6 HUMAN PHYSIOLOGY

Introduction

Research into human physiology is the foundation of modern medicine. Body functions are carried out by specialized organ systems. The structure of the wall of the small intestine allows it to move, digest and absorb food. The blood system continuously transports substances to cells and simultaneously collects waste products. The skin and immune system resist the continuous threat of invasion by pathogens. The lungs are actively ventilated to ensure that gas exchange can occur passively. Neurons transmit the message, synapses modulate the message. Hormones are used when signals need to be widely distributed.

6.1 Digestion and absorption

Understanding

- The contraction of circular and longitudinal muscle layers of the small intestine mixes the food with enzymes and moves it along the gut.
- The pancreas secretes enzymes into the lumen of the small intestine.
- Enzymes digest most macromolecules in food into monomers in the small intestine.
- Villi increase the surface area of epithelium over which absorption is carried out.
- Villi absorb monomers formed by digestion as well as mineral ions and vitamins.
- Different methods of membrane transport are required to absorb different nutrients.

Applications

- Processes occurring in the small intestine that result in the digestion of starch and transport of the products of digestion to the liver.
- Use of dialysis tubing to model absorption of digested food in the intestine.

Skills

- Production of an annotated diagram of the digestive system.
- Identification of tissue layers in transverse sections of the small intestine viewed with a microscope or in a micrograph.

Nature of science

- Use models as representations of the real world: dialysis tubing can be used to model absorption in the intestine.

Structure of the digestive system

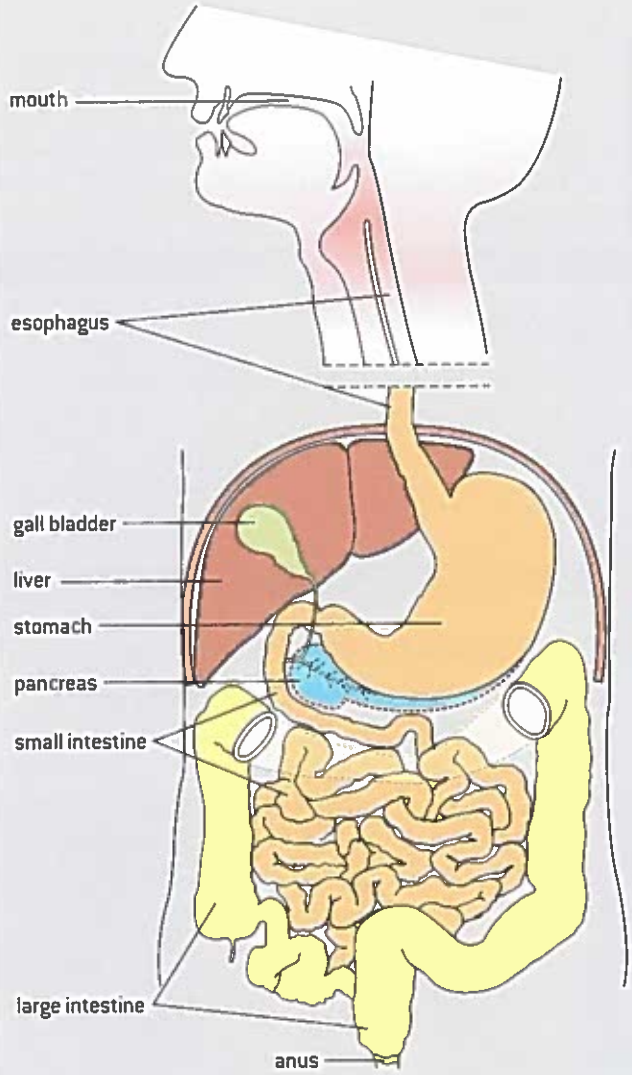
Production of an annotated diagram of the digestive system.

The part of the human body used for digestion can be described in simple terms as a tube through which food passes from the mouth to the anus. The role of the digestive system is to break down the diverse mixture of large carbon compounds in food, to yield ions and smaller compounds that can be absorbed. For proteins, lipids and polysaccharides digestion involves several stages that occur in different parts of the gut.

