Chapter 5

ENZYMES

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Identify the role and component parts of the active site of an enzyme.
- Differentiate among the three types of co-factors i.e., in organic ions, prosthetic group and co-enzymes, with examples.
- Explain the mechanism of enzyme action through the Induced Fit Model, including comparing it with Lock and Key Model.
- Explain enzyme catalysis with example of specific reactions.
- Define energy of activation and discuss through graph how an enzyme speeds up a reaction by lowering the energy of activation.
- Explain the effect of temperature on the rate of enzyme action with example of human and thermophilic bacteria
- Investigate the effect of pH on enzyme activity Compare the optimum pH of different enzymes like trypsin, pepsin, papain.
- Demonstrate that the concentration of enzyme affects the rate of enzyme action.
- Describe enzymatic inhibition, its types and its significance with examples.
- Name the molecules which act as inhibitors.
- Categorize inhibitors into competitive and non-competitive inhibitors.
- Explain feedback inhibition.
- Classify enzymes on the basis of the reactions catalyzed (oxidoreductases, transferases, hydrolases, isomerases, and ligases).
- Classify enzymes on the basis of the substrates they use (lipases, diastase, amylase, proteases etc.)

You know that the life of living organisms is a reflection of what is going on in their bodies. The sum of all chemical activities occurring in living organisms i.e., metabolism is regulated by enzymes.

5.1- ENZYMES

Enzymes may be defined as specific proteins that speed up specific chemical reactions by lowering the required activation energy, but are unaltered themselves in the process. Enzymes are also known as **biocatalysts** Rates of enzyme-catalysed reactions may be 10^3 to 10^8 times greater than the rates of corresponding uncatalyzed reactions.

All cells do not have the same set of enzymes. The chemical reactions going on in red blood cells are very different from those going on within a nerve cell because red blood cells and nerve cells contain different sets of enzymes.

All enzymes are synthesized inside cells by ribosomes. After their synthesis, either they stay and work inside cell or they are secreted out to work at other sites.

A reaction that is catalysed by an enzyme and is completed in 30 minutes, would take one year to get completed without being catalysed by enzyme. Thus, we can say that without enzymes there would have been no life at all.

Inside cell, many enzymes are dissolved in cytoplasm; for example, the enzymes of glycolysis. Many are tightly bound to membranes of certain organelles, for example, the enzyme of Calvin cycle and Krebs cycle. Some enzymes are integral part of ribosomes; for example, the enzymes of protein synthesis.

Active Site of Enzyme

Enzymes are three-dimensional globular proteins. They are made of polypeptide chains that are coiled upon themselves. There is a small cleft or depression on the surface of globular enzyme molecule. It consists of only a few amino acids. This site is known as **active site**. It is the location at which catalysis occurs.

Some enzymes may prove harmful, if become active at wrong place. For example; pepsin is a protein digesting enzyme. It can destroy protein-made structures present inside cells where it is synthesized. That is why it is produced in inactive form (pepsinogen) and is secreted out of cells. When it reaches its target site of action, it is activated (pepsin).

The shape of active site of each enzyme is very specific. So, only a certain substrate molecule can fit into it. It is three-dimensional and bears a specific charge. Active site has two distinct regions i.e., **binding site** and **catalytic site**. Substrate molecule fits into binding site by weak chemical forces, such as hydrogen bonds. Catalytic site catalyses the reaction and substrate is transformed into products.

5.2- Cofactors And Coenzymes

Many enzymes use additional chemical components to aid in catalysis. These additional non-protein components are called **cofactors**. There are three kinds of cofactor: metal ions, prosthetic groups, and coenzymes.

The protein part of enzyme is called **apoenzyme** and complete enzyme including co-factor is called **holoenzyme**.

Many enzymes use **metal ions**, such as Ca^{+2}, Mg^{+2}, Mn^{+2}, Cu^{+2}, and Zn^{+2} as their cofactors. These metal ions change the non-functional active sites of enzymes into functional sites. The attachment of a cofactor also changes the shape of enzyme and allows it to combine with substrate (Figure 5.1).

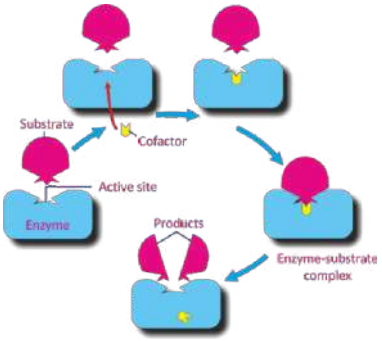


Figure 5.1: Cofactor, changing the shape of active site

Some cofactors form covalent bonds with enzyme and are known as **prosthetic groups**. Prosthetic group may be an organic compound e.g., hematin.

When the cofactor is a non-protein organic molecule and is loosely attached with enzyme, it is called a **coenzyme**. Coenzymes participate in enzyme-catalysed reactions, often by transporting electrons (hydrogen atoms), from one enzyme to another. Many vitamins (e.g., niacin and riboflavin) function as coenzymes. Some are part of coenzymes. The most important coenzyme in cell is the hydrogen acceptor nicotinamide adenine dinucleotide (NAD^+). When NAD^+ acquires a hydrogen atom from an enzyme, it reduces to NADH. The electron of hydrogen atom contains energy that NADH molecule carries. For example, when food is oxidized in cell, enzymes draw electrons from food molecules and transfer them to NAD^+, which reduces to NADH.

> Many trace elements such as molybdenum and manganese, which are necessary for our health, are used by enzymes as cofactors.

5.3- Mechanism Of Enzyme Action

The speed of a chemical reaction depends on the amount of activation energy required to initiate it. **Activation energy** is the energy which works to destabilize existing chemical bonds. Enzymes bring reactants together in correct orientation or stress particular chemical bonds of reactants. Thus, they lower the activation energy required for new bonds to form and speed up the rate of reactions (Figure 5.2). Reactions proceed much faster than their normal speed.

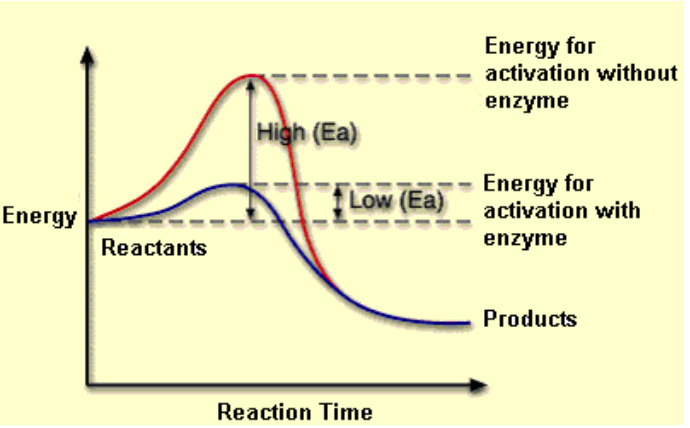


Figure 5.2: Enzymes lower theactivation energy

The presence of enzymes does not affect the nature or properties of end products. For example, sucrose (substrate) will always be hydrolysed into glucose and fructose (products) whether sucrase (enzyme) is present or not.

Due to its specificity, an enzyme recognizes a specific substrate. The substrate binds with the active site of enzyme. In this way, an enzyme-substrate complex (ES complex) is formed and catalytic site is activated. The atoms of catalytic site stress and

destabilize particular bonds of substrate. So, activation energy is lowered. This action initiates the reaction and substrate is transformed into products. After it, enzyme detaches itself from the products, in an unaltered state. The mechanism of enzyme action can be summarised as follows:

$$E + S \longrightarrow ES \longrightarrow E + P$$

Enzyme Substrate — Enzyme-substrate complex — Enzyme Product

In complex metabolic pathways e.g., respiration, photosynthesis, protein synthesis etc., many enzymes act in a sequence and regulate the steps of pathway. The successive enzymes controlling these steps are present together along with their cofactors. The products from one enzyme's catalysis serve as substrate for the enzyme of next step and are transformed into next products. The series goes on and finally end products are formed that inhibit (through feedback) the first enzyme.

Models for Mechanism of Action of Enzymes

Lock-and-Key Model

In 1894 a German chemist **Emil Fischer** proposed lock-and-key model. According to this model, "as a specific key can open only a specific lock, in the same manner a specific enzyme can transform only one specific substrate into products". This model postulates that active site is a rigid structure and there is no modification or flexibility in it before, during or after the enzyme action (Figure 5.3).

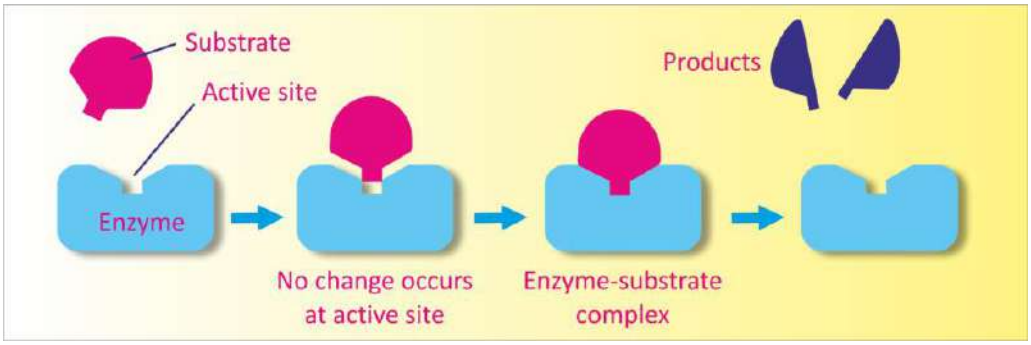


Figure 5.3: Lock-and-key model of enzyme action

Induced Fit Model

Later studies did not support lock-and-key model in all reactions. On the basis of new evidence, an American biochemist **Daniel Koshland**(1958) presented induced fit model. According to this model, "when a substrate combines with the binding site of an enzyme, it induces **changes** in enzyme structure. These changes enable the enzyme to perform its catalytic activity more effectively." This model postulates that active site is not a rigid structure and is capable of going under modification and flexibility, before the enzyme action (catalysis) starts (Figure 5.4).

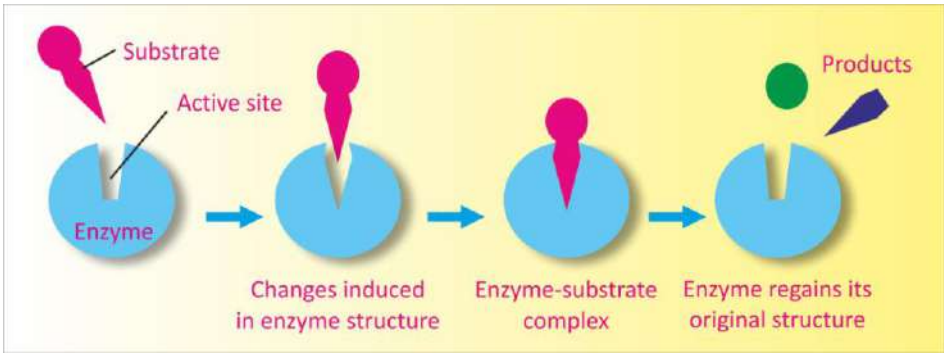


Figure 5.4: Induced-fit model of enzyme action

5.4- Factors Affecting The Rate Of Enzyme Action

Enzymes are very sensitive to the environment in which they work. The activity of an enzyme is affected by any change that alters its chemistry and its three-dimensional shape. Some of the factors that can affect the rate of enzyme action are being discussed next.

1. Temperature

The shape of a protein is determined by the hydrogen bonds and hydrophobic interactions that hold its polypeptide chains in particular position. Both the hydrogen bonds and hydrophobic interactions are easily disrupted by slight changes in temperature. Every enzyme works at its maximum rate at a specific temperature called its **optimum temperature**. The optimum temperature for human enzymes is 37 °C.

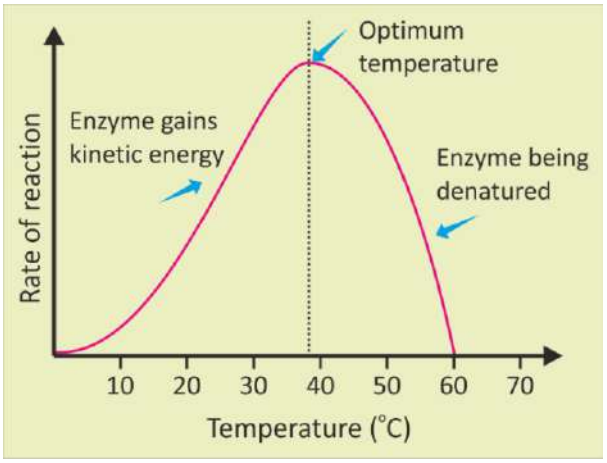


Figure 5.5: Effect of temperature on enzyme activity

When temperature fall below optimum temperature, the bonds that determine enzymes shape become less flexible. They do not permit the induced change in active sites that is necessary for enzyme action and so reaction rate is slow. When temperature is raised up to a certain limit, the heat adds in activation energy and so reactions are accelerated. Heat also provides kinetic energy to substrate and enzyme molecules. It causes them to move rapidly. Thus, they collide more frequently and reaction rate is increased. When temperature is raised well above

Thermophilic bacteria live in hot springs. They have proteins with stronger bonding between their polypeptide arms and can function at temperature of 70 °C or higher.

optimum temperature, the heat energy increases the vibrations of atoms of enzyme molecules. When vibrations become too violent, bonds cannot hold polypeptide chains in the proper position and globular structure of enzyme is lost. This phenomenon is known as **denaturation** of enzyme. It results in a rapid decrease in the rate of enzyme action and it may be blocked completely.

2. pH

All enzymes work at their maximum rate at a narrow range of pH. A slight change (increase or decrease) in this pH causes retardation in enzyme activity or blocks it completely. Every enzyme works its best at a specific pH, called its **optimum pH**. For example, **pepsin** is active in acidic medium (low pH) while **trypsin** shows its optimum activity in alkaline medium (high pH). Some enzymes like **papain** from green papaya work both in acidic and alkaline media.

In the globular structure of an enzyme, polypeptide chains are held by bonds between oppositely charged amino acids, such as glutamic acid (-) and lysine (+). These bonds are sensitive to hydrogen ion concentration. Any change in pH can change the ionization of amino acids at active site. Moreover, it may affect the ionization of substrate. Extreme change in pH can break the bonds in enzymes, resulting in enzyme denaturation.

Table: Optimum pH of important human enzymes

Enzyme	Optimum pH
Pepsin	1.5–1.6
Salivary amylase	4.6–5.2
Sucrase	6.2
Pancreatic amylase	6.7–7.0
Catalase	7.0
Urease	7.0
Trypsin	7.8–8.7
Pancreatic lipase	8.0
Arginase	10.0

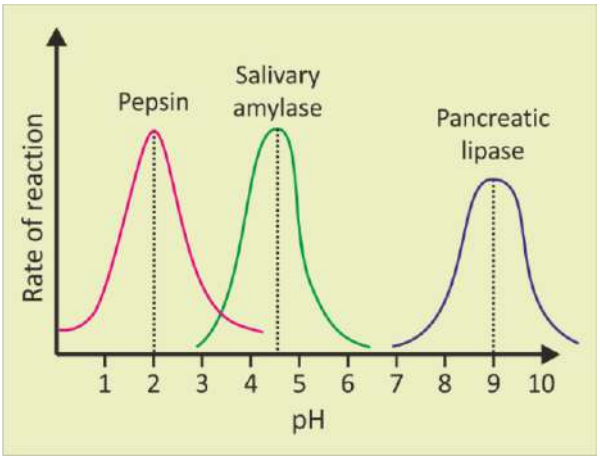


Figure 5.6: Optimum pH of some enzyme and effect of change of pH on enzyme activity

3. Enzyme Concentration

Enzymes are very efficient and a small number of enzyme molecules can catalyse reactions of large amount of substrate. The overall rate of enzyme-controlled reactions depends directly on the amount of enzyme present at a specific time (if substrate concentration is unlimited). When enzyme concentration increases, there are more enzyme molecules and more active sites. So, more substrate molecules bind with new active sites and are transformed into products. If enzyme concentration goes on

increasing but substrate concentration remains the same, no more substrate molecules will attach with enzymes. So, the rate of reaction stays constant and does not increase further (Fig.5.7).

