7.7 Digestion and Absorption

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DIGESTION AND ABSORPTION OF CARBOHYDRATES

DIETARY CARBOHYDRATES

Dietary intake of carbohydrates is 250-850 gm/day, which represents 50 to 60 per cent of the diet. Major carbohydrates in the human diet are present in following forms:

1. ***Polysaccharides.*** Polysaccharides are made up of many monosaccharides, may be upto a million. These may be present in following forms:

- *Starch* is the carbohydrate reserve of plants. It consists of two polysaccharide components:
  - Amylose (15-20%). It is a water soluble straight-chain polysaccharide, and
  - Amylopectin (80-85%). It is a water insoluble branched -chain polysaccharide.
- *Glycogen.* It is available in non-vegetarian diet and so often referred to as animal starch. In it glucose molecules are mostly long chain (1:4 $\propto$ linkages and 1:6 $\propto$ linkages) at branching points.
- *Cellulose* is another plant polysaccharide, which is present in diet in large amounts. But there is no enzyme in the human GIT to digest it, so it is excreted.

2. ***Oligosaccharides.*** Undigested oligosaccharide contains 2-10 monosaccharide molecules which are liberated on hydrolysis. Based on the number of monosaccharide units present, oligosaccharides are further subdivided into di, tri, tetra and pentasaccharide.

Disaccharides include:
- Sucrose (glucose + fructose) is also known as table sugar (cane or beet sugar).
- Lactose (glucose + galactose) is also called milk sugar.
- Maltose (glucose + glucose). It is a product of starch hydrolysis. It is present in germinating seeds.

3. ***Monosaccharides.*** Monosaccharides consumed mostly in human diet are *hexoses* such as:
- Glucose (in fruits, vegetables and honey), and
- Fructose in fruits.

Pentoses do not occur in free form, but are found in nucleic acid and in certain polysaccharides such as pentosans of fruits and gums.

Other carbohydrates, which may be present in the human diet are alcohol, lactic acid, pyruvic acid, pectin, dextrin and minor quantities of carbohydrate derivatives in the meat.

DIGESTION OF CARBOHYDRATES

The digestion of carbohydrates begins in mouth, continues in stomach but occurs mainly (almost all) in the small intestine.

Digestion of carbohydrates in the mouth

Initial starch digestion starts in the mouth by the enzyme α-amylase (ptyalin) present in the saliva. However, the role of salivary amylase in the digestion of carbohydrates is limited by the short duration of stay of the food in the mouth.

α-amylase present in the saliva acts on the 1-4 linkages (but not on 1-6 linkages). It digests cooked starch to maltose:

Digestion of carbohydrates in the stomach

In the stomach there occurs minimal carbohydrates digestive activity:

α-amylase (which enters the stomach with food) activity continues in the stomach for 20-30 minutes till the highly acidic gastric juice mixes with the food and makes it inactive. The optimum pH for the action of salivary amylase is 6-7, and its activity in the stomach completely stops when pH falls below 4.

The HCl of the gastric juice may hydrolyse some sucrose.

Digestion of carbohydrates in the small intestine

In the small intestine the carbohydrates are digested by the amylolytic enzymes present in the pancreatic juice and brush border enzymes of small intestine.

Pancreatic α-amylase is present in the pancreatic juice which is poured into the duodenum. Its actions on the carbohydrates are similar to that of salivary amylase, but it is much powerful and so it acts on boiled as well as unboiled starch and variety of other carbohydrates except cellulose. It hydrolyses almost all the starch within 15 to 30 minutes of the entry of chyme into the duodenum. Its action occurs before the chyme passes beyond the duodenum or upper jejunum.

Pancreatic amylase acts in an alkaline medium and its digestive activity is increased by the presence of bile salts. It converts the starch (polysaccharides) into (oligosaccharides) such as maltose, maltotriose and dextrin (Fig. 7.7-1).

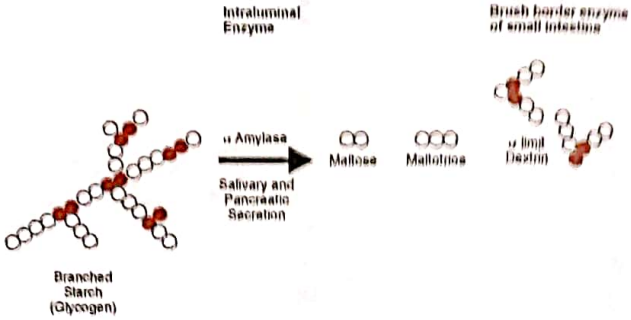


Fig. 7.7-1. Digestion of carbohydrates.

Polysaccharides —Pancreatic amylase→ Oligosaccharides
(e.g. starch and glycogen) (e.g. maltose, dextrin etc.)

