformed as they are absorbed through epithelial cells)

The absorption across plasma membrane of intestinal cells depends upon two types of processes:

(A) Passive absorptiom and (B) Active absorption

Passive absorption. In this, the nutrients are absorbed along the concentration gradient (higher concentration inside the lumen of the small intestine while lower concentration inside the intestinal blood capillaries). It depends upon the physical processes like diffusion, osmosis and facilitated diffusion (movement of molecules like fructose, mannose, etc. along concentration gradient with the help of some carrier molecules). It does not depend upon the energy so is a slow process. It continues till the concentration becomes equal on both sides of cell membrane so the substances cannot be absorbed completely. Water, some water soluble substsances, most vitamins, purines, pyrimidine and fructose are absorbed by passive absorption.

Active absorption. In this, the nutrients are absorbed through the intestinal mucosa against concentration gradient. This is a rapid process as it depends upon the energy provided

by the ATP. By active absorption, the nutrients can be absorbed completely from the intestinal lumen. If the cells are poisoned with cyanide or depressed by cold, active absorption stops. Active absorption occurs by two processes:

i) **Active transport** is that active absorption which involves the carrier molecules called permease or translocases which are generally proteinaceous in nature. Glucose, galactose, amino acids, Na^+ etc. are absorbed by active transport. For active transport of Na^+, a sodium pump operates in the cell membrane.

ii) **Endocytosis** is also an active process by which large sized liquid or solid nutrients are taken in some vesicles through the plasma membrane.

There are some evidence that the leucocytes found in the intestinal mucosa, actually pass through the intestinal wall and engulf the food particles and when become loaded with food, carry them back into the blood and lymph.

1. ABSORPTION OF CARBOHYDRATES

Carbohydrates are chiefly absorbed by the small intestine in the form of monosaccharides like glucose (80%), galactose (10%), and fructose (10%) formed by the hydrolysis of polysaccharides and oligosaccharides. Fructose is absorbed mainly by facilitated diffusion while glucose and galactose are absorbed actively.

Different monosaccharides show differential absorption (Cori, 1925). He reported that rate of absorption of monosaccharides depends upon:

a) **Size of the sugar**. The pentoses (ribose, deoxyribose) are small sized so are absorbed more rapidly than hexoses.

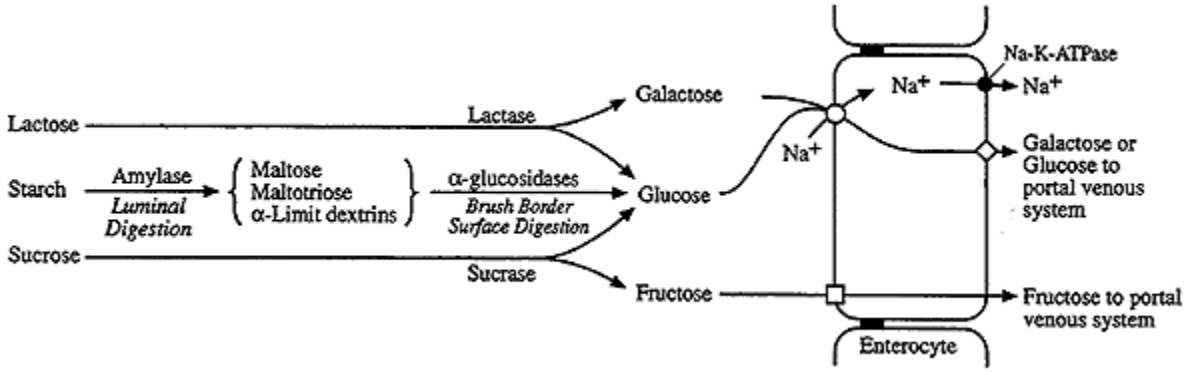
b) Configuration structure. The rapid absorption of galactose and glucose than fructose has been explained on the basis that carbohydrates having D-pyranose ring form having an intact –OH at the position 2-carbon undergo active transport while fructose having furanose ring form is absorbed by facilitated diffusion. The faster absorption of fructose than mannose was explained on the basis of its conversion into lactic acid in the epithelial cells (**Wilson and Weismann,** 1954) in rat and hamster; and glucose (**Hers and Kusaka**, 1953) in guinea pig and hamster.