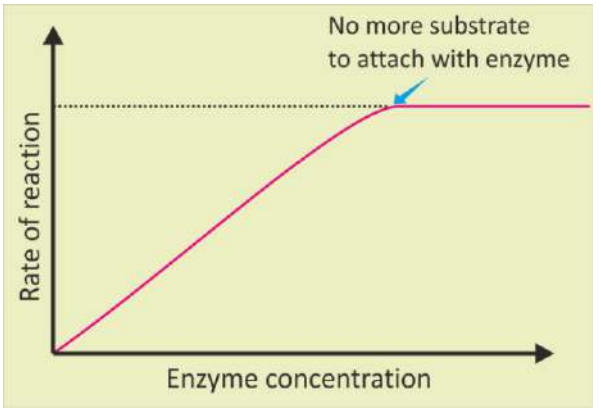


Figure 5.7: Effect of enzyme concentration on enzyme activity

4. Substrate Concentration

If there are enzyme molecules with vacant active sites, an increase in substrate concentration will increase the rate of reaction. If enzyme concentration is kept constant and the amount of substrate is increased, a point is reached where any further increase in substrate does not increase the rate of reaction any more.

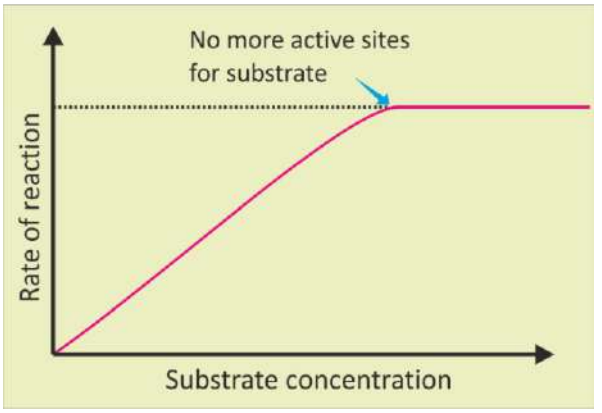


Figure 5.8: Effect of substrate concentration on enzyme activity

When enzyme molecules are free (at low substrate concentration) new substrate molecules bind with the available active sites and so more products are formed in the given time i.e., rate of enzyme action is increased. But when all active sites of enzymes are occupied (at high substrate concentration), any more substrate molecules do not find free active sites and so reaction rate does not increase (Fig.5.8)

5.6-ENZYME INHIBITION

A chemical that interferes and blocks an enzyme's activity is called an **inhibitor**. Inhibitors attach with enzymes but are not transformed into products and thus block active sites temporarily or permanently. This phenomenon is known as enzyme **inhibition**. The final products of complex enzymatic reactions also act as the inhibitors of the enzyme of the first step.

Inhibitors are often used as drugs, but they can also act as poisons. An example of an enzyme inhibitor being used as a drug is aspirin. It inhibits the enzymes that produce prostaglandin (that causes inflammation). Thus, aspirin suppresses pain and inflammation. The poison cyanide is an irreversible enzyme inhibitor that combines with copper and iron in the active site of enzyme cytochrome oxidase and blocks cellular respiration.

Types of Inhibitors

Competitive and non-competitive inhibitors

Two general classes of inhibitors are recognized; competitive and non-competitive inhibitors. A **competitive inhibitor** resembles the enzyme's substrate. It competes with substrate for the same binding site on enzyme. When competitive inhibitor is selected by binding site, it blocks active site and does not permit substrate from attaching. Thus, it prevents enzyme from acting (Figure 5.9).

Competitive inhibitors are used as antibiotics to kill bacteria. These inhibitor molecules are similar in structure to bacterial enzymes which are necessary for their life. The inhibitors bind and inhibit the enzymes of bacteria.

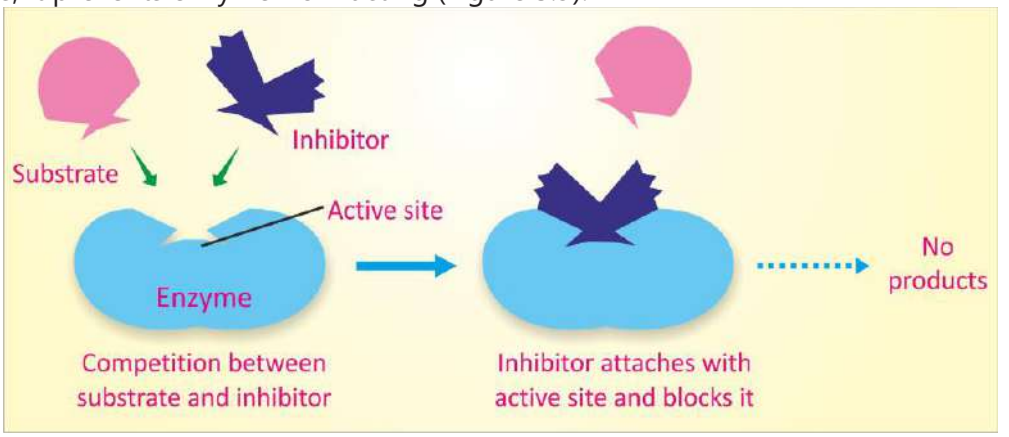


Figure 5.9: Competitive inhibition of an enzyme

The enzyme succinic dehydrogenase catalyses the oxidation of succinic acid to fumaric acid. Malonic acid has structural similarity with substrate (succinic acid). So, both of them compete for active site of enzyme. Malonic acid is selected by active site and thus blocks it.

A **non-competitive inhibitor** has no real structural similarity to substrate. So, it does not enter active site. Instead, it binds enzyme at other places. Its binding alters the shape of enzyme so that active site does not fit substrate and so enzyme is inhibited (Figure 5.10).

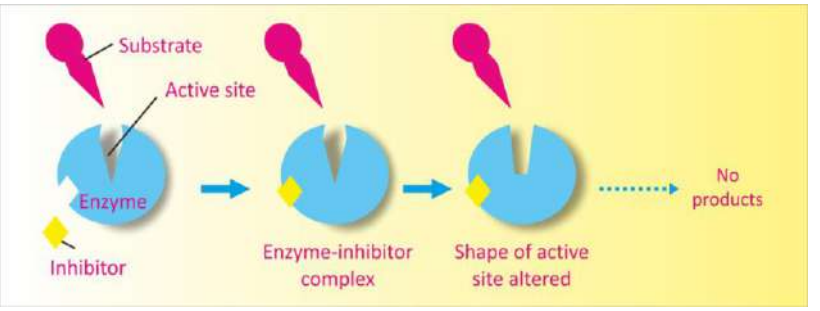


Figure 5.10: Non-competitive inhibition of an enzyme

For example; two substrates i.e., succinic acid and CoA react to form succinyl-CoA. This reaction is catalysed by enzyme succinyl-CoA synthetase. After its formation, the product i.e., succinyl CoA acts as a non-competitive inhibitor and binds with enzyme. Thus, enzyme is inhibited and no more succinyl-CoA is produced.

Reversible and Irreversible Inhibitors

The action of any inhibitor can be irreversible or reversible, depending upon the kind of bond formed between inhibitor and enzyme.

Irreversible inhibitors make covalent bonds with enzyme. Such inhibitors cannot be released by dilution or dialysis or by increasing the concentration of substrate. for example, penicillin permanently disables the enzyme responsible for building bacterial cell walls.

Reversible inhibitors make weak bonds (e.g., hydrogen bonds) with enzyme. Such inhibitors can be released and the inhibition caused by them can be neutralized by increasing the concentration of substrate. for example, malonate is a reversible inhibitor. It temporarily slows down the reaction by blocking the enzyme succinate dehydrogenase, which is involved in cellular respiration. This inhibition can be reversed when malonate is removed.

Significance of Enzyme inhibition

Enzyme inhibition is crucial in various biological processes.

1. Enzyme inhibition plays a vital role in regulating metabolic pathways. By inhibiting specific enzymes, the rate of a metabolic reaction can be controlled.
2. Many drugs work as inhibitors. For example, antibiotics inhibit the enzymes of bacteria, while cancer drugs may inhibit enzymes involved in cell division.
3. Enzyme inhibitors are used to manage various medical conditions. For example, some inhibitors of enzymes involved in blood clotting are used as anticoagulants.
4. Some toxins and poisons inhibit important enzymes in the body. Understanding how these inhibitors affect enzymes can be critical in treating cases of poisoning.
5. Enzyme inhibitors serve as valuable tools in pharmaceutical research. They are used to study the function of specific enzymes, and potential drugs.

Enzyme inhibition is an important part of studying enzyme kinetics. It helps to understand the factors that influence enzyme activity.

Feedback Inhibition of Enzymes

We know that in metabolic pathways, the product of one reaction becomes the substrate for next reaction. At the end of pathway, a desired product is synthesized. In order to regulate the concentration of that product, pathway needs to be shut down. This is done through feedback inhibition. The final product of pathway acts as inhibitor. It reacts with some initial enzyme and changes its conformation. That

enzyme can no longer bind to its substrate. So, pathway closes and no more product is prepared (Figure 5.11).

For example, when a cell has a greater number of ATP than its requirement, ATP itself acts as a non-competitive inhibitor and blocks the enzyme that catalyses ATP synthesis.

Feedback inhibition is the phenomenon where the product of a process controls the process itself, oftentimes limiting the production of more products.

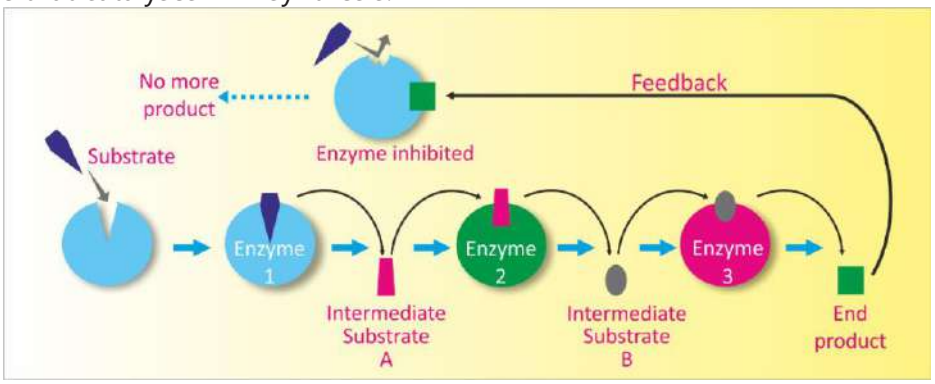


Figure 5.11: Feedback inhibition of enzyme action

5.7 - CLASSIFICATION OF ENZYMES

Enzymes are classified on the basis of reactions they catalyse and also on the basis of substrates they use.

Classification on the Basis of Reactions

According to the general type of reaction, enzymes are classified into six classes.

1- Oxidoreductases: These enzymes catalyse the oxidation / reduction of their substrates. They add or remove H^+ ions or electrons from substrates. For example, **cytochrome oxidase** catalyses the oxidation of cytochrome.

2- Transferases: The enzymes of this class catalyse the transfer of a specific functional group (e.g., methyl, acyl, amino, or phosphate) from one substrate to another. For example, **hexokinase transfers** phosphate group from ATP to glucose.

3- Hydrolases: These enzymes catalyse hydrolysis reactions. They break their substrates into monomers by adding water. For example; **lipase, amylase, peptidase,** and other digestive enzymes catalyse the hydrolysis of food molecules.

4- Lyases: These enzymes catalyse non-hydrolytic addition or removal of groups (e.g., CO_2, NH_2 etc.) from substrates. For example, **pyruvate decarboxylase** removes CO_2 from pyruvic acid.

5- Isomerases: These enzymes catalyse the intra-molecular rearrangement i.e., one isomer is converted into another. For example, **hexose isomerase** converts glucose to fructose.

6- Ligases: These enzymes catalyse the reactions in which two molecules join by forming new C-C, C-N, C-O, or C-S bonds, using energy from ATP. For example, **polymerase** enzymes join monomers by using ATP.

Classification on the Basis of Substrates

Enzymes are also classified into following groups on the basis of their substrates.

1- Proteases: This group included the enzymes which catalyse the breakdown of proteins. For example, **pepsin** and trypsin enzymes catalyse the breakdown of large polypeptides into smaller polypeptides. Similarly, **aminopeptidases** further breakdown small polypeptides into dipeptides and erypsin breaks dipeptides into amino acids.

2- Lipases: These enzymes act upon lipids and catalyse their breakdown. For example, pancreatic **lipase** hydrolyses lipids into fatty acids and glycerol.

3- Carbohydrases: These enzymes act upon bigger carbohydrates and break them into smaller units. For example, **amylase** acts upon starch or glycogen and breaks them into maltose. **Cellulase** breaks cellulose into cellobiose (a disaccharide) or glucose. Similarly, **maltase** breaks down maltose into glucose, **sucrase** breaks sucrose into glucose and fructose, and **lactase** breaks lactose into glucose and galactose.

4- Nucleases: These enzymes act upon nucleic acids and catalyse their breakdown. For example, **RNAase**, **DNAase**, **ATPase** are responsible for the breakdown of RNA, DNA and ATP respectively.

Class	Reaction type	Important subclasses
1- Oxidoreductases	A + B ⇌ A + B (red, ox, ox, red)	Dehydrogenases Oxidases Reductases
2- Transferases	AB + C ⇌ A + CB	Phospho-transferases Amino-transferases Acyl-transferases
3- Hydrases	AB + H_2O ⇌ C + D	Peptidases Lipases Glycodsidases
4- Lyases	A–B ⇌ C + B	Decarboxylases Aldolases Synthases
5- Isomerases	A ⇌ A	Epimerases Mutases *cis trans* isomerases
6- Ligases	A + B + ATP ⇌ AB + ADP	C-C ligases C-O ligases C-N ligases

Figure 5.12: Enzyme classification on the basis of reactions

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. What roles does nicotinamide adenine dinucleotide play in oxidative pathways?
   (a) Enzyme (b) Coenzyme (c) Prosthetic group (d) Inhibitor
2. The enzymes that catalyse the reactions in which two molecules are joined together by synthesis of new bonds, using energy from ATP, are placed in group;
   (a) Hydrolase (b) Ligase (c) Lyase d) Transferase
3. Which of the following is an example of hydrolases?
   (a) Lipase (b) Glycogen phosphorylase
   (c) Pyruvate decarboxylase (d) Cytochrome oxidase
4. Which of the following statements about enzymes is correct?
   (a) They increase the activation energy of a reaction.
   (b) They are consumed during the reaction.
   (c) They are specific in terms of the reactions they catalyse.
   (d) They always work optimally at high temperatures.
5. Enzyme B requires Zn2+ to catalyse the conversion of substrate X. The zinc is best identified as a(n):
   (a) Coenzyme (b) Activator (c) Substrate (d) Product
6. If an enzyme solution is saturated with substrate, the most effective way to obtain an even faster yield of products would be
   (a) Add more of the enzymes (b) Add more substrate
   (c) Add an allosteric inhibitor (d) Add a non-competitive inhibitor
7. How does a non-competitive inhibitor decrease the rate of an enzyme-catalysed reaction?
   (a) By binding the active site of the enzyme
   (b) By changing the shape of the enzyme
   (c) By changing the free energy change of the reaction
   (d) By acting as a coenzyme for the reaction
8. Which enzyme class is responsible for catalysing the addition of water to a substrate molecule?
   (a) Ligase (b) Lyase (c) Hydrolase (d) Isomerase

SECTION 2: SHORT QUESTIONS

1. Define enzyme and co-factor.
2. Differentiate between co-enzyme and prosthetic group.
3. What do you mean by hydrolases? Give two examples.
4. What is meant by activation energy?
5. Define feedback inhibition.
6. Give examples of competitive and non-competitive inhibitors.