Brush border enzymes of small intestine. The carbohydrate splitting brush border enzymes of small intestine include *dextrinase*, *maltase*, *sucrase* and *lactase*. It is believed that these brush border enzymes digest the oligosaccharides into monosaccharides on the surface of epithelial cells of villi as below:

- *α-limiting dextrinase*. It is the only enzyme in GIT which attacks 1,6 ∝ glycoside linkage, at the branching points of α-limit dextrins. It also attacks 1,4∝ glycosidic linkages resulting in sequential removal of glucose monomers from the dextrins (the breakdown products of starch by the enzyme amylase).

$$\text{Dextrin} \xrightarrow{\alpha\text{-limiting dextrinase}} \text{Glucose}$$

- *Maltase, sucrase and lactase* hydrolyse the corresponding disaccharides into monosaccharides as below:

$$\text{Maltose} \xrightarrow{\text{Maltase}} \text{Glucose}$$

$$\text{Sucrose} \xrightarrow{\text{Sucrase}} \text{Glucose} + \text{Fructose}$$

$$\text{Lactose} \xrightarrow{\text{Lactase}} \text{Glucose} + \text{Galactose}$$

End products of carbohydrate digestion

- The carbohydrate digestion is completed in the small intestine (mainly in jejunum and proximal ileum).
- The end products of carbohydrates are monosaccharides such as glucose, fructose and galactose. The glucose represents 80% and galactose and fructose combinedly represent only 20% of the end products.
- A little amount of other monosaccharide called pentoses are the end products of digestion of nucleic acids and partial digestion of pentosans.

ABSORPTION OF CARBOHYDRATES

Carbohydrates are absorbed from the GIT in the form of monosaccharides. The monosaccharides include those formed at the brush border (described above) and also those ingested as such (e.g. glucose and fructose in fruits).

Site of absorption

Most of the monosaccharides are absorbed from the mucosal surface of jejunum and upper ileum. The absorption is almost completed before the remains of meal reach the terminal ileum. Negligible absorption also occurs in stomach and colon.

Mechanism of absorption

Various monosaccharides are absorbed by following mechanisms:

- *Glucose* and *galactose* are absorbed by a common *Na^+ dependent active transport* system:
- *Fructose* is absorbed by *facilitated diffusion*. Fructose absorption occurs readily, because most of the fructose is rapidly converted into glucose and lactic acid within the epithelial cells, thus maintaining a high concentration gradient for diffusion.
- *Pentoses* are absorbed by simple diffusion.

Absorption of glucose and galactose

Glucose and galactose are absorbed into the epithelial cells (enterocytes) lining the mucous membrane of small intestine from their brush border surface (luminal surface) by an *active transport mechanism* – the *sodium co-transport* mechanism. Salient points of glucose absorption are (Fig. 7.7-2):

Binding of glucose and Na^+ to carrier protein. The carrier protein (present in the cell membrane) has two binding sites one for sodium and another for glucose. It is called *sodium dependent glucose transporter-1 (SGLT-1)*. The conformational change in the carrier protein occurs only when the binding sites are occupied by the sodium and glucose present in the gut lumen forming the sodium-glucose-carrier complex.

Creation of electrochemical gradient across the epithelial cell. The active transport of sodium by Na^+-K^+-ATPase pump through the basolateral membrane into the paracellular spaces lowers the intracellular Na^+ concentration. This creates an electrochemical gradient.

Movement of sodium and glucose inside the cell. Because of the electrochemical gradient created, the sodium moves into the cell (downhill transport). The flow of sodium ions down the gradient is so forceful that glucose (or galactose) molecule attached to the carrier protein also enters the cell even against concentration

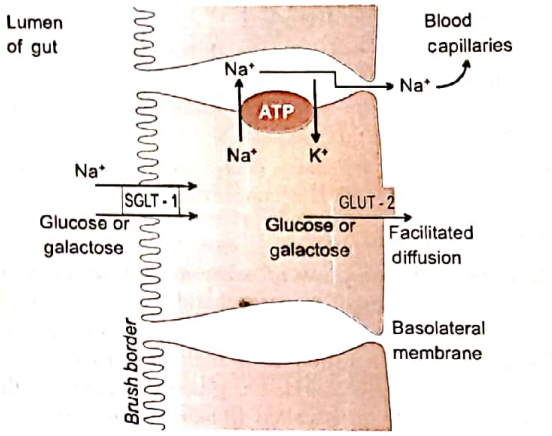


Fig. 7.7-2. Mechanism of glucose absorption across intestinal epithelial cell.

gradient for glucose (uphill movement). Because two Na^+ are transported down their electrochemical gradient, a large amount of energy is available for transport. Thus almost all of the glucose and galactose present in the intestine can be absorbed (against the concentration gradient). The energy so released is required for Na^+-K^+ pump activity to maintain the sodium gradient.

Transport of glucose into blood capillaries. From the epithelial cell the glucose is transported into the interstitial space and thence to blood capillaries of portal system through *facilitated diffusion* by *glucose transporter-2 (GLUT-2)*.

Factors affecting glucose absorption

1. ***Presence of Na^+ in the intestinal lumen.*** Due to common carrier protein the entry of glucose/galactose into the epithelial cells is favoured by the presence of Na^+ in the intestinal lumen (similarly presence of glucose and galactose in the lumen favours the absorption of Na^+).

2. ***State of mucous membrane.*** Absorption of glucose is decreased in abnormal states of mucous membrane such as in enteritis and coeliac disease.

3. ***Duration of time during which the carbohydrate remains in contact with mucous membrane.*** Absorption of glucose is decreased because of intestinal hurry in conditions like diarrhoea, excision of small intestine, and gastrocolic fistula.