Monosaccharides are absorbed by carrier mediated transport.

At least two types are known:

1. Na^+ monosaccharide transporter

2. Na^+ independent, diffusion type monosaccharide transport system



Glucose and Galactose

They are transported from the intestinal lumen into the cells by a Na^+- dependent co-transport (SGLT 1) in the luminal membrane. The sugar is transported "uphill" and Na^+ is transported "downhill."

They are then transported from cell to blood by facilitated diffusion (GLUT 2).

The Na^+–K^+ pump in the baso-lateral membrane keeps the intracellular [Na^+] low, thus maintaining the Na^+ gradient across the luminal membrane.

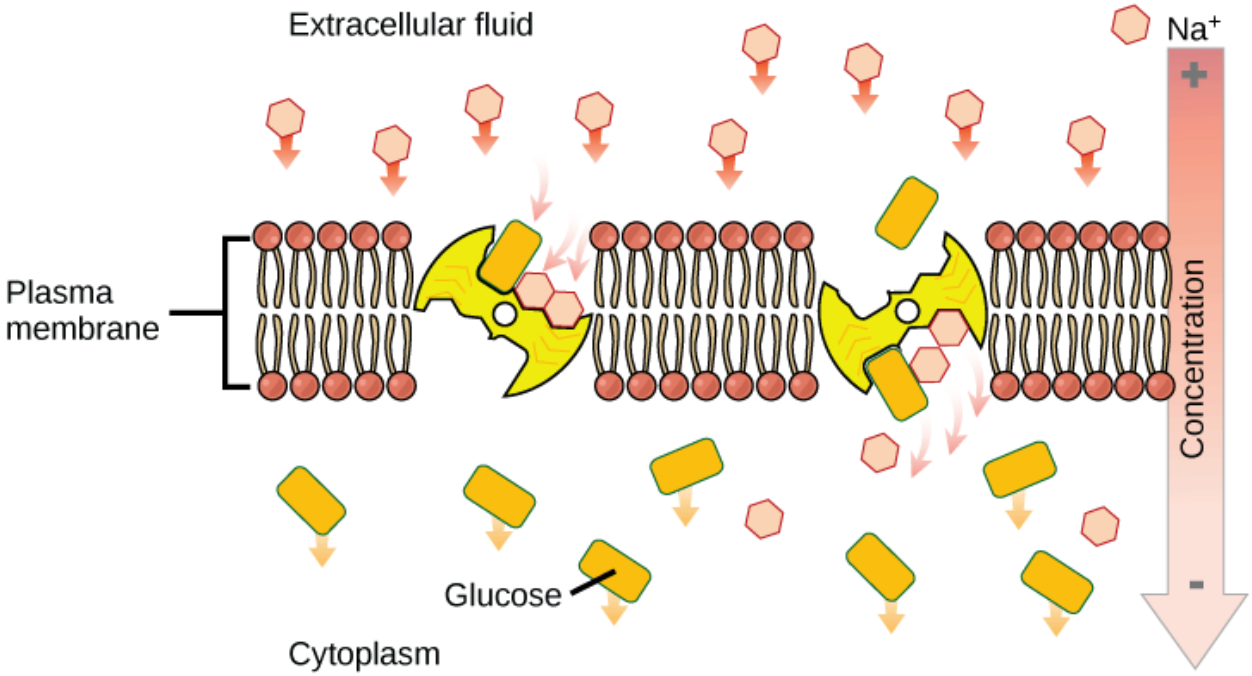


Fig – Sodium moves down its concentration gradient, bringing in glucose to the the cell.

Glucose and galactose are absorbed across the apical membrane by secondary active transport (along with Na+) through the Sodium-Glucose cotransporter (SGLT1). Both glucose and galactose exit the cell via GLUT2 receptors across the basolateral membrane into the blood. Fructose enters the cell by facilitated diffusion via GLUT5 and is transported into the blood via GLUT2 receptors.