7. What is optimum pH? Give optimum pH of three human enzymes.

SECTION 3: LONG QUESTIONS

1. Describe the structure of enzyme, explaining the role and component parts of the active site of an enzyme.
2. Differentiate among the three types of co-factors, by giving examples.
3. Explain the mechanism of enzyme action through Induced Fit Model, comparing it with Lock and Key Model.
4. Define activation energy and explain through graph how an enzyme speeds up a reaction by lowering activation energy.
5. Describe the effect of temperature on the rate of enzyme action.
6. Compare the optimum temperatures of enzymes of human and thermophilic bacteria.
7. Describe how the concentration of enzyme affects the rate of enzyme action.
8. Explain the effect of substrate concentration on the rate of enzyme action.
9. Describe enzymatic inhibition, its types and its significance.
10. Categorize inhibitors into competitive and non-competitive inhibitors.
11. Explain feedback inhibition.
12. Classify enzymes on the basis of the reactions catalysed.
13. Give examples of enzymes' naming according to substrates.

INQUISITIVE QUESTIONS

1. Does physical exercise involve anabolic processes, catabolic processes, or both? Give evidence for your answer.
2. If a chemical reaction could occur without an enzyme, why is it important to have one?
3. Construct and interpret graphs based on data about the effect of temperature, enzyme concentration and substrate concentration on the rate of enzyme action.
4. Identify the competitive and non-competitive inhibitors from a list of chemicals used in daily life.

Chapter 6

BIOENERGETICS

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Explain the role of light, carbon dioxide and water in photosynthesis.
- Identify the two general kinds of photosynthetic pigments (carotenoids and chlorophylls).
- Describe the roles of photosynthetic pigments in the absorption and conversion of light energy.
- Differentiate between the absorption spectra of chlorophyll 'a' and 'b'.
- Draw the molecular structure of chlorophyll.
- Describe the arrangements of photosynthetic pigments in the form of photosystem-I and II.
- Describe the events of non-cyclic photophosphorylation and outline the cyclic photophosphorylation.
- Draw the Z-scheme for explaining the events the light dependent reactions.
- Explain the Calvin cycle.
- Develop a flow chart for explaining the events of light reactions.
- Describe the features of ATP that make it suitable as the universal energy currency.
- Describe the synthesis and breakdown of ATP.
- Describe the four stages in aerobic respiration in eukaryotic cells:
- Explain the process of anaerobic respiration in terms of glycolysis and conversion of pyruvate into lactic acid or ethanol.
- Outline the events of glycolysis (naming the reactants and products of each step).
- Describe the link reaction, including the role of coenzyme A.
- Outline the Krebs cycle (naming the reactants and products of each step).
- Describe the role of NAD and FAD in cellular respiration.
- Explain that passage of electrons through electron transport chain highlighting the oxidation and reduction reactions (details of carriers are not required).
- Describe chemiosmosis and relate it to electron transport chain.
- Explain why the energy yield from respiration in aerobic conditions is much greater than the energy yield from respiration in anaerobic conditions.

Every living organism, from the smallest bacterium to the largest whale, is driven by energy. This energy fuels their growth, reproduction, and daily survival, making it a fundamental aspect of life. But where does this energy come from? How is it harnessed and utilized by cells to perform countless activities essential for life? The answer lies in the fascinating field of bioenergetics.

Bioenergetics is the study of how energy flows through living systems. It explores the processes through which cells store and expend energy. The processes of photosynthesis and

Nearly all the energy used by living organisms on Earth comes from photosynthesis. Plants, algae, and certain bacteria capture sunlight and convert it into chemical energy, forming the base of the food chain.

respiration help to understand some of the principles of bioenergetics. Photosynthesis acts as an energy–capturing while respiration as an energy-releasing process.

ATP: The Energy Currency of Cells

Cells use a special energy currency for their reactions. This currency is actually a **nucleotide** called **adenosine triphosphate (ATP)** When cells store energy, they make ATP. When cells need energy, they break ATP. A molecule of ATP has three subunits i.e. **adenine**, (a nitrogen containing base); **ribose** (a five-carbon sugar) and three **phosphate** groups.

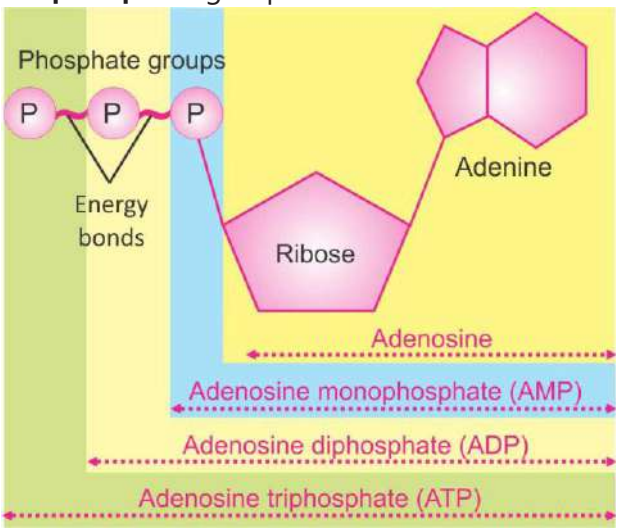


Figure 5.1: Molecular structure of ATP

ATP was discovered in 1929 by **Karl Lohmann**.
In 1941, the Nobel prize winner, **Fritz Lipmann** proposed that ATP is the main energy-transfer molecule in the cell.

The covalent bonds between two phosphates are high-energy bonds. When one of these bonds is broken, inorganic phosphate (Pi) separates and energy is released. The breaking of one phosphate bond releases about 7.3 kcal (7,300 calories) per mole of ATP.

$$ATP + H_2O \rightarrow ADP + P_i + \text{energy (7.3 kcal/mole)}$$

In common energy reactions only the outer P-P high-energy bond breaks. When this happens, ATP becomes **ADP (adenosine diphosphate)** and one Pi is released.

In some cases, ADP is further broken down to **AMP (adenosine monophosphate)** and Pi:

$$ADP + H_2O \rightarrow AMP + P_i + \text{energy (7.3 kcal/mole)}$$

Cells get energy from the oxidation of food. They store this energy by combining ADP with P_i to form ATP. So, we can summarize that ATP is made during energy-releasing processes and it is broken down during energy-consuming processes. In this way ATP transfers energy between metabolic reactions.

5.1- PHOTOSYNTHESIS

Photosynthesis involves the use of light energy that is absorbed and converted into chemical energy by photosynthetic pigments. Photosynthesis in plants can be summarized as:

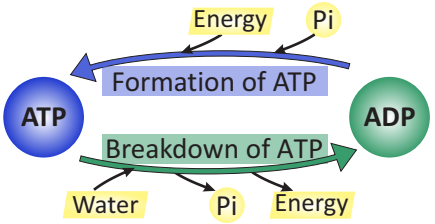


Figure 5.2: ATP-ADP Cycle

$$6CO_2 + 12H_2O + Light \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Carbon dioxide, water and light are the reactants while glucose and oxygen are the products. Water appears on both sides of the equation because water is used as reactant in some reactions and released as product in others. However, there is no net yield of water.

Recalling:
Photosynthesis is the process in which the energy-poor inorganic compounds of carbon (i.e., CO_2) are reduced to energy-rich carbohydrates.

Compensation Point: Photosynthesis uses the products of respiration and respiration uses the products of photosynthesis. Photosynthesis occurs only during day time but respiration goes on day and night. During darkness, leaves and other parts respire and utilize oxygen and release carbon dioxide. At dawn and dusk, when light intensity is low, the rate of photosynthesis and respiration may be equal for a short time. Thus, the oxygen released from photosynthesis is just equal to the amount required for cellular respiration. Also, the carbon dioxide released by respiration is just equal to the amount required by photosynthesizing cells. At this moment there is no net gas exchange between leaves and atmosphere. This is termed as compensation point. At noon, when the light intensity increases, the rate of photosynthesis also increases. At this time, there is more requirement of carbon dioxide. Respiration alone cannot supply this carbon dioxide. Similarly, the oxygen produced during photosynthesis is more than the need of the respiring cells. So, the result is the net release of oxygen coupled with the uptake of carbon dioxide.

Role of Light

Light plays a crucial role in photosynthesis, providing the energy required to drive the chemical reactions that transform simple molecules into complex organic compounds. Light energy is absorbed by chlorophyll. The absorbed light energy is converted into chemical energy, which is in turn stored in organic compounds in the form of C-H bond energy. It happens like this;

Plants convert only about 1-2% of the solar energy they receive into chemical energy during photosynthesis. Despite this seemingly low efficiency, this conversion is enough to sustain almost all life on Earth.

Action Spectrum

Photosynthetic pigments absorb different wavelengths of light at different rates. Moreover, the different wavelengths are also differently effective in photosynthesis. The effectiveness of different wavelengths of light is determined in terms of action spectrum. For getting action spectrum of light, a plant is illuminated with different colours of light one by one. While providing each colour, the rate of

photosynthesis is measured by measuring the amount of oxygen emitted from leaves. The data is plotted in a graph called action spectrum. The first action spectrum was made by a German biologist, T. W. Engelmann in 1883. He worked on the photosynthetic pigments of *Spirogyra* When the cells of a filament of *Spirogyra* were illuminated with different wavelengths of light, maximum photosynthesis occurred in the cells which received blue and red spectrum of light and so maximum oxygen was emitted from these cells.

Role of Carbon Dioxide

Sugar is formed by the reduction of CO_2 by using ATP and NADPH. In this way, CO_2 acts as the source of carbon for making sugars. Carbon dioxide enters the leaves through stomata and gets dissolved in water absorbed by the cell walls of mesophyll cells. Stomata are found in large numbers in leaves. The entry of CO_2 into the leaves is dependent upon the opening of stomata.

About 10% of total photosynthesis is carried out by terrestrial plants, the rest occurs in oceans, lakes and ponds. Aquatic photosynthetic organisms use dissolved CO_2, bicarbonates and soluble carbonates as carbon source. Land photosynthetic organisms use atmospheric CO_2 as carbon source.

Neil's hypothesis was based on the investigations on photosynthetic bacteria that make carbohydrate from carbon dioxide, but do not release oxygen.

Role of Water

Water is the source of hydrogen, for the reduction of CO_2 during photosynthesis. Oxygen released during photosynthesis comes from water, and so water is an important source of atmospheric oxygen which most organisms need for aerobic respiration and thus for obtaining energy to live.

In 1930s, **Van Neil** hypothesized that plant splits water as a source of hydrogen, releasing oxygen as a by-product. Neil's hypothesis was later confirmed by scientists during 1940s. An experiment was conducted in which isotopic tracer (^{18}O) of oxygen was used. In laboratory, scientists

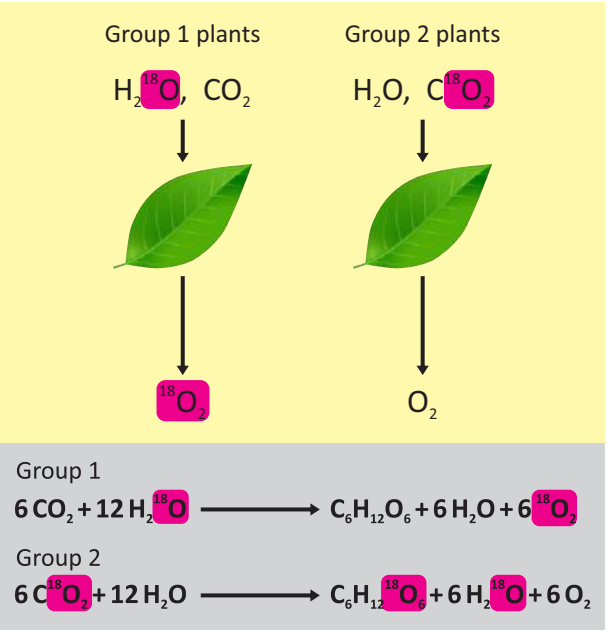


Figure 5.3: Experiment to prove that water is the source of oxygen released in photosynthesis

prepared water with heavy-oxygen i.e., $H_2{}^{18}O$. They also prepared carbon dioxide with heavy oxygen i.e., $C^{18}O_2$. Experimental green plants in one group were given water $H_2{}^{18}O$ and normal carbon dioxide i.e., $C^{16}O_2$. Plants in the second group were given $C^{18}O_2$ and normal water i.e., $H_2{}^{16}O$. Both plants were given an environment to conduct photosynthesis. Oxygen released during photosynthesis of both plants was collected and tested. It was found that plants of first group produced ^{18}O but the plants of second group produced normal oxygen (^{16}O).

In photosynthesis water is split to release hydrogen. This hydrogen reduces the coenzyme nicotinamide adenine dinucleotide phosphate (NADP) to NADPH. The reduced coenzyme i.e., NADPH serves as the "reducing power" for the reduction of CO_2 to form sugar.

Role of Photosynthetic Pigments

Photosynthetic pigments are present in thylakoid membranes. These pigments capture light energy necessary for photosynthesis. Soe of the pigments are chlorophyll a, chlorophyll b, xanthophylls, carotenes. Different pigments absorb light of different wavelengths (colours). Light behaves like a stream of particles called photons. Pigment molecules absorb one photon at a time.

Short wavelength photons (blue) have a higher energy than long wavelength (red) photons. More energetic photons (shorter wavelength) promote electrons to higher energy levels.

When a pigment molecule absorbs a photon, its electrons move to higher energy level, So, it becomes energy-rich or excited.

Chlorophylls

Chlorophyll is a lipid molecule. Chlorophylls are of different kinds. Chlorophyll a, b, c and d are found in plants and algae, while the others are found in photosynthetic bacteria and are known as bacteriochlorophylls.

A molecule of chlorophyll consists of two parts i.e., a hydrophilic head and a hydrophobic tail. The head is made of a porphyrin ring, which further consists of four pyrrole rings (5-sided N-containing compounds). The four pyrrole rings are held together by a magnesium atom in the centre. In chlorophyll-a, the second pyrrole ring has methyl (CH_3) group while in chlorophyll-b, it has aldehyde (CHO) group at the same spot. The porphyrin ring of chlorophyll absorbs light. The tail is made of long hydrocarbon chain. It anchors the molecule in the thylakoid membrane.

Chlorophylls absorb mainly violet-blue and orange-red wavelengths of light. Green wavelengths are least absorbed by chlorophylls and are transmitted or reflected.