4. ***Role of endocrines*** in glucose absorption is as below:

- *Thyroid.* Thyroxine increases the glucose absorption by directly acting on the mucosa. Therefore, in thyrotoxicosis glucose absorption is increased and in

myxoedema it is decreased.

- *Anterior pituitary* affects the glucose absorption by its effects on the thyroid gland. Hyperpituitarism causes hyperthyroidism and thus increases the glucose absorption and vice versa.
- *Adrenal cortex deficiency*, decreases glucose absorption by decreasing the Na^+ concentration.

Note

Regulation of absorption of monosaccharides does not exist, i.e. absorption of monosaccharides is *not regulated.* The intestines can absorb over 5 kg of sucrose per day. Therefore, after ingestion of a high carbohydrate diet there can occur glycosuria, i.e. glucose appears in the urine. This condition is called *alimentary glycosuria.*

Rate of absorption of monosaccharides is variable, being:

- Fastest with glucose and galactose,
- Intermediate with fructose, and
- Slowest with mannose or pentoses.

FATE OF GLUCOSE IN THE BODY

1. *Storage as glycogen.* About 5% of the total glucose absorbed is stored as glycogen in the liver and muscles.

2. *Catabolism to produce energy.* About 50-60% of the glucose absorbed is catabolised in the body tissues to produce energy. One gm of glucose produces about 4 K cal of energy when it is completely oxidised to CO_2 and H_2O. Amino acids are formed on transamination of some intermediary products of glucose breakdown.

3. *Conversion into fat.* About 30-40% of glucose is converted into fat and is stored in the fat depot.

ABNORMALITIES OF CARBOHYDRATE DIGESTION AND ABSORPTION

Lactose intolerance

Congenital lactose intolerance refers to a condition in which lactose (milk sugar) cannot be digested due to congenital deficiency of enzyme lactase.

- The undigested lactose acts as osmotic particles and draws excessive fluids into intestine resulting in *diarrhoea.*
- In the colon, the undigested lactose is metabolized by bacteria producing variety of gases (e.g. hydrogen, methane and CO_2) and variety of intestinal irritants which increase the colonic motility
- The diarrhoea so produced can lead to life-threatening dehydration and electrolyte imbalance.
- Avoidance of milk and milk products prevents the symptoms from developing if the infant can be fed by synthetic milk containing sucrose instead of lactose.

Secondary lactase deficiency, occurring in adults is very common. It produces intestinal distension, diarrhoea and flatulence. For adults, it is usually not a problem, as they can easily avoid milk and milk products.

DIGESTION AND ABSORPTION OF PROTEINS

SOURCES OF PROTEINS

The proteins that are digested and absorbed in the GIT come from two sources: exogenous and endogenous.

1. Exogenous (dietary) proteins

- *Daily requirement* of dietary proteins for adults is 0.5-0.7 gm/kg body weight and for children (1-3 years), it is 4 gm/kg.
- *Quantity of dietary proteins* varies with the socio-economic status of the individuals, balanced diet contains about 95-100 gm/day.
- *Sources of dietary proteins* with high biological value are meat, fish, eggs, cheese and other milk products. Soyabeans, wheat and various types of pulses are also rich source of proteins.
- *Proteins of important dietary items* are:
  - Wheat : Glutenin, glycinin and gliadin.
  - Milk : Casein, lactalbumin, albumin and myosin.
  - Egg : Albumin and vitelline.
  - Meat : Collagen, albumin, and myosin.
- *Structure of dietary proteins*. The dietary proteins are made of long chains of amino acids bound together by peptide linkages.

2. Endogenous proteins

Endogenous proteins, totaling 30-50 gm/day, are the proteins which reach the intestine through various gastrointestinal secretions and those which are present in the desquamated epithelial cells of the gut.

DIGESTION OF PROTEINS

Proteins are digested by the proteolytic enzymes to amino acids and small polypeptides before they are absorbed. Digestion of proteins does not occur in the mouth, as there are no proteolytic enzymes in the saliva. Digestion of proteins, thus begins in the stomach and is completed in the small intestine.

Digestion of proteins in the stomach

Pepsin, secreted by chief cells of the main gastric glands in an inactive form (pepsinogen), is responsible for digesting about 10-15% proteins entering the gastrointestinal tract.

- Pepsinogen is converted into pepsin (active form) by the action of HCl or preformed pepsin.
- Pepsin splits proteins into proteoses, peptones and polypeptides (Fig. 7.7-3).
- It is important to note that the optimum pH for the action of pepsin is 2.0, therefore HCl secretion by the stomach is as essential as pepsinogen secretion for the digestion of proteins.
- Pepsin is unique in its proteolytic action because of its ability to digest collagen (which is a major constituent of the intercellular connective tissue of meat). By digesting collagen tissue the pepsin breaks apart the meat particles and facilitates further digestion of cellular proteins of meat.
- Protein digestion within the stomach is particularly important because the protein digestion products act as *secretagogues*, i.e. stimulate secretion of proteolytic enzymes of pancreas.

Digestion of proteins in the small intestine

In the small intestine the proteins are digested by the pancreatic proteases, brush border peptidases and intracellular peptidases.