Fructose: It differs from that of glucose and galactose:

- **i)** Fructose is transported exclusively by facilitated diffusion;
- **ii)** It cannot be absorbed against a concentration gradient;
- **iii)** It is partly converted into glucose in the intestinal cells and then released in the portal blood.

Absorption of Disaccharides

Millner and Crane (1960) showed that the disaccharides like sucrose (cane sugar), maltose (malt sugar), and lactose (milk sugar) first enter the enterocytes. Sucrose is mainly absorbed in the jejunum in man. Inside enterocytes of intestinal mucosa, these are hydrolysed by the disaccharidases like sucrose, maltase, and lactase respectively into their monosaccharides. These are then passed from enterocytes into the blood capillary within villus. So the earlier belief that dietary disaccharides are first broken into monosaccharides in intestinal lumen and then absorbed, is not applicable. Out of these disaccharides, lactose is less taken by the enterocytes so lactose reaches the lower part of the intestine and promotes the growth of highly beneficial certain lactose- fermenting micro-organism.

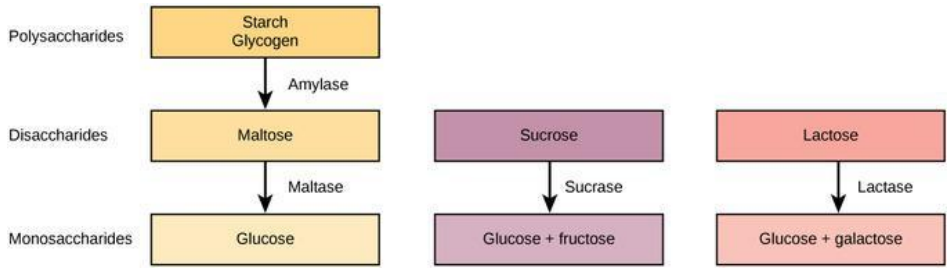


Fig. Digestion of carbohydrates: Digestion of carbohydrates is performed by several enzymes. Starch and glycogen are broken down into glucose by amylase and maltase. Sucrose (table sugar) and lactose (milk sugar) are broken down by sucrase and lactase, respectively.

2. ABSORPTION OF PROTEINS

In the gastro-intestinal tract, exogenous proteins (dietary) as well as endogenous proteins (enzymatic proteins and epithelial cellular proteins) are hydrolyzed by proteases into tri and dipeptides or free amino acids. In all, about 98% of the dietary proteins are hydrolyzed into amino acids. Amino acids are 2 types: L-amino acids (naturally occurring) and D-amino acids (optical isomers). The L-amino acids are absorbed by active transport in the presence of vitamin B6 while D-amino acids are absorbed passively by diffusion. The small intestine also shows differential absorption of amino acids which depends upon:

i) **Molecular weight**. Small sized amino acids with low molecular weight are absorbed faster e.g.,glycine is absorbed more rapidly followed by alanine, cysteine, glutamic acid, valine and so on.

ii) **Form of amino acids**. L-amino acids are absorbed rapidly than the corresponding D-amino acids (Gibson and Weismann, 1951).

Free amino acids. Almost all the L-amino acids are too large to diffuse through the pores of the plasma membrane, so amino acids are mainly absorbed by facilitated or active transport involving carrier mechanisms. The carrier molecules have been reported in the brush border of the enterocytes. Four types of transport systems (because different amino acids have different binding properties) have been reported to be involved in the transport of amino acids. Each system being involved with a specific subset of amino acids with specific molecular characteristics and all being dependent upon high concentration of Na^+ in the intestinal lumen because amino acids and Na^+ show symport as in glucose transport.

Na+-dependent amino acid cotransport occurs in the luminal membrane. It is analogous to the cotransporter for glucose and galactose. The amino acids are then transported from cell to blood by facilitated diffusion. There are four separate carriers for neutral, acidic, basic, and imino amino acids, respectively.