Carotenoids, such as beta-carotene, play dual role in photosynthesis. They capture light energy in the blue and green regions of the spectrum and protect the photosynthetic apparatus from damage by excess light.

Accessory Pigments

Accessory pigments include all the pigments, other than chlorophyll-a, which can gather light for photosynthesis. Chlorophyll b is an accessory pigment and others are carotenoids (carotenes and xanthophylls) and phycobilins. Chlorophyll b and carotenoids are found in plants while phycobilins are found in the red algae and cyanobacteria.

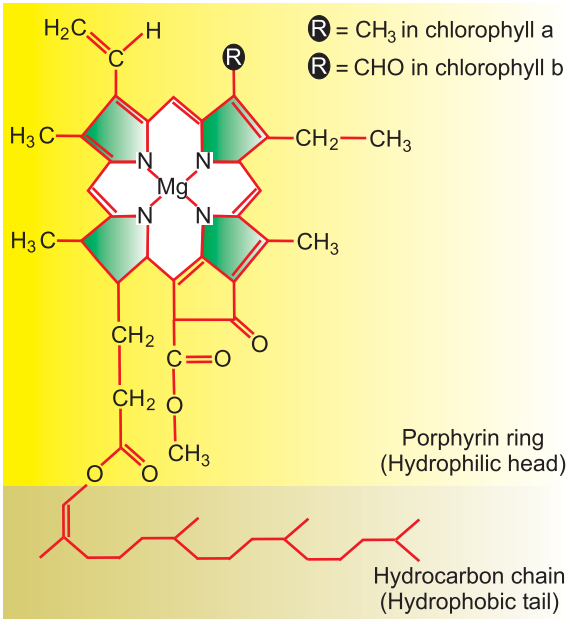


Figure 5.4: Molecular structure of chlorophyll a and chlorophyll b

When accessory pigments absorb light, they pass on the energy towards chlorophyll a. It is generally believed that the order of transfer of energy in plants is;

Carotenoids → Chlorophyll b → Chlorophyll a

Absorption Spectrum

A graph showing different wavelengths absorbed by a pigment, is called absorption spectrum of the pigment. Absorption spectrum of chlorophylls indicates that absorption of blue light (430 nm) and red light (670 nm) is maximum. Absorption peaks of carotenoids are different from those of chlorophylls (Fig 5.5-a). Action spectrum of photosynthesis also shows that blue and red parts lights are the most effective. This means that the action spectrum of photosynthesis coincides with the absorption spectrum of photosynthetic pigments.

Some wavelengths not absorbed by chlorophyll-a are very affectively absorbed by chlorophyll-b and vice-versa. Such differences increase the range of light absorbed by both chlorophylls.

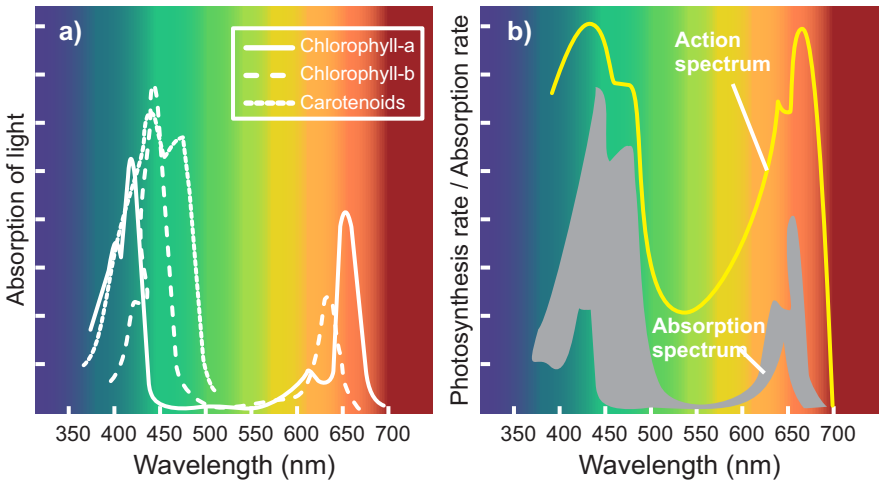


Figure 5.5: (a)- Absorption spectrum; (b)- Action spectrum

Organization of Photosynthetic Pigments (Photosystems)

For efficient absorption and utilization of solar energy, photosynthetic pigments are organized into clusters, called photosystems. These photosystems are embedded in thylakoid membranes of chloroplasts.

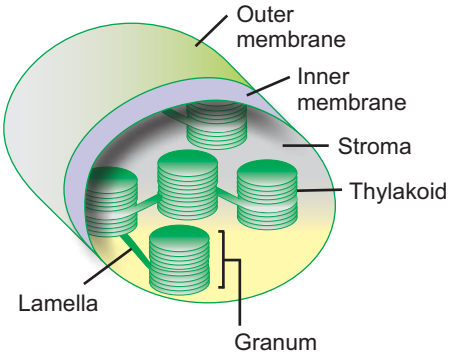


Figure 5.6: Structure of Chloroplast

Photosystems contain photosynthetic pigments and the carriers of electron transport chain. Each photosystem consists of a light gathering **'antenna complex'** and a **'reaction centre'** (Fig 5.7). Antenna complex has many pigment molecules which capture light energy and pass the excitation energy (in the form of high-energy electrons) to the reaction centre. The reaction centre has one or more molecules of chlorophyll-a, which pass the high-energy electrons to a primary electron acceptor. The electron acceptor passes them on to the series of electron carriers, collectively called electron transport chain.

In chloroplast, there are two photosystems, photosystem-I (PS-I) and photosystem-II (PS-II). These are named so in order of their discovery. PS-I has P700 chlorophyll-a molecule in its reaction centre and it absorbs maximum light of 700 nm.

The reaction centre of PS-II has P680 chlorophyll-a, which absorbs best the light of 680 nm.

Mechanism of Photosynthesis

Photosynthesis is a redox (oxidation-reduction) process. As indicated in the photosynthesis equation below, when water molecules are split apart, they are actually oxidized (they lose electrons and hydrogen ions) and yield oxygen. Meanwhile, CO_2 is reduced to sugar as electrons and hydrogen ions are added to it. In this way oxidation and reduction go hand in hand.

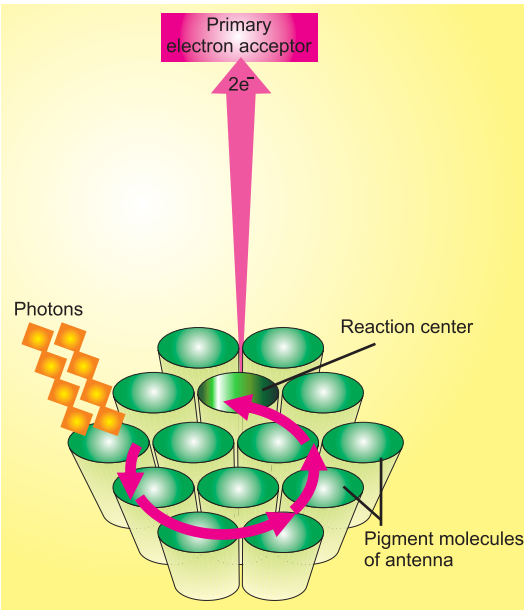
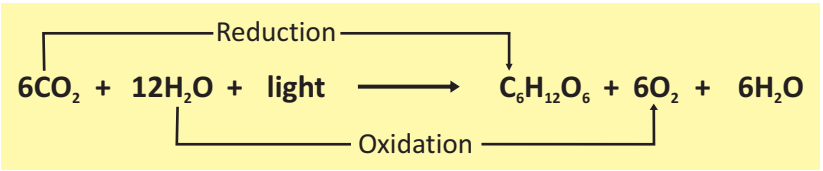


Figure 5.7: Photosystem



However, it is not a simple, single-step process. Rather, it is a complex metabolic pathway consisting of a series of reactions. The light-dependent reactions take place on the thylakoid membranes of the grana while the light-independent reactions take place in the stroma of the chloroplasts. Figure 5.8 shows the summary of these reactions.

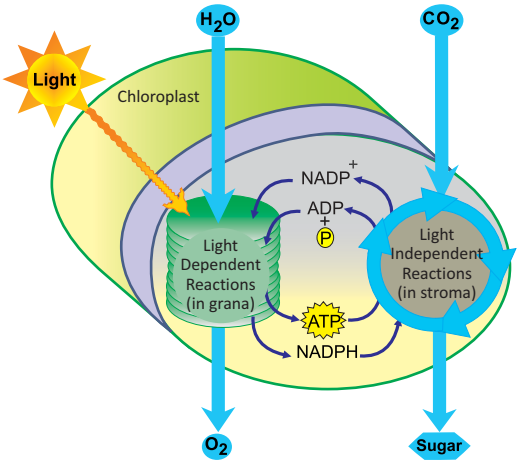


Figure 5.8: Overview of photosynthesis

1- Light- Dependent Reactions

The key events in the light-dependent reactions of photosynthesis are (1) the absorption of light energy by photosynthetic pigments, (2) the excitation of electrons by that energy, and (3) the formation of ATP and NADPH.

During light dependent reactions, light energy is absorbed and converted into chemical energy, which is in the form of reducing and assimilating powers i.e., NADPH and ATP.
Light independent reactions use NADPH and ATP for the reduction CO_2 and thus store chemical energy in the form of C-H bond energy

The formation of ATP is the most important step of light-dependent reactions. It is called photophosphorylation. This process is either non-cyclic photophosphorylation or cyclic photophosphorylation.

a)- Non-Cyclic Photophosphorylation

It is the usual way of the production of ATPs during light-dependent reactions. In non-cyclic pathway, both photosystems i.e., PS-I and PS-II participate and two electron chains are involved (Fig. 5.9). It happens in the following way.

1- **Absorption of light by PS-II:** When light falls on PS-II, the energy level of chlorophyll molecules of its antenna centre rises. Two excited electrons move from them and pass to different chlorophyll molecules. The excited electrons reach P680 chlorophyl present in the reaction centre. Due to energy boost of P680 chlorophyll, its two excited electrons pass to the primary electron acceptor of photosystem-II. Due to it, an electron "hole" is created in p680 chlorophyll, which has become a strong oxidizing agent.

2- **Photolysis of water:** The electron "hole" in chlorophyll molecule is filled by the electrons from water. When water molecule reacts with oxidized chlorophyll in PS-II, it breaks into two hydrogen ions, an oxygen atom (which immediately combines with another oxygen to form O_2), and two electrons. These two electrons fill the "hole" in P680 chlorophyll. This water splitting step of photosynthesis is called **photolysis**.

The oxygen produced during photolysis is the main source of atmospheric oxygen.

3- **Electron flow from PS-II to PS-I:** In step 1, the photoexcited electrons of P680 chlorophyll were received by primary electron acceptor of PS-II. Now, these electrons pass to PS-I via an electron transport chain of PS-II. This chain consists of electron carriers called plastoquinone (PQ), cytochrome complex, and plastocyanin (PC). As electrons move down the chain, their energy goes on decreasing and is used by thylakoid membrane to produce ATP through the process of chemiosmosis.

4- **Absorption of light by PS-I:** In the next step light energy is absorbed by PS-I. The energy level of its chlorophyll molecules boosts to very hight level. The excited

electrons of P700 chlorophyll of the reaction centre pass to the primary electron acceptor of PS-I. The electrons coming from PS-II fill the electron "hole" of P700 chlorophyll of PS-I.

5- Electron flow from PS-I to $NADP^+$: The primary electron acceptor of PS-I passes the photoexcited electrons to a second electron transport chain. These electrons are received by ferredoxin (FD). An enzyme NADP reductase transfers these electrons from FD to $NADP^+$. When $NADP^+$ gets two electrons and an H^+ ion, it is reduced to NADPH. This reaction stores the high-energy electrons in NADPH.

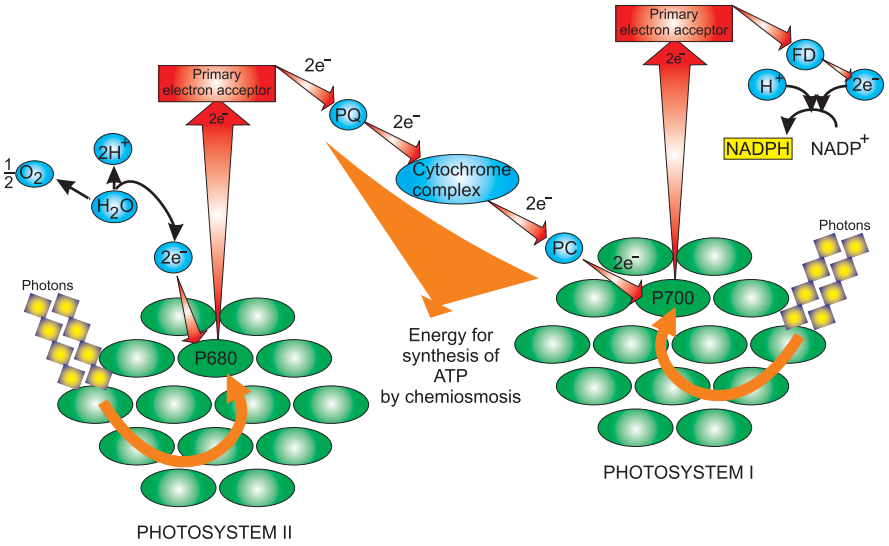


Figure 5.9: Light-dependent reactions (noncyclic photophosphorylation)

So, the light energy gets converted into chemical energy (ATP and NADPH). The zigzag path taken by electrons through PS-II and PS-II and electron transport chains, is called **Z-scheme**

b)- CyclicPhotophosphorylation

Under certain conditions, photoexcited electrons of PS-I take an alternative path called cyclic electron flow. This path uses PS-I but not PS-II. These electrons cycle-back from primary electron acceptor of PS-I to P700 chlorophyll via the electron transport chain. There is no production of NADPH and no release of oxygen. Cyclic flow however generates ATP (Fig 5.10). It happens when Calvin cycle slows down and NADPH accumulates in chloroplast.

Chemiosmosis

During light-dependent reactions when electrons are transferred to the series of carriers of electron transport chain, it results in oxidation and reduction reactions. A carrier is oxidized when it loses electrons and next carrier is reduced when it gets

electrons. Electrons lose energy during this carrier-to-carrier transport. Chemiosmosis is the mechanism in which thylakoid membranes couple these redox reactions with the synthesis of ATPs.

How does chemiosmosis use the energy released from electrons to synthesize ATP? Actually, this energy is spent for the active transport of H^+ ions from the stroma of chloroplast to its inner compartment (lumen). In this way many H^+ ions are deposited in the lumen. This H^+ ion gradient in lumen has potential energy. The H^+ ions diffuse back from lumen in stroma (from higher concentration in lumen to lower concentration). While diffusing, they pass through a special protein of the membrane of thylakoid cells. This protein is an enzyme called ATP synthase. This enzyme uses the energy yielded from the flow of H^+ ions to make a bond between ADP and inorganic phosphate (Pi). So, ADP is converted into ATP and energy is packed in it (Fig 5.11).