Pancreatic proteases or proteolytic enzymes of pancreas play a major role in protein digestion. These can digest all the proteins, even if gastric pepsin is absent.

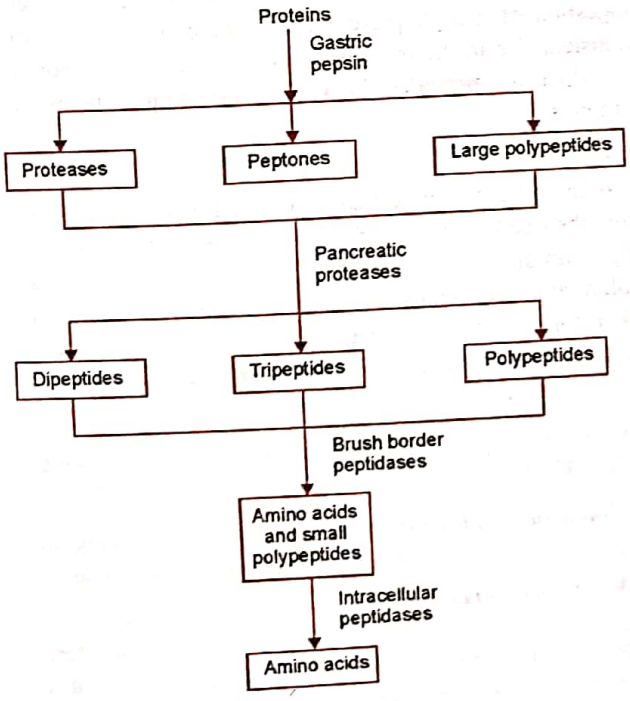


Fig.7.7-3. Digestion of proteins.

- *Various types of proteases* along with their functions are described on page 621.
- *Pancreatic proteases* digest the proteins and split them into dipeptides, tripeptides and small polypeptides, which are further digested by brush border peptidases (Fig.7.7-3).
- Some of the dipeptides and tripeptides are absorbed directly into the epithelial cells of mucosa of small intestine and are further digested by intracellular enzymes into amino acids.

Brush border peptidases are the proteolytic enzymes which form an integral constituent of the epithelial cell membrane with active sites projecting into the lumen.

- Brush border peptidases include aminopeptidases, dipeptidases, tripeptidases, nuclease and related enzymes.
- These enzymes continue the digestive process begun by the pancreatic proteases, eventually converting the proteins to small polypeptides and amino acids (Fig. 7.7-3).

Intracellular peptidases are the proteolytic enzymes present in the cytosol of epithelial cells of small intestine. The multiple peptidases present in the enterocytes are specific for linkages between the various amino acids. Within minutes, these digest the last dipeptides and tripeptides into amino acids which then enter the blood.

Digestion of nucleic acid and nucleoproteins

Nucleic acid and nucleoproteins are found in abundance in the foodstuffs which are rich in nuclei such as liver, kidney, pancreas, yeast, etc.

In the stomach, HCl hydrolyses the nucleoproteins, removing proteins which are digested together with other proteins as described above.

$$\text{Nucleoproteins} \xrightarrow{\text{HCl}} \text{Proteins} + \text{Free nucleic acids}$$

In the small intestine, the free nucleic acids are digested by the pancreatic enzymes and brush border enzymes.

- *Pancreatic enzymes* such as ribonuclease and deoxyribonuclease in the duodenum digest free nucleic acids into nucleotides and nucleosides

$$\text{Free nucleic acids (RNA and DNA)} \xrightarrow[\text{Deoxyribonuclease}]{\text{Ribonuclease}} \text{Nucleotides and nucleosides}$$

- Brush border enzymes such as nucleases, nucleotidases and nucleosidases convert nucleotides and nucleosides into pentoses (purine and pyrimidine).

Nucleotides and Nucleosides —(Nucleases, Nucleotidase; Nucleosidases)→ Pentoses (purine and pyrimidine)

End products of protein digestion

The protein digestion which starts in the stomach is completed in the enterocyte of small intestine.

The end products of protein digestion are amino acids.

ABSORPTION OF PROTEINS

Mechanisms of absorption into the intestinal epithelial cells

The end products of protein digestion (amino acids, dipeptides and tripeptides) are absorbed through the luminal membrane of the epithelial cells of small intestine. Absorption of amino acids is faster in duodenum and jejunum and slower in ileum. Following mechanisms of absorption are known:

1. ***Na^+ dependent active transport mechanism.*** The levo amino acids, dipeptides and tripeptides are absorbed by a Na^+ dependent active transport mechanism.

- Separate transporters (carriers) are present for the absorption of basic, acidic and neutral amino acids. At least two different polypeptide transporters exist.
- Steps of active transport mechanism are similar to those described for glucose absorption (see page 659). these include (Fig. 7.7-4):
  - Binding of amino acid and Na^+ to carrier protein
  - Creation of electrochemical gradient across the epithelial cells.
  - Movement of Na^+ and amino acids inside the cell.