Dipeptides and tripeptides. They are absorbed faster than free amino acids but in different ways. These first enter the enterocytes where these are hydrolyzed into amino acids by peptidases present in the brush border of the enterocytes and are then released into the portal blood.

The intestinal cells of the new born can absorb the whole proteins by pinocytosis so is able to absorb the proteinaceous antibodies from the mother's milk to get immunity against the pathogenic microbes. But this power is lost within a few week.

H^+-dependent co-transport of dipeptides and tripeptides also occurs in the luminal membrane. After the dipeptides and tripeptides are transported into the intestinal cells, cytoplasmic peptidases hydrolyze them to amino acids. The amino acids are then transported from cell to blood by facilitated diffusion.

3. ABSORPTION OF FATS

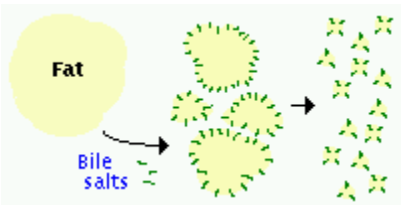
The bulk of dietary lipid is neutral fat or triglyceride, composed of a glycerol backbone with each carbon linked to a fatty acid. Foodstuffs typically also contain phospholipids, sterols like cholesterol and many minor lipids, including fat-soluble vitamins. Finally, small intestinal contents contain lipids from sloughed epithelial cells and considerable cholesterol delivered in bile. The end products of fats are a mixture of monoglycerides, fatty acids and glycerol. Glycerol is water soluble so is directly absorbed by the mucosal cells of small intestine. The short chain fatty acids (less than 14-carbon atoms) are directly absorbed into the portal circulation because these are more water-soluble so are readily diffusible into the blood capillaries of the villi through the epithelial cells. But the long chain fatty acids and monoglycerides are insoluble in water.

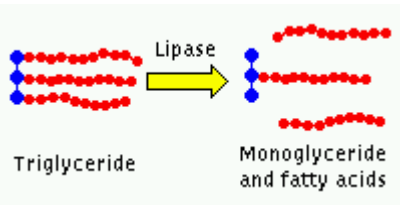
In order for the triglyceride to be absorbed, two processes must occur:

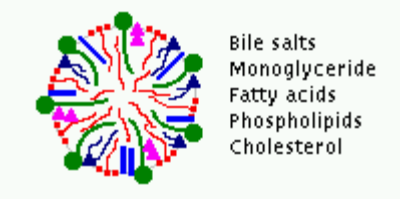
Large aggregates of dietary triglyceride, which are virtually insoluble in an aqueous environment, must be broken down physically and held in suspension - a process called emulsification.

Triglyceride molecules must be enzymatically digested to yield monoglyceride and fatty acids, both of which can efficiently diffuse or be transported into the enterocyte

The key players in these two transformations are bile acids and pancreatic lipase, both of which are mixed with chyme and act in the lumen of the small intestine. Bile acids are also necessary to solubilize other lipids, including cholesterol.







Emulsification, Hydrolysis and Micelle Formation

Bile acids play their first critical role in lipid assimilation by promoting emulsification. As derivatives of cholesterol, bile acids have both hydrophilic and hydrophobic domains (i.e. they are amphipathic). On exposure to a large aggregate of triglyceride, the hydrophobic portions of bile acids intercalate into the lipid, with the hydrophilic domains remaining at the surface. Such coating with bile acids aids in breakdown of large aggregates or droplets into smaller and smaller droplets.

Hydrolysis of triglyceride into monoglyceride and free fatty acids is accomplished predominantly by pancreatic lipase. The activity of this enzyme is to clip the fatty acids at positions 1 and 3 of the triglyceride, leaving two free fatty acids and a 2-monoglyceride. The drug orlistat (Xenical) that is promoted for treatment of obesity works by inhibiting pancreatic lipase, thereby reducing the digestion and absorption of fat in the small intestine.

Lipase is a water-soluble enzyme, and with a little imagination, it's easy to understand why emulsification is a necessary prelude to its efficient activity. Shortly after a meal, lipase is present within the small intestine in rather huge quantities, but can act only on the surface of triglyeride droplets. For a given volume of lipid, the smaller the droplet size, the greater the surface area, which means more lipase molecules can get to work.