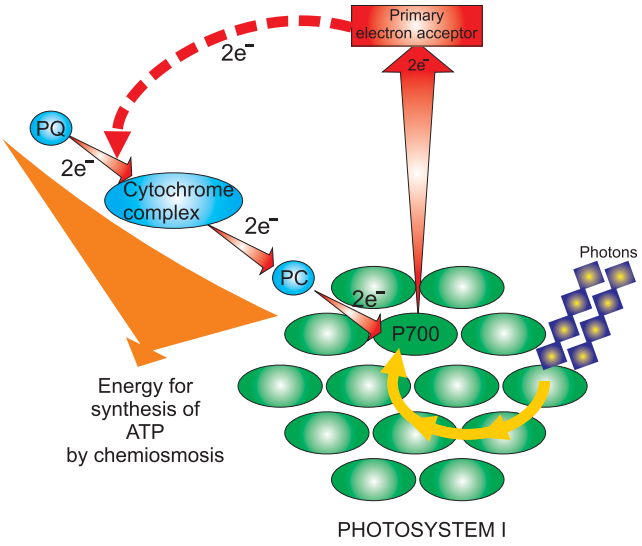


Figure 5.10: Cyclic Photophosphorylation

The electron transport chains in mitochondria and chloroplasts generate ATP by the same mechanism of chemiosmosis.

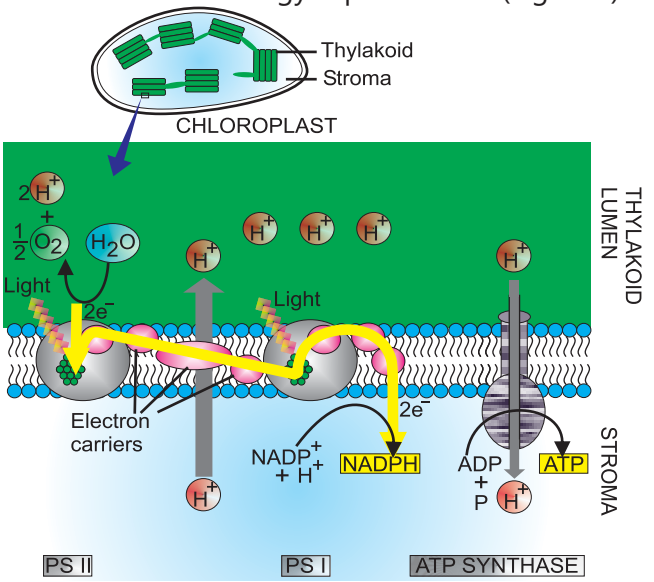


Figure 5.11: Electron transport chain and chemiosmosis in chloroplast

2- Light-Independent Reactions

Light-independent reactions are a series of reactions which happen in the stroma of chloroplast. These reactions use carbon from CO_2, energy from ATP, and hydrogen ions from NADPH to construct energy-rich sugar molecules. These are also called **dark reactions**. These reactions can occur in the absence as well as in the presence of light, as long as ATP and NADPH are available (Fig 5.11). The Calvin cycle is divided into the following phases.

The details of dark reactions were discovered by **Melvin Calvin** and his colleagues at the University of California. That is why, the dark reactions are also called the Calvin cycle. Calvin was awarded Nobel Prize in 1961 for this work.

Phase I: Carbon Fixation

Since the product of initial carbon fixation is a three–carbon compound, the Calvin cycle is also known as C-3 pathway.

Carbon fixation refers to the initial incorporation of CO_2 into organic material. An enzyme known as ribulose biphosphate carboxylase (or Rubisco; probably the most abundant protein on Earth) combines three molecules of CO_2 with three molecules of a five-carbon sugar named ribulose biphosphate (RuBP). It results in the formation of six molecules of a three–carbon compound called 3–phosphoglyceric acid (3-PGA) or 3-phosphoglycerate.

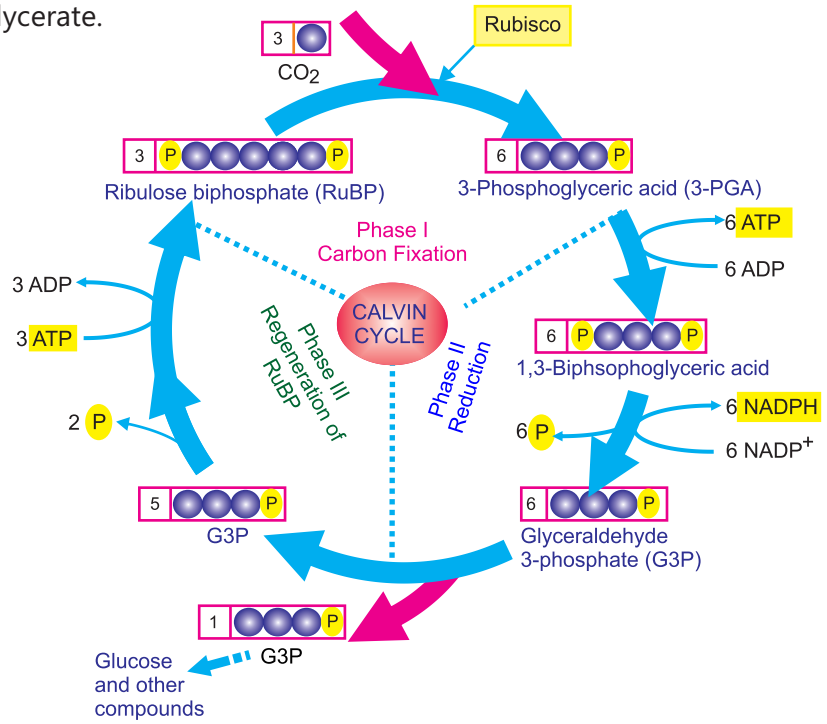


Figure 5.12: The Calvin cycle

Phase II: Reduction

In this phase, six phosphate groups are taken from six ATPs and added to molecules of 3-PGA. In this way, each 3-PGA changes into 1,3-biphsophoglyceric acid. Each 1,3-biphsophoglyceric acid is then reduced to Glyceraldehyde 3-phosphate (G3P). NADPH provides hydrogen for this reduction. During this step, phosphate groups are also detached from 1,3-biphsophoglyceric acid.

G3P is the same three-carbon sugar which is formed in glycolysis (first phase of cellular respiration) by the splitting of glucose.

In this way, six molecules of G3P are produced, out of which one molecule leaves the cycle. It combines with another G3P and makes glucose, which may be then converted to other carbohydrates.

Phase III: Regeneration of RuBp

Through a series of reactions, five molecules of G3P are converted into three molecules of Ribulose phosphate (RuP). One phosphate group is added to each RuP to make three molecules of RuBP by using three ATPs of light reactions. These RuBP receive CO_2 again, and the cycle continues.

5.2. CELLULAR RESPIRATION

Cellular respiration is the universal process by which organisms break down complex carbon containing compounds (e.g., glucose) to get useable energy. Cellular respiration can be summarized as:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

The exchange of CO_2 and O_2 between the organism and its environment is called external respiration or breathing. Cellular respiration is the process by which energy is made available to cells in a step-by-step oxidation of food in the cells.

You can see that the arrangement of atoms in glucose has more stored energy while there is much less energy in the arrangement of atoms in CO_2 and H_2O. The reason is that there are many C-H bonds in glucose but there are no such bonds in CO_2 and H_2O.

The basic events in cellular respiration in all cells are much similar. Almost all cells in all organisms use glucose as energy source. That is why, glucose is known as respiratory fuel. There are two main types of cellular respiration:

Many of the reactions that occur in your cells also occur in the cells of frog, mice, planaria, mushrooms and radishes.

1. Anaerobic respiration (fermentation) takes place in the absence of oxygen.
2. Aerobic respiration takes place in the presence of oxygen.

In the first step of both these types, glucose is split into two molecules of pyruvic acid ($C_3H_4O_3$) in a process called glycolysis. The next reactions of pyruvic acid are different in anaerobic and aerobic respiration.

Mechanism of Anaerobic Respiration

Anaerobic respiration happens in many microorganisms and in some cells of higher plants. It also happens in the muscle cells of vertebrates. In anaerobic respiration, glucose is not completely oxidized. This type of respiration yields relatively small amount of energy from glucose molecule. As a result of anaerobic respiration, one glucose molecule yields only two ATPs (only about 2% of the energy present in glucose). The energy in two ATPs is equivalent to 14.6 kcal.

Anaerobic respiration consists of glycolysis followed by the reduction of pyruvic acid by NADH to either lactic acid or alcohol and CO_2 i.e., it may again be classified as;

a- Alcoholic Fermentation: In primitive prokaryotic cells (bacteria) and in some eukaryotic cells such as yeast, pyruvic acid is further broken down by alcoholic fermentation into alcohol (C_2H_5OH) and CO_2.

$$2(C_3H_4O_3) \xrightarrow{4H} 2(C_3H_6O_3)$$

Pyruvic acid — Ethyl alcohol

b- Lactic acid Fermentation: In lactic acid fermentation, each pyruvic acid molecule is converted into lactic acid $C_2H_6O_3$ in the absence of oxygen gas.

$$2(C_3H_4O_3) \longrightarrow 2(C_2H_5OH) + 2CO_2$$

Pyruvic acid — Ethyl alcohol

This form of anaerobic respiration occurs in muscle cells of humans and other animals. It happens during extreme physical activities, when oxygen cannot be transported to the cells as rapidly as it is needed. Many bacteria also use lactic acid fermentation to get energy.

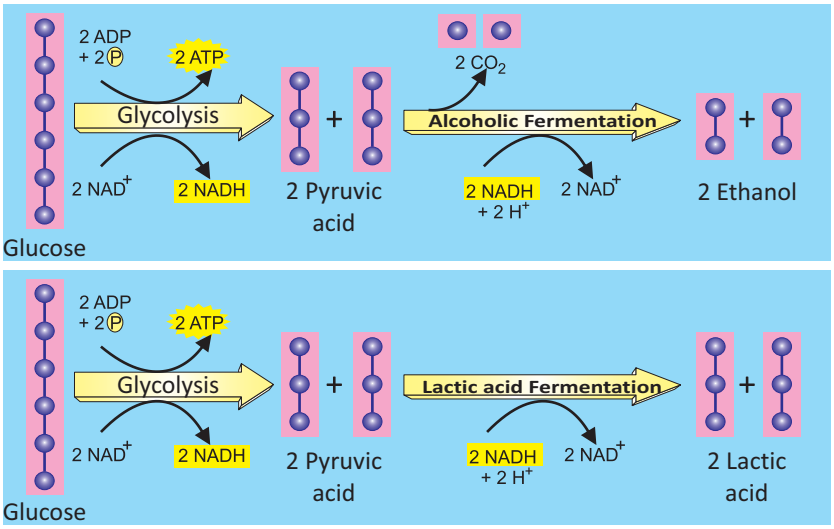


Figure 5.13: Alcoholic fermentation and lactic acid fermentation

Mechanism of Aerobic Respiration

The complete breakdown of glucose molecule occurs only in aerobic respiration. During aerobic respiration, glucose is broken down to pyruvic acid which is then completely oxidized to CO_2 and water and all the energy stored in its C-H bonds, is released.

When life evolved on planet Earth free O_2 was not available. So, only anaerobic respiration was possible. But with the evolution of photosynthesis on Earth, molecular oxygen accumulated slowly in the atmosphere. The presence of free oxygen made evolution of aerobic respiration possible.

Cellular respiration is a continuous process, but for study purposes we can divide it into four main stages.

1- Glycolysis **2-** Pyruvic acid oxidation

3- Krebs cycle or citric acid cycle **4-** Electron transport chain and Chemiosmosis

Glycolysis occurs in the cytosol and oxygen is not essential for this stage. The other three stages occur within mitochondria where the presence of oxygen is essential (Fig 5.14).

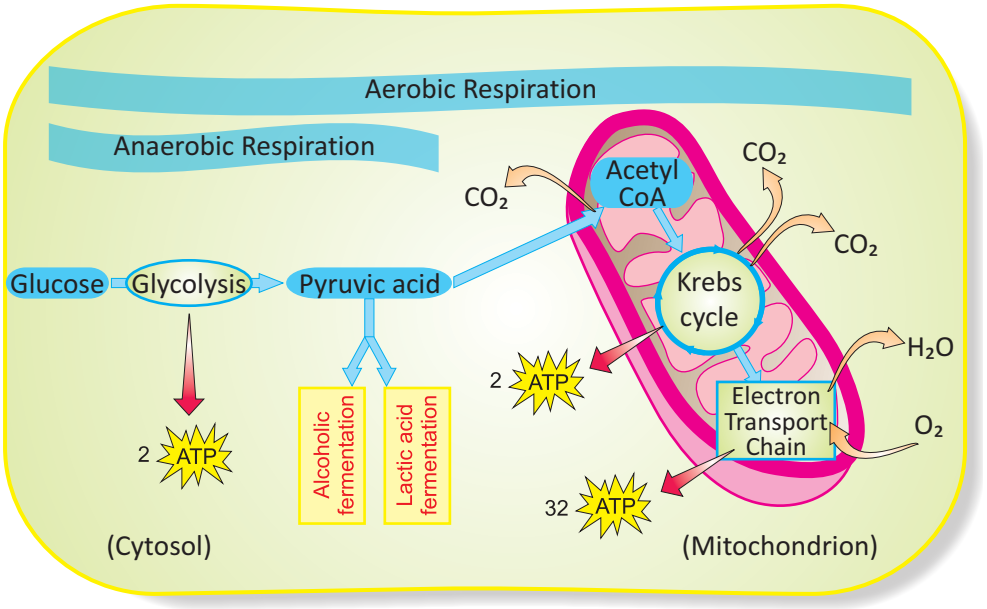


Figure 5.14: Overview of cellular respiration

Stage 1: Glycolysis

Glycolysis is the breakdown of glucose into two molecules of pyruvic acid. Glycolysis takes place in both types of respiration i.e., anaerobic and aerobic. The breakdown of glucose takes place in a series of steps, each catalysed by a specific enzyme (Fig 5.15). All these enzymes are found dissolved in the cytosol. In addition to the enzymes, ATP and coenzyme NAD^+ (nicotinamide adenine dinucleotide) are also essential. Glycolysis involves following reactions.

Preparatory Phase

It involves the expenditure of energy and the breakdown of glucose. It consists of the following steps:

1. A phosphate group is transferred from ATP to glucose. As a result, glucose changes into of glucose 6-phosphate.
2. Glucose 6-phosphate is converted into its isomer called fructose 6-phosphate.
3. Another ATP molecule transfers a second phosphate group to fructose 6-phosphate. So, it becomes fructose 1, 6-biphosphate.
4. Fructose 1, 6-biphosphate is highly reactive and breaks into two molecules of three-carbon intermediates i.e., glyceraldehyde 3-phosphate (G3P) and dihydroxy acetone phosphate (DAP). These are inter-converted and result in two molecules of G3P.