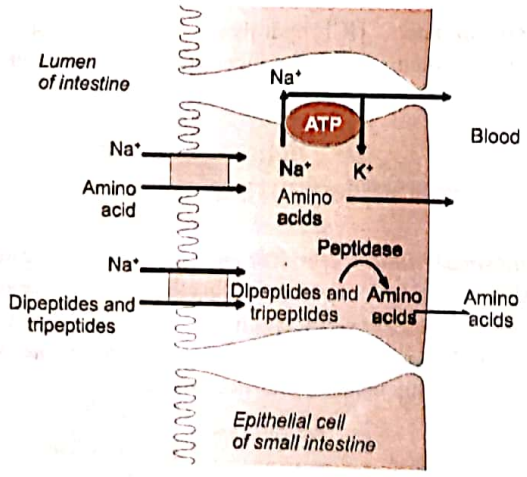


Fig.7.7-4. *Mechanism of absorption of amino acids, dipeptides and tripeptides by intestinal epithelial cells.*

2. ***Simple diffusion.*** The dextro amino acids are absorbed solely by passive diffusion.

3. ***Endocytosis.*** Larger polypeptides cannot be absorbed into the epithelial cells. Occasionally, small amounts of larger polypeptides are absorbed by endocytosis. Proteins absorbed by endocytosis usually excite immunological/ allergic reaction. In newborn infants, immunoglobulins present in the colostrum are absorbed in the intestinal mucosa by endocytosis and impart passive immunity to child.

Further digestion in the epithelial cells

Once amino acids and polypeptides are absorbed into the intestinal epithelial cells, the intracellular peptidases break the remaining linkages of tripeptides, and dipeptides causing release of amino acids.

Transport of amino acids into blood capillaries

From inside the epithelial cells the amino acids are transported into the interstitial space across the basolateral membrane of the cells by facilitated or simple diffusion. From the interstitium the amino acids enter the capillaries of villus by simple diffusion, and then via portal vein, they reach the liver and general circulation. Therefore, after ingestion of a high protein meal, there occurs a sharp transient rise in the free amino acid content of the portal blood, which provides the whole body requirements of proteins.

Note

It is important to note that, almost all proteins ingested are absorbed. About 2-5% of proteins which escape digestion and absorption in the small intestine, enter the colon and are finally digested by bacterial digestion. Therefore, the proteins that appear in the stool are not of dietary origin, but are derived from the bacterial and cellular debris.

ABNORMALITIES OF PROTEIN DIGESTION AND ABSORPTION

1. Inadequate absorption of proteins, due to lack of trypsin is a common consequence of pancreatic diseases.

2. Malabsorption of amino acids due to lack of transporters is relatively rare. For example, in *Hartnup disease* there occurs malabsorption of neutral amino acids due to lack of specific carrier protein.

DIGESTION AND ABSORPTION OF FATS

DIETARY FATS

Types of fats. Fats are of three types:

- Simple fats or neutral fats, e.g. triglycerides and cholesterol.
- Compound fats, e.g. phospholipids.
- Associated fats, e.g. steroids and fat soluble vitamins.

Dietary fat is of both vegetable and animal origin. Mostly it is in the form of neutral fat (triglycerides). It also includes small amounts of phospholipids, cholesterol, some free fatty acids, lecithin and cholesterol esters.

Daily intake of fats in the diet varies widely, from about 25-160 gm.

DIGESTION OF FATS

Site of digestion

Although lipolytic enzymes are secreted in the mouth (*lingual lipase*) and stomach (*gastric lipase*), their action is so insignificant that practically digestion of all the dietary fats occurs in the small intestine. Gastric lipase which initiates fat digestion acts only on butter. Under normal conditions gastric lipase is soon inactivated by gastric juice (pH 1-2), as it is inactivated at pH 2.5 and acts at an optimum pH of 4.5. Some fat digestion in stomach may occur under following exceptional circumstances:

- Achlorhydria (i.e. gastric juice cannot inactivate gastric lipase),
- Regurgitation of pancreatic lipase from the duodenum into the stomach, and
- In young suckling animals which ingest large quantities of milk, the fat of milk is present in an emulsified form and digested, and inhibit the secretion of gastric juice.

Mechanism of digestion of fats

The digestion of fat includes three steps:

- Emulsification of fat by bile salts,
- Hydrolysis of fat by pancreatic and intestinal lipolytic enzymes, and
- Acceleration of fat digestion by micelle formation.

1. Emulsification of fat by bile salts

- Emulsification, i.e. breaking of large fat drops into smaller droplets is a prerequisite for action of pancreatic lipase. It is so, because the pancreatic lipase being water soluble acts only on the oil-water interface of fat. The surface area available for the action of lipase is increased many thousand times by the emulsification of fats.

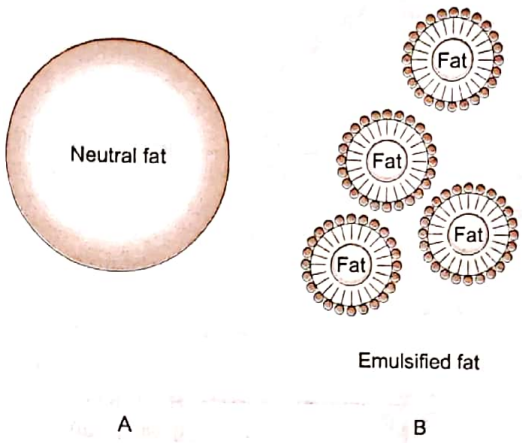


Fig.7.7-5. Emulsification of fats by bile salts: A, a large fat particle; and B, small fat particles surrounded by bile salts.