Digestion requires surfactants to break up lipid droplets and enzymes to catalyse reactions. Glandular cells in the lining of the stomach and intestines produce some of the enzymes.

Surfactants and other enzymes are secreted by accessory glands that have ducts leading to the digestive system. Controlled, selective absorption of the nutrients released by digestion takes place in the small intestine and colon, but some small molecules, notably alcohol, diffuse through the stomach lining before reaching the small intestine.

Figure 1 is a diagram of the human digestive system. The part of the esophagus that passes through the thorax has been omitted. This diagram can be annotated to indicate the functions of different parts. A summary of functions is given in table 1 below.



▲ Figure 1 The human digestive system

Structure	Function
Mouth	Voluntary control of eating and swallowing. Mechanical digestion of food by chewing and mixing with saliva, which contains lubricants and enzymes that start starch digestion
Esophagus	Movement of food by peristalsis from the mouth to the stomach
Stomach	Churning and mixing with secreted water and acid which kills foreign bacteria and other pathogens in food, plus initial stages of protein digestion
Small intestine	Final stages of digestion of lipids, carbohydrates, proteins and nucleic acids, neutralizing stomach acid, plus absorption of nutrients
Pancreas	Secretion of lipase, amylase and protease
Liver	Secretion of surfactants in bile to break up lipid droplets
Gall bladder	Storage and regulated release of bile
Large intestine	Re-absorption of water, further digestion especially of carbohydrates by symbiotic bacteria, plus formation and storage of feces

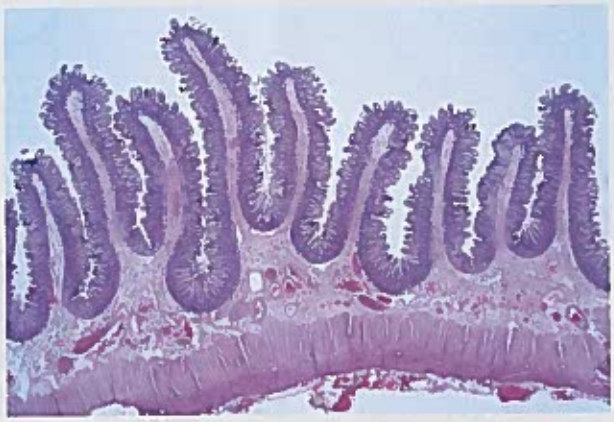
▲ Table 1

Structure of the wall of the small intestine

Identification of tissue layers in transverse sections of the small intestine viewed with a microscope or in a micrograph.

The wall of the small intestine is made of layers of living tissues, which are usually quite easy to distinguish in sections of the wall. From the outside of the wall going inwards there are four layers:

- serosa – an outer coat
- muscle layers – longitudinal muscle and inside it circular muscle
- sub-mucosa – a tissue layer containing blood and lymph vessels
- mucosa – the lining of the small intestine, with the epithelium that absorbs nutrients on its inner surface.



▲ Figure 2 Longitudinal section through the wall of the small intestine. Folds are visible on the inner surface and on these folds are finger-like projections called villi. All of the four main tissue layers are visible, including both circular and longitudinal parts of the muscle layer. The mucosa is stained darker than the sub-mucosa

Peristalsis

The contraction of circular and longitudinal muscle layers of the small intestine mixes the food with enzymes and moves it along the gut.

The circular and longitudinal muscle in the wall of the gut is smooth muscle rather than striated muscle. It consists of relatively short cells, not elongated fibres. It often exerts continuous moderate force, interspersed with short periods of more vigorous contraction, rather than remaining relaxed unless stimulated to contract.

Waves of muscle contraction, called peristalsis, pass along the intestine. Contraction of circular muscles behind the food constricts the gut to prevent it from being pushed back towards the mouth. Contraction of longitudinal muscle where the food is located moves it on along the gut. The contractions are controlled unconsciously not by the brain but by the enteric nervous system, which is extensive and complex.