Oxidative Phase

It involves the removal of hydrogen from G3P and packing of released energy in the form of ATP. It consists of the following steps:

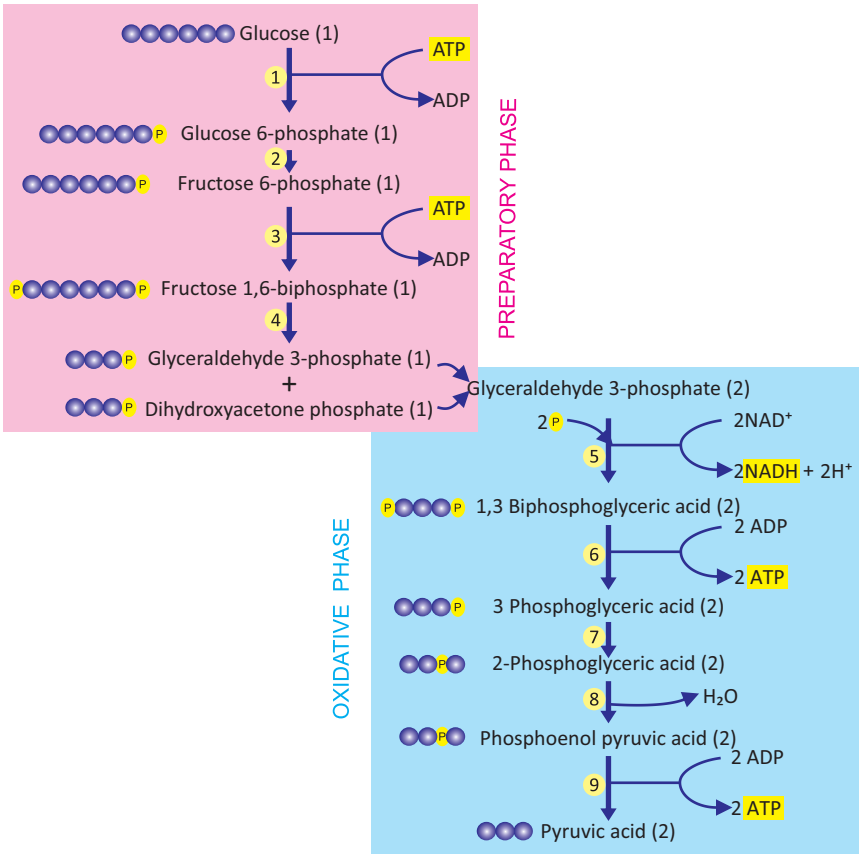


Figure 5.15: Steps in glycolysis

1. Each G3P is oxidized to its acidic form. In this step, two hydrogen atoms (containing two high-energy electrons) are removed from G3P and transferred to NAD^+. At the same time, an inorganic phosphate group is also added to G3P. It results in a molecule of 1, 3-biphosphoglyceric acid (1,3-BPGA).
2. The phosphate group is transferred from 1,3-BPGA to ADP. So, 1,3-BPGA changes into 3-phosphoglyceric acid (3-PGA). A molecule of ATP is also formed in this step.
3. 3-PGA is converted to 2-phosphoglyceric acid (2-PGA).
4. 2-PGA is dehydrated (water removed) into phosphoenol pyruvic acid (PEP).
5. PEP gives up its high energy phosphate to convert a second molecule of ADP to ATP. As a result, PEP is changed into pyruvic acid.

Stage 2: Pyruvic acid Oxidation

Pyruvic acid does not directly participate in Krebs cycle. It has to go through the following changes before entering the Krebs cycle.

Glucose enters cells from the tissue fluid by passive transport using a specific glucose carrier. This carrier can be controlled (gated) by hormones such as insulin.

Pyruvic acid can also be turned back into glucose by reversing glycolysis. This is called gluconeogenesis.

1. A molecule of carbon dioxide is removed from pyruvic acid. So, it changes into acetaldehyde.
2. Acetaldehyde is oxidized (hydrogen is removed) to make acetyl group. A molecule of NAD^+ is reduced to NADH.
3. Acetyl group combines with coenzyme-A (CoA) to form acetyl-CoA (Fig 5.16).

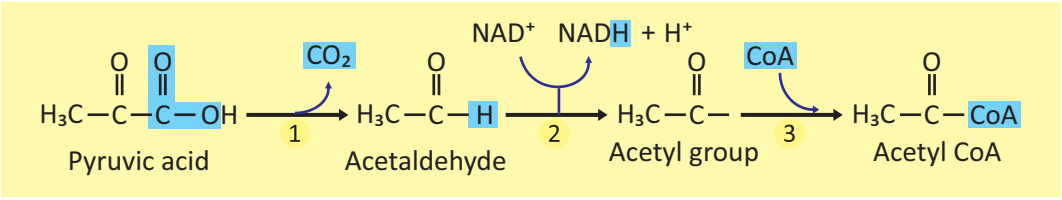


Figure 5.16: Pyruvic acid oxidation

Stage 3: Krebs Cycle

Acetyl-CoA now enters a cyclic series of chemical reactions during which oxidation process is completed (Fig 5.17). Much of this cycle was worked out by a British biochemist, Sir Hans Krebs so it is called the Krebs cycle. It is also called the citric acid cycle, after the six-carbon citric acid molecule formed in its first step. All steps of the citric acid cycle occur in mitochondria. It involves following reactions.

The release of carbon dioxide takes place before oxygen is involved. It is therefore not true to say that respiration turns oxygen into carbon dioxide. It is more correct to say that respiration turns glucose into carbon dioxide, and oxygen into water.

1. Acetyl-CoA splits into CoA and acetyl group. The acetyl group combines with a four-carbon molecule, oxaloacetic acid. As a result, a six-carbon citric acid is formed.
2. Citric acid undergoes an oxidative decarboxylation reaction. It is decarboxylated (releasing a molecule of CO_2) and then oxidized (reducing an NAD^+ to NADH). So, a five-carbon molecule called alpha-ketoglutaric acid is formed.
3. Alpha-ketoglutaric acid undergoes further oxidation and decarboxylation. It results in the formation of a four-carbon molecule i.e., succinic acid. Succinic acid joins with CoA and makes succinyl CoA.

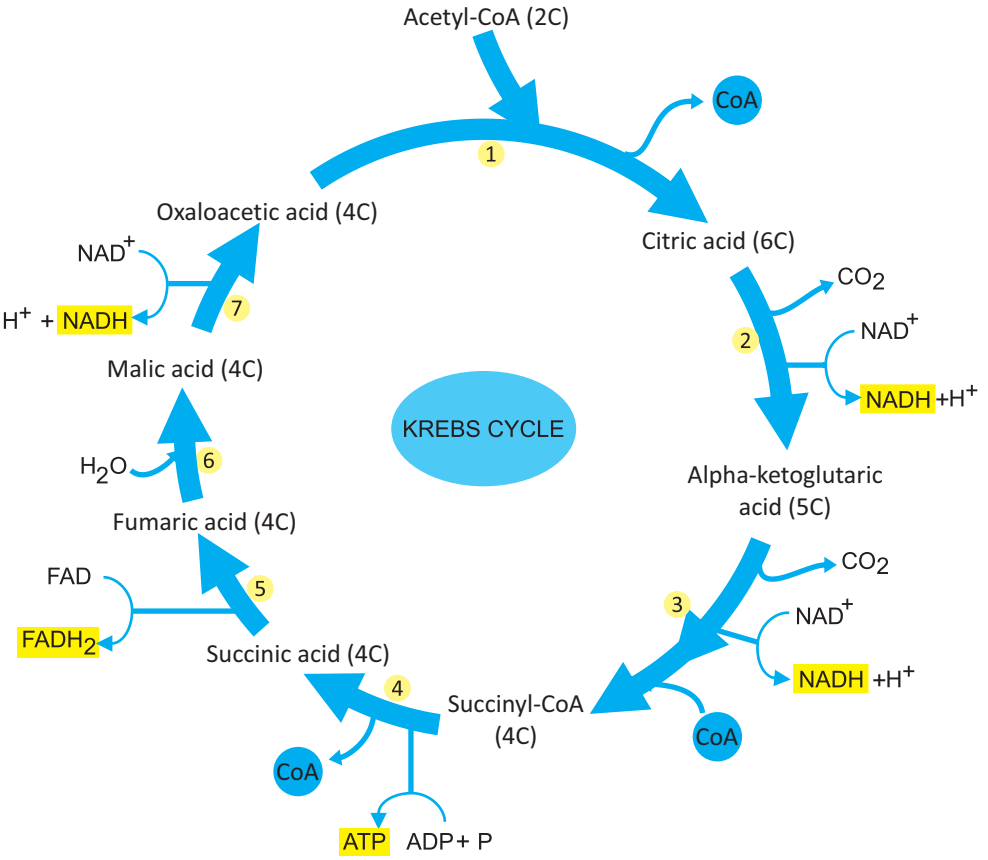


Figure 5.17: Krebs cycle

4. The bond between succinic acid and CoA is a high-energy linkage. It again splits into CoA and succinic acid. The energy released in this reaction, is used in making a molecule of ATP.
5. Succinic acid is oxidized to fumaric acid. When its two hydrogen atoms are removed, the free energy is not enough to reduce NAD+. So, a different

electron acceptor i.e., the coenzyme flavin adenine dinucleotide (FAD) is used and is reduced to FADH2.

6. In order to regenerate oxaloacetic acid, a molecule of water added to fumaric acid and it is changed to malic acid.
7. Malic is oxidized to produce oxaloacetic acid. The hydrogen and electrons released from malic acid convert an NAD+ to NADH. This completes the cycle and oxaloacetic acid is now free to bind another molecule of acetyl CoA to initiate the cycle.

Stage 4: Electron Transport Chain and Chemiosmosis

In electron transport chain the electrons are transferred from the reduced coenzymes i.e., NADH and $FADH_2$ to a series of electron carriers and finally to oxygen. After getting the electrons, the oxygen attaches with hydrogen ions and forms water (Fig. 5.18).

You have seen that in redox reactions electrons and hydrogen ions are removed from substrates and transferred to coenzymes NAD^+ and FAD.

The transfer of electrons to the series of carriers of electron transport chain results in oxidation and reduction reactions i.e., a carrier is oxidized when it loses electrons and next carrier is reduced when it gets electrons. Electrons loose energy during this carrier-to-carrier transport. Chemiosmosis is the mechanism in which membranes are used to couple these redox reactions with the synthesis of ATPs.

Pathway of electrons: The electron transport chain of respiration is built in the inner membrane of the mitochondrion. At the start of electron transport chain, NADH is oxidized and the released electrons are taken up by coenzyme Q. If $FADH_2$ is also to be oxidized, its electrons also move to coenzyme Q. The reduced CoQ transports electrons to cytochrome 'b' which in turn transports them to cytochrome 'c'. Cytochrome 'c' then transports electrons to cytochrome 'a' complex (a complex of two cytochromes). This complex transports electrons to an atom of oxygen that is present at the bottom end of the chain.

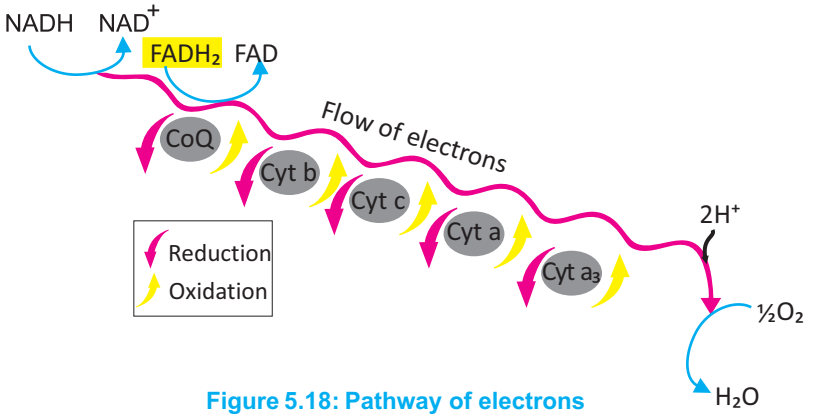


Figure 5.18: Pathway of electrons

Synthesis of ATP: As redox occurs, the energy released from the electrons is used for the active transport of H^+ ions from one side (the matrix of mitochondrion) of the membrane to the other (the inter-membrane space). In this way, many H^+ ions are deposited in the inter-membrane space. The resulting H^+ ion gradient stores potential energy. The H^+ ions diffuse back along their concentration gradient from the inter-membrane space to the matrix (Fig. 5.19).

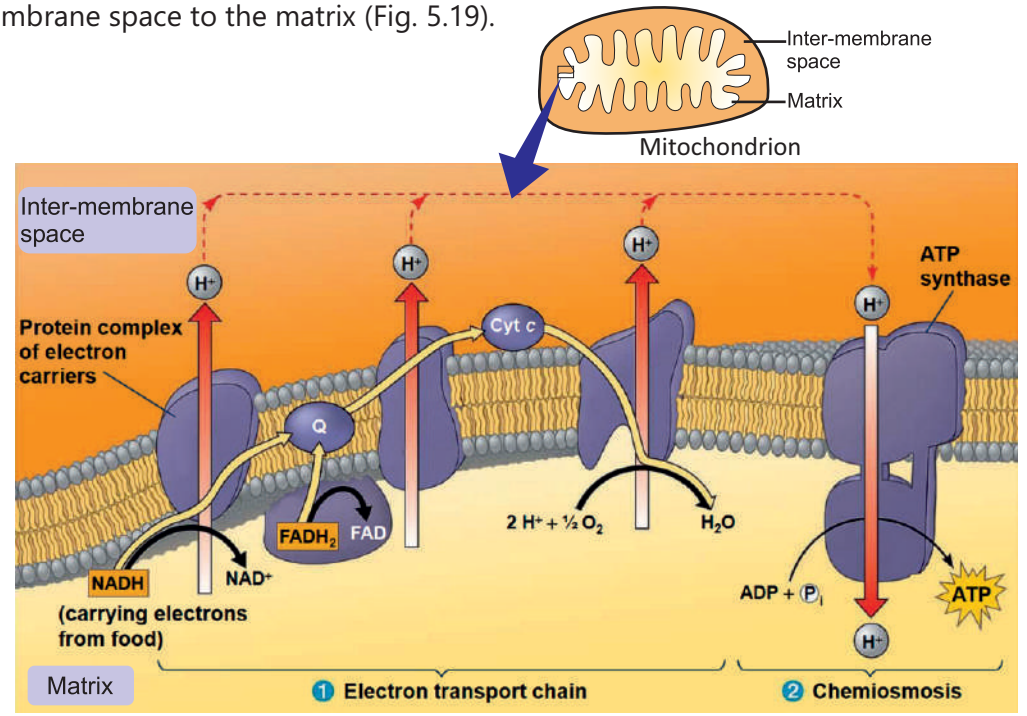


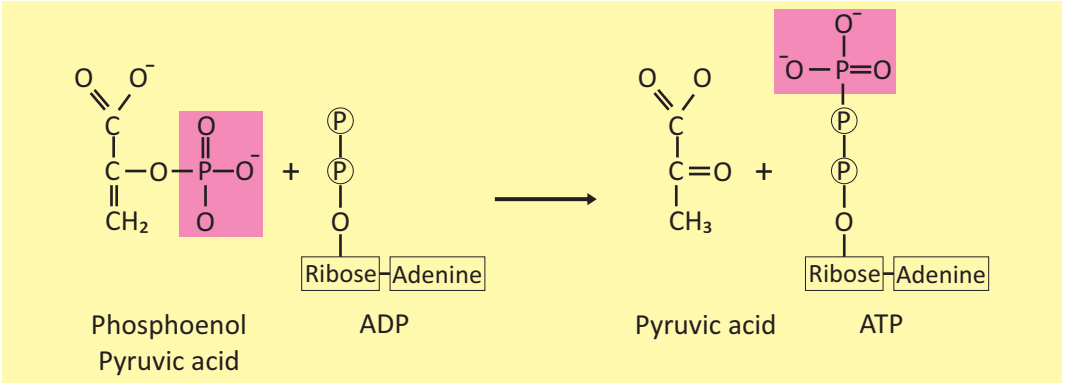
Figure 5.19: Electron transport chain and chemiosmosis in mitochondrion

On their way they pass through a special protein known as ATP synthase. As the H^+ ions move through this protein, their flow drives the synthesis of ATP (Fig 5.19). Oxidation of one molecule of NADH in electron transport chain produces three ATP. While oxidation of one $FADH_2$ produces two ATP. At the end, the two hydrogen ions are taken by the oxygen atom which has also taken two electrons to form water.