- Emulsification of fat is caused by bile salts because of their property of lowering the surface tension (detergent like action). With the lowered surface tension of the fats, the segmentation movements of small intestine break up large fat globules into fine droplets (1 µm in diameter). Lecithin (a component of bile) which has a stabilization action on the emulsions, greatly enhances the emulsifying action of bile salts. The bile salts surround the fine fat droplets in such a way that their lipophilic non-polar ends are towards the fat and their hydrophilic polar ends separate the fat droplets from the aqueous phase (Fig. 7.7-5).

2. Hydrolysis of fat droplets by pancreatic and intestinal lipolytic enzymes

Pancreatic juice is markedly alkaline (pH 7.8 to 8.4). When it mixes with the acidic chyme (pH 6.0) coming from stomach into the duodenum, the pH of chyme is adjusted to about 7 (which is optimal pH for the action of pancreatic lipases).

Pancreatic lipolytic enzymes. Pancreatic juice contains three types of lipolytic enzymes. Their hydrolysing effects on fats are given:

i. ***Pancreatic lipase.*** Pancreatic lipase is a very powerful lipolytic enzyme. Fat digestion by it occurs very rapidly after emulsification because of the large-surface-to-volume ratio of the small globules. The colipase a protein present in the pancreatic juice displaces the bile salts from the fat droplet and allows the action of lipase. The pancreatic lipase hydrolyses almost all the triglycerides (neutral fat) of the food to produce two fatty acids and a 2-monoglycerides.

ii. ***Cholesterol ester hydrolase.*** Most of the dietary cholesterol is in the form of cholesterol esters which are

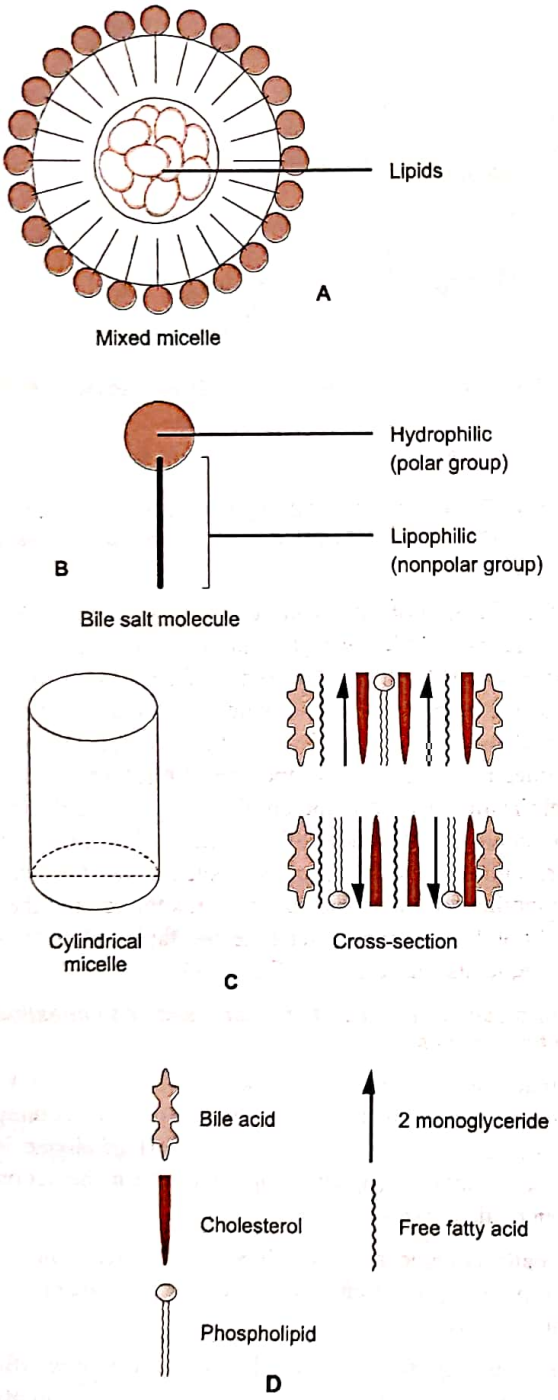
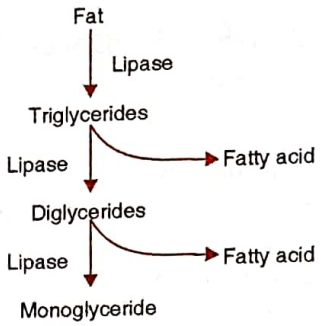


Fig. 7.7-6. *Structure of micelle: A, a mixed micelle composed of lipids (monoglycerides, fatty acids, cholesterol) in the centre surrounded by bile salts; B, bile salt molecule showing globular (hydrophilic or polar) end and lipophilic (non-polar) end; C, a model of the structure of mixed (bile salt, and lipid) micelle and its cross-section showing arrangement of various lipid molecules; and D, diagrammatic structure of different lipid molecules.*



hydrolysed to cholesterol and fatty acid by the cholesterol ester hydrolase.

iii. ***Phospholipase A_2.*** It is secreted in an inactive form pro-phospholipase A_2 and gets converted to active form. It hydrolyses phospholipids and separates fatty acid from them.