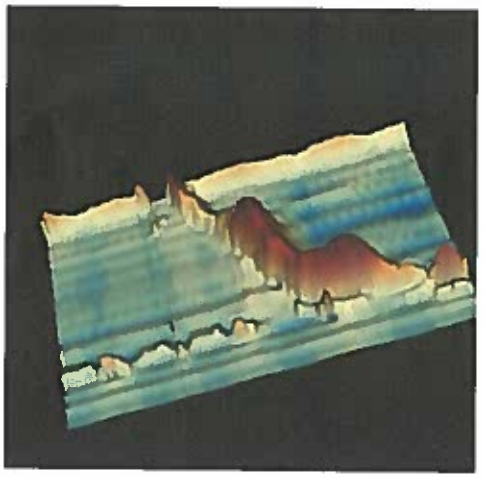
Swallowed food moves quickly down the esophagus to the stomach in one continuous peristaltic wave. Peristalsis only occurs in one direction, away from the mouth. When food is returned to the mouth from the stomach during vomiting, abdominal muscles are used rather than the circular and longitudinal muscle in the gut wall.

In the intestines the food is moved only a few centimetres at a time so the overall progression through the intestine is much slower, allowing time for digestion. The main function of peristalsis in the intestine is churning of the semi-digested food to mix it with enzymes and thus speed up the process of digestion.

Activity

Tissue plan diagrams of the intestine wall

To practice your skill at identifying tissue layers, draw a plan diagram of the tissues in the longitudinal section of the intestine wall in figure 2. To test your skill further, draw a plan diagram to predict how the tissues of the small intestine would appear in a transverse section.



▲ Figure 3 Three-dimensional image showing the wave of muscle contraction (brown) in the esophagus during swallowing. Green indicates when the muscle is exerting less force. Time is shown left to right. At the top the sphincter between the mouth and the esophagus is shown permanently constricted apart from a brief opening when swallowing starts

Pancreatic juice

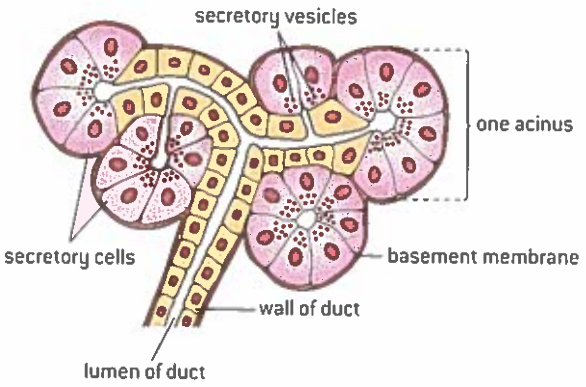
The pancreas secretes enzymes into the lumen of the small intestine.

The pancreas contains two types of gland tissue. Small groups of cells secrete the hormones insulin and glucagon into the blood. The remainder of the pancreas synthesizes and secretes digestive enzymes into the gut in response to eating a meal. This is mediated by hormones synthesized and secreted by the stomach and also by the enteric nervous system. The structure of the tissue is shown in figure 4. Small groups of gland cells cluster round the ends of tubes called ducts, into which the enzymes are secreted.

The digestive enzymes are synthesized in pancreatic gland cells on ribosomes on the rough endoplasmic reticulum. They are then processed in the Golgi apparatus and secreted by exocytosis. Ducts within the pancreas merge into larger ducts, finally forming one pancreatic duct, through which about a litre of pancreatic juice is secreted per day into the lumen of the small intestine.

Pancreatic juice contains enzymes that digest all the three main types of macromolecule found in food:

- amylase to digest starch
- lipases to digest triglycerides, phospholipids
- proteases to digest proteins and peptides.



▲ Figure 4 Arrangement of cells and ducts in a part of the pancreas that secretes digestive enzymes

Digestion in the small intestine

Enzymes digest most macromolecules in food into monomers in the small intestine.

The enzymes secreted by the pancreas into the lumen of the small intestine carry out these hydrolysis reactions:

- starch is digested to maltose by amylase
- triglycerides are digested to fatty acids and glycerol or fatty acids and monoglycerides by lipase
- phospholipids are digested to fatty acids, glycerol and phosphate by phospholipase
- proteins and polypeptides are digested to shorter peptides by protease.