Substrate-level Phosphorylation

Cells generate ATP by phosphorylation i.e. adding a phosphate group to ADP. A cell has two ways to do this: chemiosmotic phosphorylation (chemiosmosis) and substrate-level phosphorylation. Substrate-level phosphorylation is much simpler than chemiosmosis. It does not involve any membrane or electron transport chain. In this process, an enzyme transfers a phosphate group from an organic substrate molecule to ADP. The products are a new organic molecule and a molecule of ATP. For example; during the last step of glycolysis, an enzyme transfers phosphate group from

phosphoenol pyruvic (PEP) acid to ADP. As a result, ADP becomes ATP and PEP is changed into pyruvic acid. Substrate–level phosphorylation accounts for only a small percentage of the ATP that a cell generates. This reaction can be shown as:



Overview of the energy extracted from the Oxidation of Glucose

The NADH and $FADH_2$ produced during glycolysis and Krebs cycle pass on their energy-rich electrons to the electron transport chain and ATPs are produced.

- The NADH molecule generated in the Krebs cycle causes the production of three ATP molecules, during chemiosmosis.

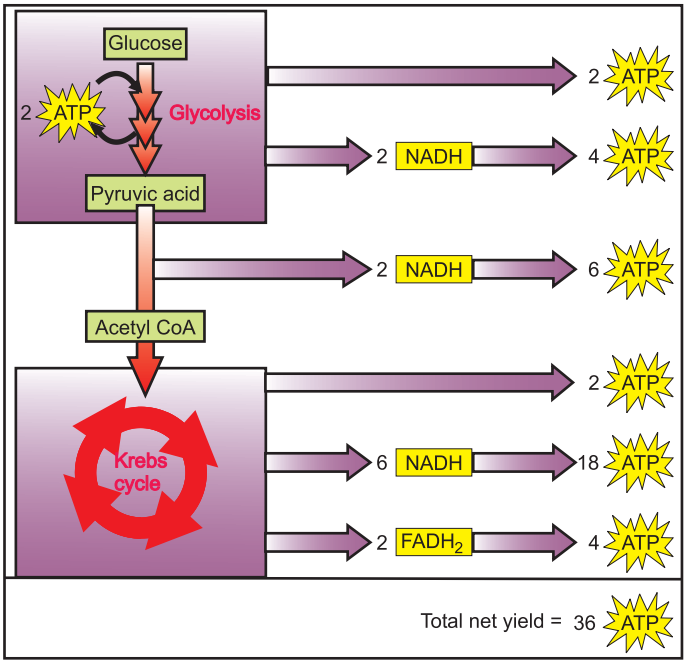


Figure 5.20: An overview of the energy extracted from the aerobic oxidation of glucose

- Glycolysis takes place in cytoplasm and the NADH, produced during glycolysis, have to be transported across the mitochondrial membrane. It costs one ATP molecule

per NADH. Thus, each NADH of glycolysis produces two ATP molecules in the final balance sheet instead of three.

- Each $FADH_2$ molecule leads to the production of two ATP molecules.

In this way, aerobic oxidation of glucose yields a net profit of 36 ATP molecules. While during the glycolysis of anaerobic oxidation only 2 ATP molecules are generated. Thus, aerobic oxidation is 18 times more efficient than anaerobic (Fig 5.20).

Other Organic Molecules as fuel for Cellular Respiration

Free glucose molecules are not common in our diet. Rather, we consume sucrose and other disaccharides, starch, and fats and proteins. Proteins may also be used as fuel but they must be digested to their constituent amino acids. Typically, a cell uses most of the amino acids to make its own proteins. Some amino acids are de-aminated (amino group detached) and then are converted to other organic compounds. These compounds are usually converted to pyruvic acid, acetyl CoA, or the organic acids in the Krebs cycle, and their energy is converted to ATP.

Lipids are excellent cellular fuel because they contain many carbon-hydrogen bonds. They are first hydrolysed into glycerol and fatty acids. Glycerol is converted to glyceraldehyde 3-phosphate, an intermediate in glycolysis, while the fatty acids are changed into acetyl CoA. In this way both the fatty acids and the glycerol enter cellular respiration.

5.3- PHOTORESPIRATION

The respiratory activity that occurs in green cells in the presence of light resulting in release of carbon dioxide is termed as photorespiration. It needs oxygen and produce CO_2 and H_2O like aerobic respiration. However, ATP is not produced during photorespiration.

Recalling:
During carbon fixation, rubisco combines three molecules of CO_2 with three molecules of RuBP and makes six molecules of 3–phosphoglyceric acid (3-PGA).

Mechanism of Photorespiration

We know that RuBP carboxylase (rubisco) catalyses the addition of CO_2 to RuBP to make phosphoglyceric acid (phosphoglycerate), which is further reduced to form glucose. However, when the relative concentration of CO_2 decreases and there is more oxygen in leaf cells, rubisco adds O_2 in RuBP instead of CO_2. It results in the breakdown of RuBP into two molecules i.e., one phosphoglycerate and one phosphoglycolate (a two-carbon molecule).

Phosphoglycolate is converted into glycolate, which moves from chloroplast to peroxisome. Here, it is metabolized to glyoxylate by using O_2. This reaction also produces toxic hydrogen peroxide (H_2O_2). Glyoxylate is then converted to glycine, which is transported to mitochondrion. Here, two molecules of glycine form a molecule

of serine. Serine is then transported to peroxisome. Here, it is converted to glycerate. From peroxisome, glycerate moves to chloroplast, where it is changed to phosphoglycerate which can re-enter Calvin cycle.

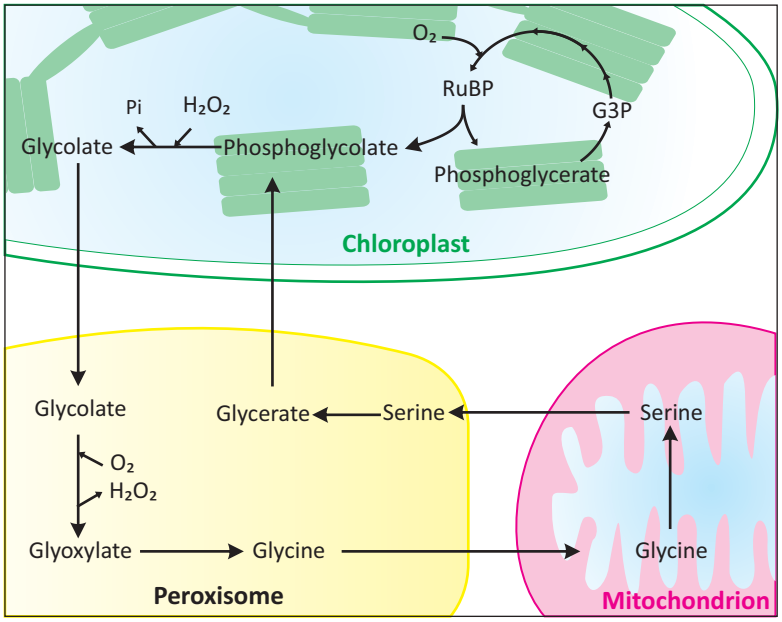


Figure 5.21: Reactions of photorespiration

Disadvantages of Photorespiration

Plants that use Calvin cycle to fix carbon are called C-3 plants. When photorespiration occurs in these plants, they lose between a 25% to 50% of their fixed carbon. It results in reduction in their yields. The rate of photorespiration also depends on temperature. At higher temperatures the oxidative activity of rubisco increases than its carbon fixing activity. In tropical climates, especially those in which the temperature is often above 28 °C, the problem is a severe and it has a major negative impact on agricultural yields.

When photosynthesis first evolved, there was little oxygen in the atmosphere. So, there was little or no photorespiration. After millions of years, free O_2 accumulated in the atmosphere and competition started between CO_2 and O_2 for the same active site of rubisco. It led to the problem that photorespiration now poses.

Adaptations to the problems of Photorespiration

Plants of warmer climates evolved the following two ways to deal with the problem of photorespiration.

C-4 plants carry out C-4 as well as C-3 photosynthesis.

i. C-4 Photosynthesis

Some plants including grasses (corn, sugarcane and sorghum) and about two dozen other plant groups run a special pathway called C-4 photosynthesis in addition

to the normal Calvin cycle. In their leaves, the mesophyll cells have less air spaces. The enzymes of Calvin cycle are more deposited in specialized cells called bundle-sheath cells, which are impermeable to CO_2.

In C-4 photosynthesis, the energy cost for making a glucose molecule is almost double. However, in hot climates, in which photorespiration would otherwise remove more than half of the carbon fixed, it is best compromise available.

During C-4 photosynthesis (Fig 5.22) in mesophyll cells, CO_2, is attached with a 3-carbon molecule called phosphoenol pyruvic acid. It results in the formation of a four-carbon molecule oxaloacetic acid. Due to this first 4-C product, this process is called C-4 photosynthesis and the plants are called C-4 plants. Oxaloacetic acid is then converted to malic acid, by using NADH. Malic acid is transported to an adjacent bundle-sheath cell. Here, malic acid is broken down to pyruvic acid and CO_2. These cells can hold CO_2 in them. So, concentration of CO_2 increases in these cells and they run Calvin cycle instead of photorespiration. Pyruvic acid produced in bundle sheath cells returns to mesophyll cell and is converted again to phosphoenol pyruvic acid b using an ATP.

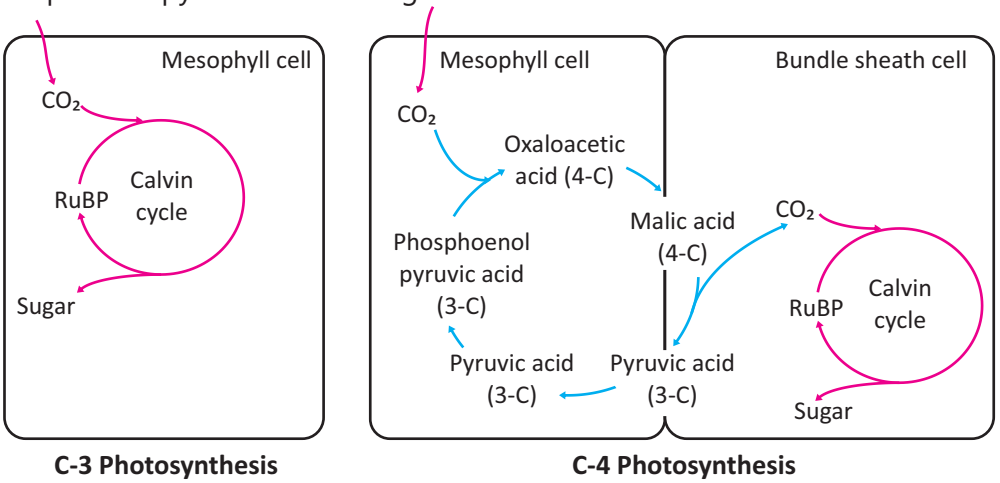
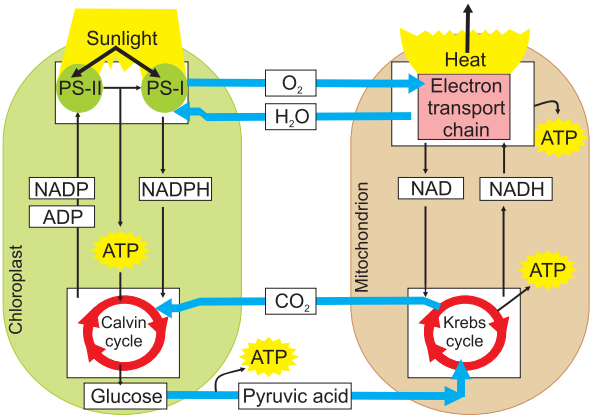


Figure 5.22: C-3 photosynthesis andC-4 photosynthesis

CAM Metabolism

In hot climates, many succulent plants such as *Cacti*, pineapples and some other plant groups perform Crassulaceal acid metabolism or CAM (after the plant family Crassulaceae in which it was first discovered). In these plants, the stomata open during the night and close during the day. Closing stomata during the day prevents water loss and removal of CO_2. So, rate of photorespiration is reduced due to high concentration of carbon dioxide. The carbon dioxide necessary for producing sugar is provided from organic molecules made the night before. Like C-4 plants, these plants use both C-4 and C-3 pathways.

From the given flowchart, build a paragraph that can describe a comparison between photosynthesis and respiration in terms of reactants and products of major steps.



EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1- What main process occurs during the dark reaction of photosynthesis?

(a) Release of oxygen (b) Energy absorption by chlorophyll

(c) Adding of hydrogen to CO_2 (d) Formation of ATP

2- What is TRUE about glycolysis?

(a) It produces no ATP

(b) It takes place only in aerobic respiration

(c) It takes place in the mitochondrion

(d) It reduces 2 molecules of NAD+ for every glucose molecule processed

3- Which of the following are produced by the reactions that occur in the thylakoid and consumed by the reactions that occur in the stroma?

(a) CO2 and H_2O (b) Glucose and O_2

(c) NADP+ and ADP (d) ATP and NADPH

4- When deprived of oxygen, yeast cells obtain energy by fermentation, producing CO2, ATP and;

(a) Acetyl CoA (b) Ethyl alcohol (c) Lactic acid (d) Pyruvic acid

5- Conversion of Glucose 6-phosphate into Fructose 6-phosphate is;

(a) Isomerization (b) Polymerization

(c) Condensation (d) Phosphorylation

6- In which of the following conversions, ATP is produced?

(a) Alpha ketoglutaric acid into succinyl CoA

(b) Succinyl CoA into succinic acid

(c) Succinic acid into fumaric acid

(d) Fumaric acid into malic acid

7- In electron transport chain, FADH:H produces how many ATPs?

(a) One (b) Two (c) Three (d) Four

8- Which of these is CO_2 acceptor during photosynthesis?

(a) Malic acid (b) Ribulose biphosphate

(c) Oxaloacetic acid (d) Phosphoglyceric acid

9- Which of the following takes the electrons lost by Photosystem I on absorption of light energy?

(a) Ferredoxin (b) Cytochrome (c) Cytochrome a-3 (d) Plastocyanin

10- Photosystem-II makes up the electrons lost due to light excitation by taking up the electrons released from,

(a) Ferredoxin (b) $NADPH:H^+$

(c) Plastocyanin (d) Photolysis of water

SECTION 2:SHORT QUESTIONS

1- Differentiate between action spectrum and absorption spectrum.
2- How is photosynthesis a redox reaction?
3- Which molecule contributes Oxygen in glucose? Water or carbon dioxide!
4- State the role of CO_2 in photosynthesis.
5- Define electron transport chain.
6- What do you mean by glycolysis?
7- What is the main structural difference between chlorophyll-a and chlorophyll-b?
8- How can a cell synthesize ATP through substrate-level phosphorylation?
9- Can pyruvic acid enter Krebs cycle as such? If not, what changes are made to it before Krebs cycle?
10- Differentiate between C-3 and C-4 photosynthesis.