As monoglycerides and fatty acids are liberated through the action of lipase, they retain their association with bile acids and complex with other lipids to form structures called micelles. Micelles are essentially small aggregates (4-8 nm in diameter) of mixed lipids and bile acids suspended within the ingesta. As the ingesta is mixed, micelles bump into the brush border of small intestinal enterocytes, and the lipids, including monoglyceride and fatty acids, are taken up into the epithelial cells.

Transport of lipids into the circulation is also different from what occurs with sugars and amino acids. Instead of being absorbed directly into capillary blood, chylomicrons are transported first into the lymphatic vessel that penetrates into each villus called the central lacteal. Until recently, it was not understood how the large chylomicrons are taken up into the lacteals. As it turns out, there are patches of the lacteal in which endothelial cells are held

together through specialized "button junctions" that are much more permeable to chylomicrons than normal cellular junctions. Chylomicron-rich lymph then drains into the system lymphatic system, which rapidly flows into blood. Blood-borne chylomicrons are rapidly disassembled and their constitutent lipids utilized throughout the body.

SUMMARY OF LIPID ABSORPTION

Lipids within the digestive system will tend to hydrophobically aggregate to form large fat globules.

Bile salts, secreted from the gall bladder, emulsify these fat globules and break them up into smaller droplets.

Hydrolytic enzymes called lipases then digest the fats into their component parts.

When the fatty acids are absorbed into the epithelial cells of the intestinal lining, they are combined to form triglycerides.

The triglycerides are combined with proteins inside the Golgi apparatus to form chylomicrons.

Chylomicrons are released from the epithelial cells and are transported via the lacteals to the liver.

While in the liver, chylomicrons may be modified to form a variety of lipoproteins.

Low density lipoproteins will transport lipids via the bloodstream to cells.

High density lipoproteins will scavenge excess lipids from the bloodstream and tissues and return them to the liver.

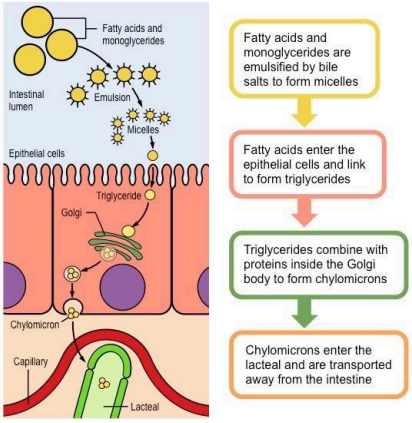


Fig. Lipid absorption in small intestine

Cholesterol

Another lipid of importance that is absorbed in the small intestine is cholesterol. Cholesterol homeostatis results from a balance of cholestrol synthesis, absorption of dietary cholesterol, and elimination of cholesterol by excretion in bile. Years ago it was shown that cholesterol, but not plant sterols, is readily absorbed in the intestine. More recently, a specific transport protein (NPC1L1) has been identified that ferries cholesterol from the intestinal lumen into the enterocyte. From there, a bulk of the cholesterol is esterified, incorporated into chylomicrons and shuttled into blood by the mechanisms described above. In enterocytes, the cholesterol is re-esterified and finally slowly released into the lacteals.

4. ABSORPTION OF OTHER SUBSTANCES

Nucleic Acid Absorption

The products of nucleic acid digestion—pentose sugars, nitrogenous bases, and phosphate ions—are transported by carriers across the villus epithelium via active transport. These products then enter the bloodstream.

Mineral Absorption

The electrolytes absorbed by the small intestine are from both GI secretions and ingested foods. Since electrolytes dissociate into ions in water, most are absorbed via active transport throughout the entire small intestine. During absorption, co-transport mechanisms result in the accumulation of sodium ions inside the cells, whereas anti-port mechanisms reduce the potassium ion concentration inside the cells. To restore the sodium-potassium gradient across the cell membrane, a sodium-potassium pump requiring ATP pumps sodium out and potassium in.