This does not complete the process of digestion into molecules small enough to be absorbed. The wall of the small intestine produces a variety of other enzymes, which digest more substances. Some enzymes produced by gland cells in the intestine wall may be secreted in intestinal juice but most remain immobilized in the plasma membrane of epithelium cells lining the intestine. They are active there and continue to be active when the epithelium cells are abraded off the lining and mixed with the semi-digested food.

- Nucleases digest DNA and RNA into nucleotides.
- Maltase digests maltose into glucose.

- Lactase digests lactose into glucose and galactose.
- Sucrase digests sucrose into glucose and fructose.
- Exopeptidases are proteases that digest peptides by removing single amino acids either from the carboxy or amino terminal of the chain until only a dipeptide is left.
- Dipeptidases digest dipeptides into amino acids.

Because of the great length of the small intestine, food takes hours to pass through, allowing time for digestion of most macromolecules to be completed. Some substances remain largely undigested, because humans cannot synthesize the necessary enzymes. Cellulose for example is not digested and passes on to the large intestine as one of the main components of dietary fibre.

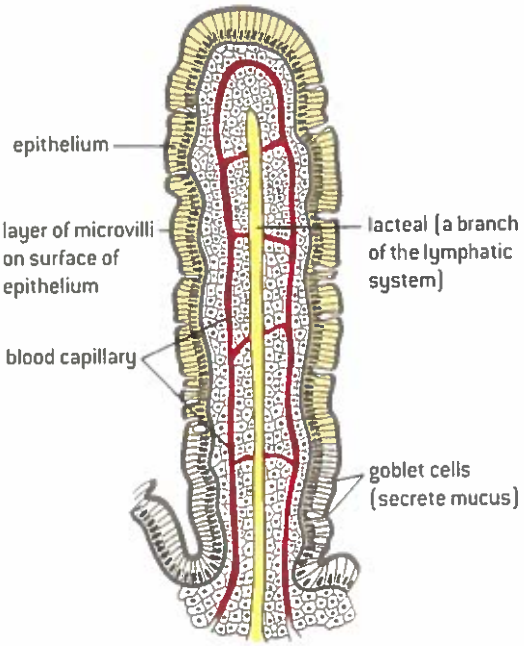
▲ Figure 5 Cystic fibrosis causes the pancreatic duct to become blocked by mucus. Pills containing synthetic enzymes help digestion in the small intestine. The photograph shows one day's supply for a person with cystic fibrosis

Villi and the surface area for digestion

Villi increase the surface area of epithelium over which absorption is carried out.

The process of taking substances into cells and the blood is called absorption. In the human digestive system nutrients are absorbed principally in the small intestine. The rate of absorption depends on the surface area of the epithelium that carries out the process. The small intestine in adults is approximately seven metres long and 25–30 millimetres wide and there are folds on its inner surface, giving a large surface area. This area is increased by the presence of villi.

Villi are small finger-like projections of the mucosa on the inside of the intestine wall. A villus is between 0.5 and 1.5 mm long and there can be as many as 40 of them per square millimetre of small intestine wall. They increase the surface area by a factor of about 10.



▲ Figure 6 Structure of an intestinal villus

Absorption by villi

Villi absorb monomers formed by digestion as well as mineral ions and vitamins.

The epithelium that covers the villi must form a barrier to harmful substances, while at the same time being permeable enough to allow useful nutrients to pass through.

Villus cells absorb these products of digestion of macromolecules in food:

- glucose, fructose, galactose and other monosaccharides
- any of the twenty amino acids used to make proteins
- fatty acids, monoglycerides and glycerol
- bases from digestion of nucleotides.

They also absorb substances required by the body and present in foods but not needing digestion:

- mineral ions such as calcium, potassium and sodium
- vitamins such as ascorbic acid (vitamin C).

▲ Figure 7 Scanning electron micrograph of villi in the small intestine

Some harmful substances pass through the epithelium and are subsequently removed from the blood and detoxified by the liver. Some harmless but unwanted substances are also absorbed, including many of those that give food its colour and flavour. These pass out in urine. Small numbers of bacteria pass through the epithelium but are quickly removed from the blood by phagocytic cells in the liver.