Intestinal lipolytic enzymes. Brush border of epithelial cells covering the intestinal villi contain small amount of lipase and cholesterol esterase. Their effects though minor, but are similar to that of pancreatic lipase.

3. Acceleration of fat digestion by micelle formation

The hydrolysis of triglycerides is highly reversible; therefore accumulation of monoglycerides and free fatty acids in the vicinity of digesting fats quickly blocks further digestion. This problem is solved by the property of bile salts to form micelle. The micelles are small water soluble cylindrical disc-shaped particles. Each micelle is composed of a central fat globule surrounded by about 30 molecules of bile salts in such a way that their lipid soluble non-polar ends are in the central fat globule and water soluble polar ends fan out to form the outer covering of micelle. The monoglycerides and free fatty acids released from the digestion of fat are quickly incorporated into the central fatty portion of the micelles forming, what are known as the *mixed micelles* (Fig. 7.7-6). In this way bile salts accelerate the fat digestion by allowing the lipolytic action to continue.

ABSORPTION OF FATS

Most of the fat absorption occurs in the duodenum; almost all the digested lipids are totally absorbed by the time the chyme reaches the mid jejunum. Absorption of fats is accomplished by following steps (Fig. 7.7-7):

1. Transportation as micelles to the brush border membrane. The micelle so formed (as described above) not only accelerates the fat digestion, but are also essential for the fat absorption as explained.

The insolubility of fat globules prevents their diffusion

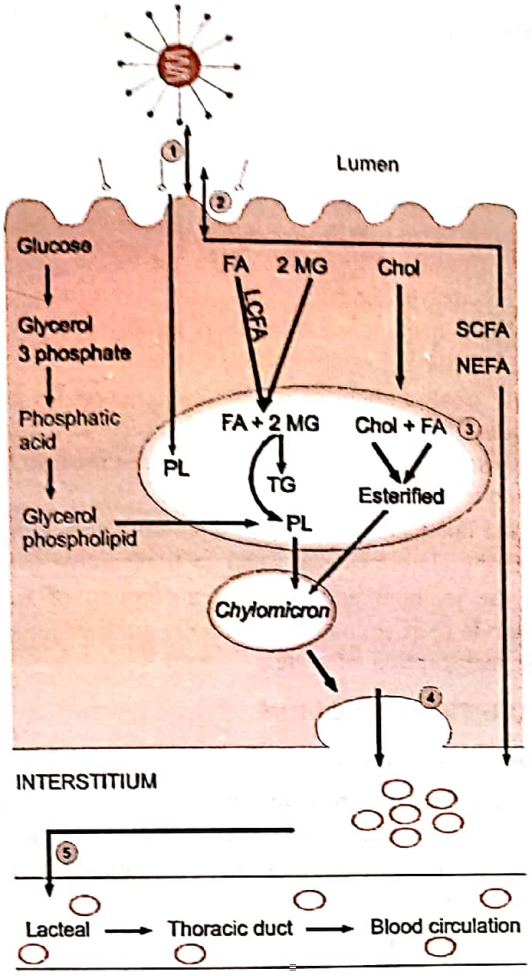


Fig. 7.7-7. Steps of fat absorption: 1, transportation of micelle to enterocytes brush border; 2, diffusion of lipids across the enterocyte membrane leaving bile salt in the lumen; 3, formation of chylomicron in the endoplasmic reticulum; 4, release of lipids into interstitium by exocytosis; and 5, diffusion of lipids from interstitium into lacteal (from where lipids enter into lymphatic circulation) and through thoracic duct into circulation. FA: fatty acid, MG: monoglycerides, chol: cholesterol, TG: triglycerides, LCFA: long chain fatty acid, SCFA: short chain fatty acids, NEFA: non-esterified fatty acids, and PL: phospholipid.

through the aqueous medium of the intestinal lumen to reach the brush border. This problem is solved by the bile salts by forming the micelle. As described above (Fig. 7.7-6) the outer surface of micelle is formed by water-soluble polar ends of bile salts, which helps the micelle to diffuse through the aqueous medium to reach the brush border membrane. Thus, the bile salt micelle acts as a transport vehicle for the products of fat digestion.

2. Diffusion of lipids across the enterocyte cell membrane. Once the micelle comes in contact with the cell membrane, the monoglycerides, free fatty acids, cholesterol and fat soluble vitamins (being soluble in the cell membrane) *diffuse passively* at a rapid speed through the enterocyte cell membrane to the interior of the cell, leaving bile salts in the intestinal lumen. Thus the *rate-limiting* step in lipid absorption is the formation and migration of the micelles from the intestinal chyme to the microvilli surface. It is important to note that the bile salts must be present in certain minimum concentration called *critical micellar concentration* before micelles are formed.

The bile salts released from micelle after diffusion of their associated lipids, are absorbed in the terminal ileum by a Na^+ dependent active transport process.