In general, all minerals that enter the intestine are absorbed, whether you need them or not. Iron and calcium are exceptions; they are absorbed in the duodenum in amounts that meet the body’s current requirements, as follows:

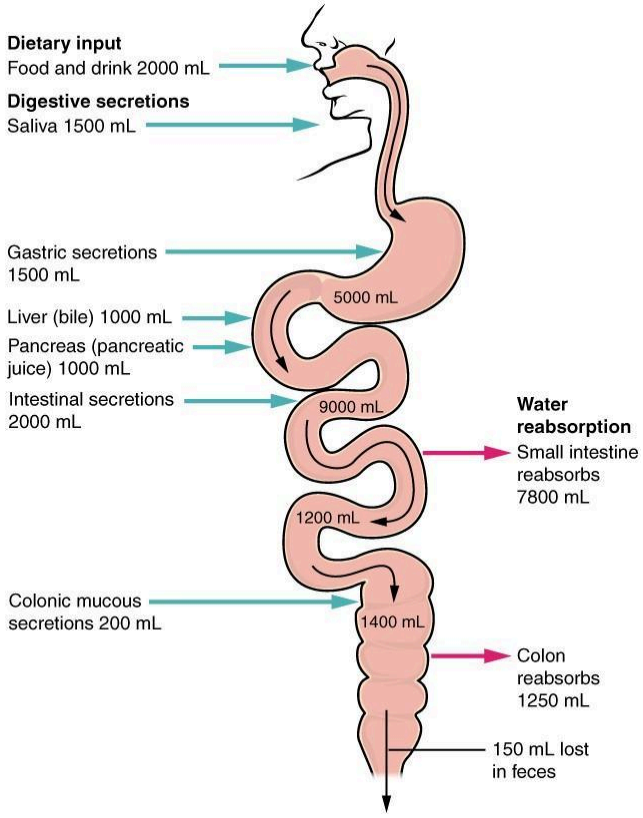


Figure Absorption is a complex process, in which nutrients from digested food are harvested.

Iron—The ionic iron needed for the production of hemoglobin is absorbed into mucosal cells via active transport. Once inside mucosal cells, ionic iron binds to the protein ferritin, creating iron-ferritin complexes that store iron until needed. When the body has enough iron, most of the stored iron is lost when worn-out epithelial cells slough off. When the body needs iron because, for example, it is lost during acute or chronic bleeding, there is increased uptake of iron from the intestine and accelerated release of iron into the bloodstream. Since women experience significant iron loss during menstruation, they have around four times as many iron transport proteins in their intestinal epithelial cells as do men.

Calcium—Blood levels of ionic calcium determine the absorption of dietary calcium. When blood levels of ionic calcium drop, parathyroid hormone (PTH) secreted by the parathyroid glands stimulates the release of calcium ions from bone matrices and increases the reabsorption of calcium by the kidneys. PTH also upregulates the activation of vitamin D in the kidney, which then facilitates intestinal calcium ion absorption.

Vitamin Absorption

The small intestine absorbs the vitamins that occur naturally in food and supplements. Fat-soluble vitamins (A, D, E, and K) are absorbed along with dietary lipids in micelles via simple

diffusion. This is why you are advised to eat some fatty foods when you take fat-soluble vitamin supplements. Most water-soluble vitamins (including most B vitamins and vitamin C) also are absorbed by simple diffusion. An exception is vitamin B12, which is a very large molecule. Intrinsic factor secreted in the stomach binds to vitamin B12, preventing its digestion and creating a complex that binds to mucosal receptors in the terminal ileum, where it is taken up by endocytosis.

Water Absorption

Each day, about nine liters of fluid enter the small intestine. About 2.3 liters are ingested in foods and beverages, and the rest is from GI secretions. About 90 percent of this water is absorbed in the small intestine. Water absorption is driven by the concentration gradient of the water: The concentration of water is higher in chyme than it is in epithelial cells. Thus, water moves down its concentration gradient from the chyme into cells. As noted earlier, much of the remaining water is then absorbed in the colon.

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