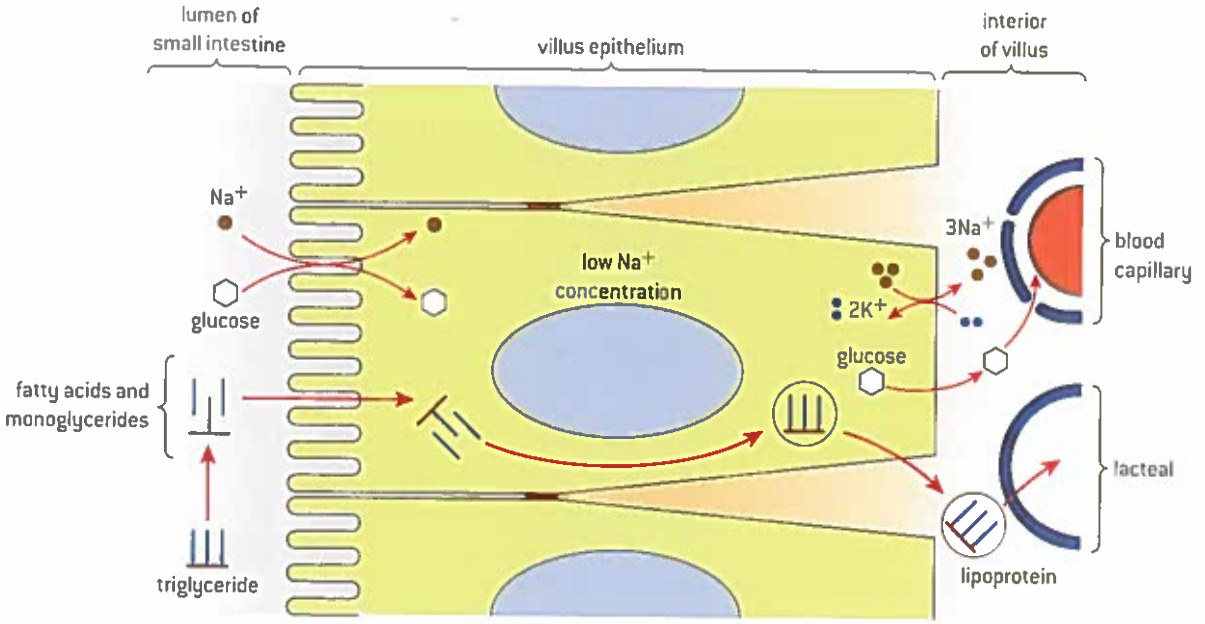
Methods of absorption

Different methods of membrane transport are required to absorb different nutrients.

To be absorbed into the body, nutrients must pass from the lumen of the small intestine to the capillaries or lacteals in the villi. The nutrients must first be absorbed into epithelium cells through the exposed part of the plasma membrane that has its surface area enlarged with microvilli. The nutrients must then pass out of this cell through the plasma membrane where it faces inwards towards the lacteal and blood capillaries of the villus.

Many different mechanisms move nutrients into and out of the villus epithelium cells: simple diffusion, facilitated diffusion, active transport and exocytosis. These methods can be illustrated using two different examples of absorption: triglycerides and glucose.

- Triglycerides must be digested before they can be absorbed. The products of digestion are fatty acids and monoglycerides, which can be absorbed into villus epithelium cells by simple diffusion as they can pass between phospholipids in the plasma membrane.
- Fatty acids are also absorbed by facilitated diffusion as there are fatty acid transporters, which are proteins in the membrane of the microvilli.
- Once inside the epithelium cells, fatty acids are combined with monoglycerides to produce triglycerides, which cannot diffuse back out into the lumen.