3. Transport of lipids from inside the enterocytes to the interstitial space. Once inside the cell, the end products of fat digestion enter the interstitium by two mechanisms:

i. Diffusion across the basal border of enterocyte. The small chain fatty acids (SCFA) with less than 12-14 carbon atoms are able to diffuse across the basal border of enterocytes to enter the interstitium.

ii. Formation and excretion of chylomicrons from enterocytes by exocytosis. The large chain fatty acids, cholesterol and lysophosphatides, enter the smooth endoplasmic reticulum, where they are reconstituted:

- 2-Monoglycerides are combined with fatty acids to produce triglycerides,
- Lysophosphatides are combined with fatty acids to form phospholipids, and
- Cholesterol is re-esterified.

The re-formed lipids coalesce to form a small lipid droplets (about 1 nm in diameter) called chylomicrons which are lined by β-lipoproteins synthesized. The chylomicrons are then excreted into the interstitium by *exocytosis* from the basolateral membrane of enterocyte. Covering of β-lipoproteins is essential for the exocytosis to occur. Therefore, in the absence of β-lipoprotein, exocytosis will not occur, and the enterocytes become engorged with lipids.

4. Transport of lipids into circulation. After exiting the enterocytes (i.e. in the interstitium), the chylomicrons merge into larger droplets that vary in size from 50-500 nm, depending on the amount of lipid being absorbed. From the interstitium the lipids diffuse into the *lacteals*, from which they enter the lymphatic circulation and via thoracic duct gain access into the blood circulation.

APPLIED ASPECTS

Lipid malabsorption

- Lipid malabsorption is much more common than carbohydrate and protein malabsorption.

- Causes of lipid malabsorption include:
  - Deficiency of pancreatic lipase in certain pancreatic diseases,
  - Bile deficiency in disorders of liver and gall bladder.
- Steatorrhoea, i.e. increased amount of fat in the stools is common manifestation of fat malabsorption.

Serum lipid profile

Lipids are present as lipoprotein complexes. Depending upon the density the lipoproteins are of following types:

i. Very low density lipoproteins (VLDL). Density is <1.060
ii. Low density lipoproteins (LDL)
iii. High density lipoproteins (HDL). Density is 1.060-1.200)

Normal values:

- Serum triglycerides: 30-150 mg%
- Serum cholesterol: 150-240 mg%
- Serum phospholipids: 150-300 mg%
- Serum free fatty acids (FFA or NEFA = 10-30 mg%).

ABSORPTION OF WATER, ELECTROLYTES, MINERALS AND VITAMINS

WATER ABSORPTION

Water balance in the GIT

- The gastrointestinal tract receives about 9 litres of water per day which includes about 2L of ingested water and about 7L contained in salivary, gastric, biliary, pancreatic and intestinal secretions (Table 7.7-1).
- The gastrointestinal tract absorbs about 8.8 litres of water (about 95% of total water received) per day. About 60% of absorption occurs in jejunum, 20-25% in ileum and 10-15% in colon (Table 7.7-1).
- The gastrointestinal tract excretes about 0.2 litres of water in the faeces per day.

Table 7.7-1 : Daily water balance in GIT

Input (in litres)	Absorption (in litres)	Faecal excretion (in litres)
WATER INGESTED : 2 WATER IN GIT : 7 SECRETIONS • Saliva: 1.5 • Gastric juice: 2.5 • Bile: 0.75 • Pancreatic juice: 0.75 • Intestinal juice: 1.5	Jejunum (60%) : 5.5 Ileum (25%) : 2.0 Colon (10-15%): 1.3	0.2
TOTAL 9	8.8	0.2

Mechanism of water absorption

- In general water is absorbed passively and iso-osmotically across the gastrointestinal mucosa following the osmotic gradient created by the active absorption of electrolytes and nutrients.
- Because osmotic equilibrium is rapidly achieved, the fluid in the intestine is always isotonic to plasma.
- Only small amount of water moves across the gastric mucosa, but water moves in both directions across the mucosa of small intestine and colon in reponse to the osmotic gradient.
- In the duodenum, the osmotic pressure created by the entering chyme causes water to flow into it.
- In the jejunum and ileum, reabsorption of sodium chloride (NaCl) creates an osmotic gradient favouring the reabsorption of water.

ABSORPTION OF SODIUM

Sodium balance in GIT

Gastrointestinal tract receives about 40 gm of sodium per day, out of which about 10 gm is ingested with food and about 30 gm is contained in the gastrointestinal secretions. All of it is reabsorbed.

Site of absorption

Though sodium can be reabsorbed in the entire length of the intestine, but maximum absorption occurs in the jejunum.

Mechanisms of absorption

Absorption of sodium is two-step process:

1. Transport of sodium from the lumen into the enterocyte occurs by following mechanisms:

- Na^+ glucose, Na^+-amino acids and Na^+- di- or tri peptide co-transport system account for 30% of Na^+ transport into the cell.
- Neutral Na^+-Cl^- co-transport system also transports about 30% of Na^+.
- Na^+-H^+ exchange, and
- Passive diffusion (through Na^+ channels) down an electrochemical gradient is responsible for transport of remainder 40% of Na^+.

In the small intestine, Na^+-glucose co-transport, Na^+-amino acid co-transport, and Na^+-H^+ exchange mechanisms are most important (these co-transport and exchange mechanisms are similar to those in renal proximal tubule). Thus, the presence of glucose in the intestinal lumen