▲ Figure 8 Methods of absorption in the small intestine

- Triglycerides coalesce with cholesterol to form droplets with a diameter of about 0.2 μm, which become coated in phospholipids and protein.
- These lipoprotein particles are released by exocytosis through the plasma membrane on the inner side of the villus epithelium cells. They then either enter the lacteal and are carried away in the lymph, or enter the blood capillaries in the villi.
- Glucose cannot pass through the plasma membrane by simple diffusion because it is polar and therefore hydrophilic.
- Sodium–potassium pumps in the inwards-facing part of the plasma membrane pump sodium ions by active transport from the cytoplasm to the interstitial spaces inside the villus and potassium ions in the opposite direction. This creates a low concentration of sodium ions inside villus epithelium cells.
- Sodium–glucose co-transporter proteins in the microvilli transfer a sodium ion and a glucose molecule together from the intestinal lumen to the cytoplasm of the epithelium cells. This type of facilitated diffusion is passive but it depends on the concentration gradient of sodium ions created by active transport.
- Glucose channels allow the glucose to move by facilitated diffusion from the cytoplasm to the interstitial spaces inside the villus and on into blood capillaries in the villus.

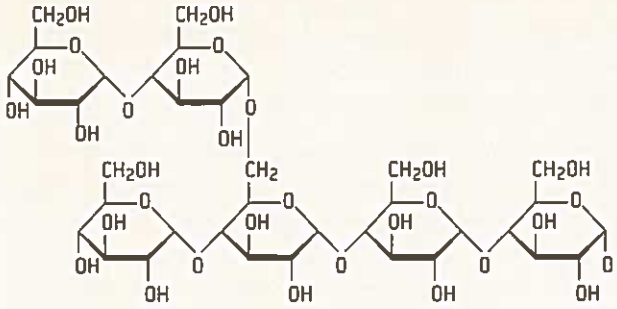
Starch digestion in the small intestine

Processes occurring in the small intestine that result in the digestion of starch and transport of the products of digestion to the liver.

Starch digestion illustrates some important processes including catalysis, enzyme specificity and membrane permeability. Starch is a macromolecule, composed of many α-glucose monomers linked together in plants by condensation reactions. It is a major constituent of plant-based foods such as bread, potatoes and pasta. Starch molecules cannot pass through membranes so must be digested in the small intestine to allow absorption.

All of the reactions involved in the digestion of starch are exothermic, but without a catalyst they happen at very slow rates. There are two types of molecule in starch:

- amylose has unbranched chains of α-glucose linked by 1,4 bonds;
- amylopectin has chains of α-glucose linked by 1,4 bonds, with some 1,6 bonds that make the molecule branched.



▲ Figure 9 Small portion of an amylopectin molecule showing six α-glucose molecules, all linked by 1,4 bonds apart from one 1,6 bond that creates a branch

The enzyme that begins the digestion of both forms of starch is amylase. Saliva contains amylase but most starch digestion occurs in the small intestine, catalysed by pancreatic amylase. Any 1,4 bond in starch molecules can be broken by this enzyme, as long as there is a chain of at least four glucose monomers. Amylose is therefore

digested into a mixture of two- and three-glucose fragments called maltose and maltotriose.

Because of the specificity of its active site, amylase cannot break 1,6 bonds in amylopectin. Fragments of the amylopectin molecule containing a 1,6 bond that amylase cannot digest are called dextrins. Digestion of starch is completed by three enzymes in the membranes of microvilli on villus epithelium cells. Maltase, glucosidase and dextrinase digest maltose, maltotriose and dextrins into glucose.

Glucose is absorbed into villus epithelium cells by co-transport with sodium ions. It then moves by facilitated diffusion into the fluid in interstitial spaces inside the villus. The dense network of capillaries close to the epithelium ensures that glucose only has to travel a short distance to enter the blood system. Capillary walls consist of a single layer of thin cells, with pores between adjacent cells, but these capillaries have larger pores than usual, aiding the entry of glucose.

Blood carrying glucose and other products of digestion flows though villus capillaries to venules in the sub-mucosa of the wall of the small intestine. The blood in these venules is carried via the hepatic portal vein to the liver, where excess glucose can be absorbed by liver cells and converted to glycogen for storage. Glycogen is similar in structure to amylopectin, but with more 1,6 bonds and therefore more extensive branching.

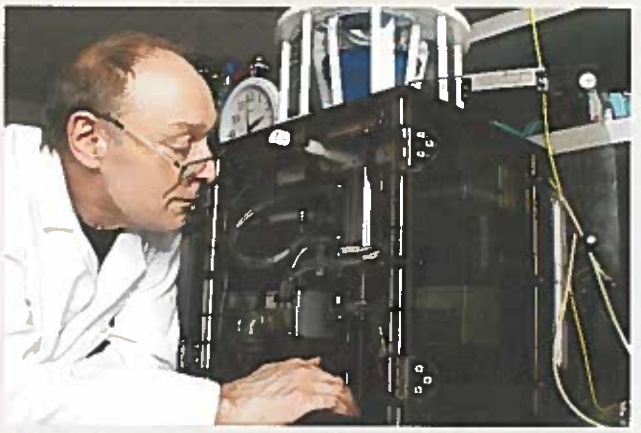
Modelling physiological processes

Use models as representations of the real world: dialysis tubing can be used to model absorption in the intestine.

Living systems are complex and when experiments are done on them, many factors can influence the results. It can be very difficult to control all of the variables and analysis of results becomes difficult. Sometimes it is better to carry out experiments using only parts of systems. For example, much research in physiology has been carried out using clones of cells in tissue culture rather than whole organisms.

Another approach is to use a model to represent part of a living system. Because it is much simpler, a model can be used to investigate specific aspects of a process. A recent example is the Dynamic Gastric Model, a computer-controlled model of the human stomach that carries out mechanical and chemical digestion of real food samples. It can be used to investigate the effects of diet, drugs, alcohol and other factors on digestion.

A simpler example is the use of dialysis tubing made from cellulose. Pores in the tubing allow water and small molecules or ions to pass through freely, but not large molecules. These properties mimic the wall of the gut, which is also more permeable to small rather than large particles. Dialysis tubing can be used to model absorption by passive diffusion and by osmosis. It cannot model active transport and other processes that occur in living cells



▲ Figure 10 The Dynamic Gastric Model with its inventor, Richard Faulks, adjusting the antrum mechanism

Modelling the small intestine

Use of dialysis tubing to model absorption of digested food in the intestine.

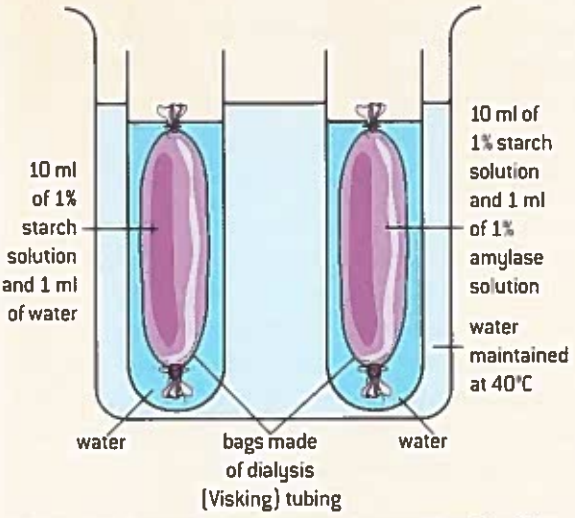
To make a model of the small intestine, cut a length of dialysis tubing and seal one end by tying a knot in the tubing or tying with a piece of cotton thread. Pour in a suitable mixture of foods and seal the open end by tying with a piece of cotton thread. Two experiments using model intestines made in this way are suggested here:

1 Investigating the need for digestion using a model of the small intestine

Set up the apparatus shown in figure 11 and leave it for one hour.

Results

To obtain the results for the experiment, take the bags out of each tube, open them and pour the solutions from them into separate test tubes from the liquids in the tubes. You should now have four samples of fluid. Divide each of these samples into two halves and test one half for starch and the other half for sugars.



▲ Figure 11 Apparatus for showing the need for digestion

Record all the results in the way that you think is most appropriate.

Conclusions and evaluation

State carefully all the conclusions that you can make from your results.

Discuss the strengths and weaknesses of this method of investigating the need for digestion.

Suggest improvements to the method, or suggest an entirely different method of investigating the need for digestion.

2 Investigating membrane permeability using a model of the small intestine

Cola drinks contain a mixture of substances with different particle sizes. They can be used to represent food in the small intestine. Dialysis tubing is semi-permeable so can be used to model the wall of the small intestine.

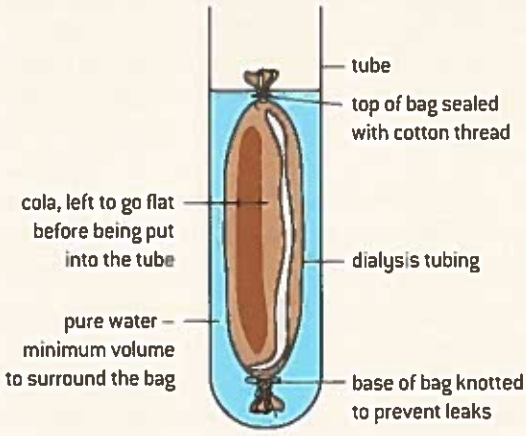
Predictions

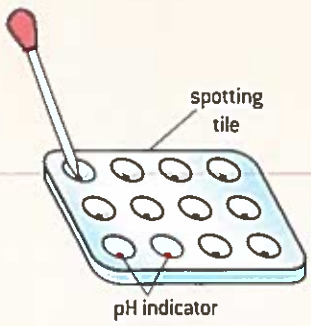
Cola contains glucose, phosphoric acid and caramel, a complex carbohydrate added to produce a brown colour. Predict which of these substances will diffuse out of the bag, with reasons for your predictions. Predict whether the bag will gain or lose mass during the experiment.

Instructions

1 Make the model intestine with cola inside.

2 Rinse the outside of the bag to wash off any traces of cola and then dry the bag.





▲ Figure 12 Apparatus for membrane permeability experiment

3 Find the mass of the bag using an electronic balance.

4 When you are ready to start the experiment, place the bag in pure water in a test tube.

5 Test the water around the bag at suitable time intervals. A suggested range is 1, 2, 4, 8 and 16 minutes. At each time lift the bag up and down a few times to mix the water in the tube, then do these tests:

- Look carefully at the water to see whether it is still clear or has become brown.
- Use a dropping pipette to remove a few drops of the water and test them in a spotting tile with a narrow-range pH indicator. Use a colour chart to work out the pH.
- Dip a glucose test strip into the water and record the colour that it turns. Instructions vary for these test strips. Follow the instructions and work out the glucose concentration of the water.

6 After testing the water for the last time, remove the bag, dry it and find its mass again with the electronic balance.

Conclusions

a) Explain the conclusions that you can draw about the permeability of the dialysis tubing from the tests of the water and from the change in mass of the bag. [5]

b) Compare and contrast the dialysis tubing and the plasma membranes that carry out absorption in villus epithelium cells in the wall of the intestine. [5]

c) Use the results of your experiment to predict the direction of movement of water by osmosis across villus epithelium cells. [5]

TOK

What are some of the variables that affect perspectives as to what is "normal"?

In some adult humans, levels of lactase are too low to digest lactose in milk adequately. Instead, lactose passes through the small intestine into the large intestine, where bacteria feed on it, producing carbon dioxide, hydrogen and methane. These gases cause some unpleasant symptoms, discouraging consumption of milk. The condition is known as lactose intolerance. It has sometimes in the past been regarded as an abnormal condition, or even as a disease, but it could be argued that lactose intolerance is the normal human condition.

The first argument for this view is a biological one. Female mammals produce milk to feed their young offspring. When a young mammal is weaned, solid foods replace milk and lactase secretion declines. Humans who continue to consume milk into adulthood are therefore unusual. Inability to consume milk because of lactose intolerance should not therefore be regarded as abnormal.

The second argument is a simple mathematical one: a high proportion of humans are lactose intolerant.

The third argument is evolutionary. Our ancestors were almost certainly all lactose intolerant, so this is the natural or normal state. Lactose tolerance appears to have evolved separately in at least three centres: Northern Europe, parts of Arabia, the Sahara and eastern Sudan, and parts of East Africa inhabited by the Tutsi and Maasai peoples. Elsewhere, tolerance is probably due to migration from these centres.