SECTION 3: LONG QUESTIONS

1- What are photosynthetic pigments and what role they play in the absorption and conversion of light energy?
2- How are the absorption spectra of chlorophyll 'a' and 'b' different?
3- Describe and illustrate how photosynthetic pigments are organized in thylakoid membrane?
4- Describe how the role of water in photosynthesis can be explained through experiment.
5- What are the events that capture light and convert it into chemical energy during light dependent reactions?
6- Illustrate the cyclic photophosphorylation.
7- Describe light independent reactions of photosynthesis in terms of paragraph and illustrate in terms of Calvin cycle.

8- What happens with glucose in anaerobic respiration and how different organisms modify the end products?
9- How is glucose broken down to pyruvic acid in glycolysis?
10- Describe how Krebs cycle is the completion of the oxidation of glycolytic products.
11- Explain the passage of electron through electron transport chain.
12- Define chemiosmosis. How would you relate it with electron transport chain?
13- Through which ways proteins and fats enter cellular respiration?
14- Define photorespiration and present it in proving that "photosynthesis is not perfect".
15- What are the effects of temperature on the oxidative activity of Rubisco?
16- How is the process of C4 photosynthesis an adaptation to deal with the problem of photorespiration?

INQUISITIVE QUESTIONS

1. Why does cellular respiration release energy more efficiently than fermentation?
2. Why is the conversion of glucose into ATP during cellular respiration considered a more efficient use of energy than burning glucose directly?
3. Why might a disruption in either photosynthesis or respiration processes affect global carbon and oxygen cycles?

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Define structural biology.
- Explain that structure determination of biomolecules are important.
- Describe how X-ray crystallography works.
- Outline the online databases where biomolecule structures are available.
- Describe computational biology.
- Define sequence homology.
- Define structural homology.

Structural biology deals with the study of three dimensional (3D) structures of macromolecules (including proteins and nucleic acids) at atomic levels. It provides the detailed information about the structure of biomolecule, its functions, dynamics and interaction with ligands and other macromolecules.

7.1- APPLICATIONS OF STRUCTURAL BIOLOGY

Structural biology has a wide range of applications especially in the field of medical research. Some of these are discussed here:

1- Determining the Active sites and Domains

Structural biologists can determine the three-dimensional (3D) structures of macromolecules such as proteins and nucleic acids. The 3D structures reveal the exact location, shape, and environment of the active sites and different domains (distinct structural units with independent functions) of macromolecules. For example, structural studies of the enzyme HIV-1 reverse transcriptase have identified its polymerase domain (which synthesizes DNA) and RNase H domain (which breaks down the RNA strand of RNA-DNA hybrids). Knowing the location and structure of these domains has helped in the design of antiviral drugs that specifically target them. Similarly, the structure of serine proteases reveals its well-defined active site, which is responsible for breaking down peptide bonds.

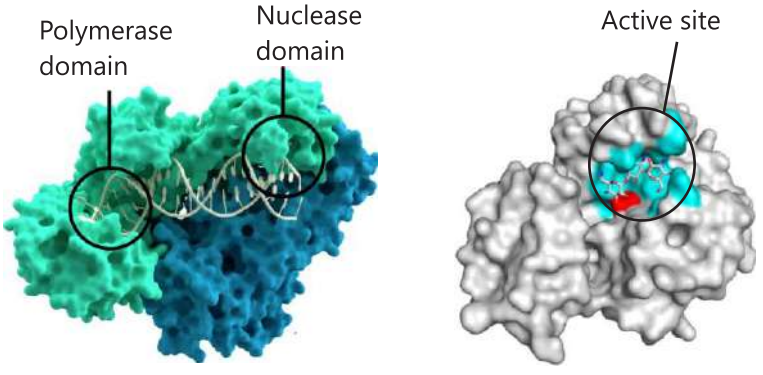


Figure 7.1: (a) 3D structure of HIV-1 reverse transcriptase (b) 3D structure of serine protease

2- Identifying Drug Targets

Structural biology helps scientists find the right place on a disease-causing molecule where a drug can work. These places are usually proteins and are called drug targets. By studying the 3D shape of these proteins, scientists can find specific spots where a drug can attach and stop the protein from working. For example, in COVID-19, scientists used structural biology to study the spike protein of the coronavirus (SARS-CoV-2). This protein helps the virus to enter human cells. By knowing its 3D structure, scientists identified it as a drug target. Thus, they designed vaccines and medicines that block the spike protein, preventing the virus from infecting more cells.

3- Identifying Host–Pathogen Interactions

Structural biology also helps in understanding how pathogens (like viruses or bacteria) interact with the host's body cells. This is called host–pathogen interaction. By studying the 3D structures of both the pathogen and the host cell proteins, scientists can see how the pathogen attaches to and enters the host cell, and which molecules are involved in the process. For example, structural biologists studied the spike protein of coronavirus, which sticks out from the surface of the virus. They also looked at a protein on human cells that acts as receptor of virus spike protein. So, the scientists discovered exactly how the virus enters human cells. This information was vital in developing the drugs that can bind with receptor proteins. Such drug inhibits the interaction of the virus with the receptor and consequently blocks the entry of virus into the host cells.

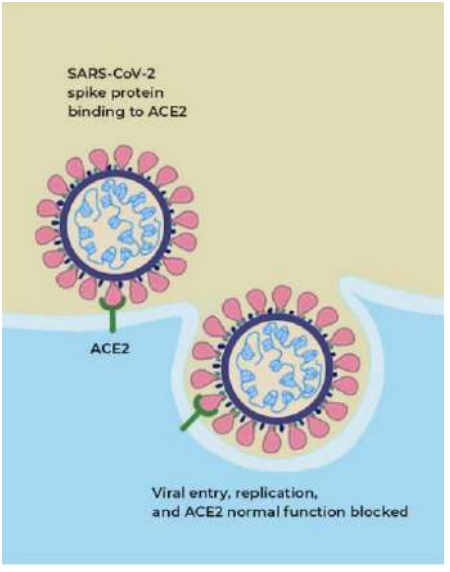


Figure 7.2: Mechanism of corona virus binding with receptorof human cell.

4- Identifying Protein Misfolding

The functionality of proteins depends on the correct folding into three dimensional shapes. Several diseases (including cyctic fibrosis, Parkinsons, Alziemer's) originate due to incorrect folding of proteins. Structural biology provides understanding of intricate folding pathways and how misfolding leads to the diseases.

7.2- X-RAY CRYSTALLOGRAPHY

X-ray crystallography was developed in 1912 by William Henry Bragg and William Lawrence Bragg. They were awarded 1915 Nobel Prize in Physics for their work. Since then it has been used to analyze the diverse substances including minerals, salts, metals, proteins, carbohydrates, nucleic acids and vitamins. In this technique, x-rays beam strikes a crystals and atoms and molecules in the crystals diffract the x-rays beam in specific directions. From the angles and intensities of diffracted beams, a 3D picture of electron density within the crystals are produced. The electron density is exploited to create 3D structure of the molecule.

In order to understand the working of X-ray crystallography, let us take the example of protein structure determination. The method can be divided into following steps:

(i) **Protein crystallization:** Protein crystallization means turning a purified protein into a solid crystal form. Crystals are needed because they arrange protein molecules in a regular, repeating pattern, which is important for getting a clear image during the X-ray process. To make crystals, scientists slowly mix the protein with special solutions that cause the protein molecules to stick together in an orderly way. This process can take hours, days, or even weeks. It often

requires careful control of temperature, pH, and salt concentration. Once a clear and stable protein crystal is formed, it can be used in the next steps.

(ii) Production of a diffraction pattern: Once a good quality crystal is formed, it is mounted on the x-ray machine. The x-rays beam is bombarded at the crystal at various angles. The atoms in the crystal diffract the x-rays beam and a diffraction pattern (which is a series of spots) is created on the detectors.

(iii) Creating density map: The angles and intensities of these spots contain information about the arrangement of atoms in the crystal. Diffraction pattern is used to make a density map.

(iv) Determination of protein structure: Then the data is analyzed mathematically by using computational programs. These calculations transform data into the 3D structure of protein.

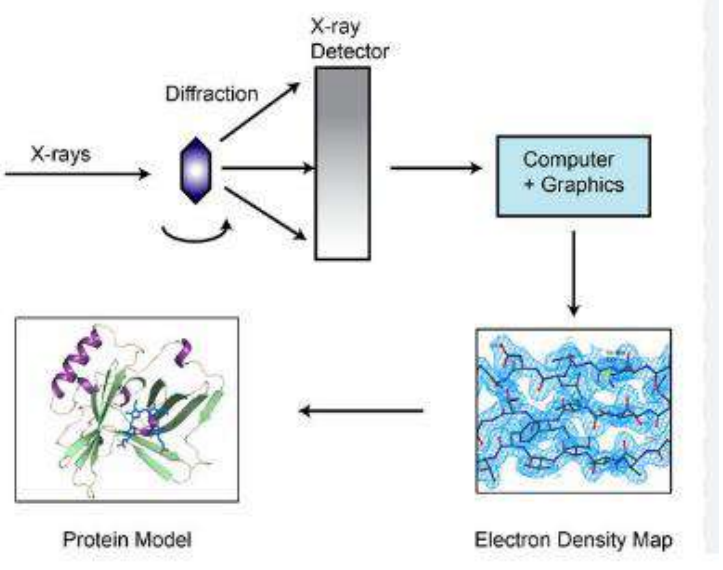


Figure 7.3: Schematic representation of X-ray crystallography

7.3- COMPUTATIONAL BIOLOGY

Computational biology is an interdisciplinary field that uses computational techniques and tools to solve biological problems. It integrates knowledge from biology, computer science, mathematics, and statistics to analyze and interpret biological data. The importance of computational biology lies in its ability to handle large datasets, uncover hidden patterns, and generate predictive models that can lead to new biological insights and applications. Major areas in the computational biology include:

(i) Genomics i.e., the study of genomes, which are the complete set of DNA within a single cell of an organism. Genomics involves sequencing, assembling, and

analyzing the function and structure of genomes. It helps in understanding genetic variations, gene function, and evolutionary relationships.

(ii) **Proteomics** i.e., the large-scale study of proteins, including their structures and functions. Proteins are essential molecules that perform many functions within organisms. Proteomics aims to map the entire set of proteins (the proteome) produced by an organism and understand their interactions and roles in cellular processes.

(iii) **Bioinformatics** i.e., the application of computer technology to manage and analyze biological data. Bioinformatics tools and techniques are used to store, retrieve, and analyze DNA, RNA, and protein sequences.

Applications of Computational Biology

Though computation biology has vast application, some of these are discussed here.

(i) **Drug Discovery:** Computational biology helps in identifying potential drug targets and simulating the effects of drugs on biological systems. It accelerates the drug discovery process by predicting how drugs interact with proteins and other molecules.

(ii) **Genetic Research:** By analyzing DNA sequences, computational biology helps identify genetic variations associated with diseases. It aids in understanding the genetic basis of diseases and can lead to the development of personalized medicine.

(iii) **Evolutionary Biology:** Computational tools are used to compare genetic information across different species, helping to reconstruct evolutionary relationships and understand the process of evolution.

Key Databases: Here are some of the key databases used to analyze nucleic acid and proteins. **GenBank:** https://www.ncbi.nlm.nih.gov/nuccore/

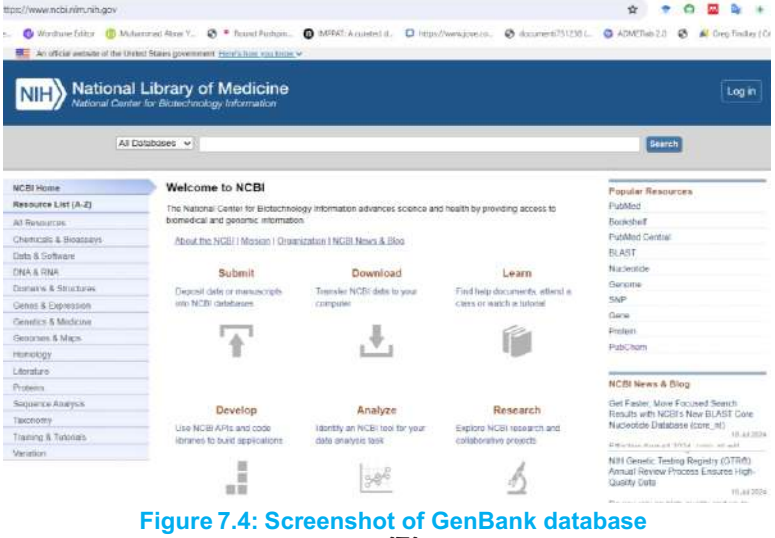


Figure 7.4: Screenshot of GenBank database

It is a comprehensive public database of nucleotide sequences and supporting bibliographic and biological annotations. It provides access to a vast repository of DNA sequences from various organisms, facilitating genetic research and comparative genomics.

Protein Data Bank (PDB)

This database provides 3D structural data of large biological molecules, such as proteins and nucleic acids. It is important for studying the structures of macromolecules, understanding their functions, and designing drugs that target specific protein structures.

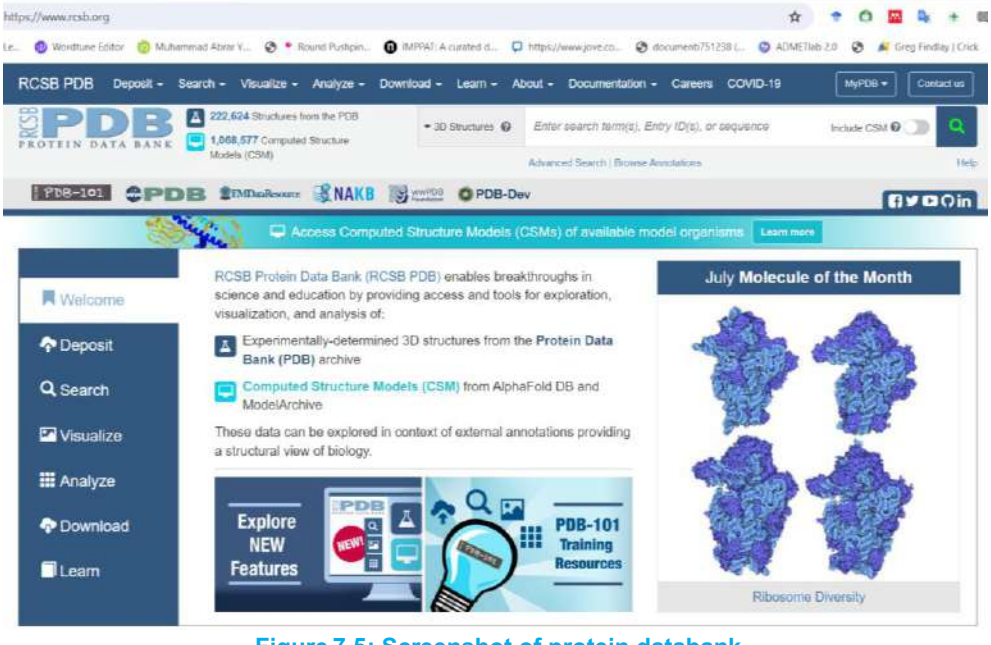


Figure 7.5: Screenshot of protein databank

Ensembl

It is a genome browser providing information on genome sequences, gene models, and comparative genomics for various species. Ensembl helps to access and visualize genomic data, supporting studies in genomics and evolutionary biology.

Key Algorithms

In addition to above mentioned databases, some algorithms being used in data analysis are discussed below.

BLAST (Basic Local Alignment Search Tool) It is used for comparing primary biological sequence information, such as the amino-acid sequences of proteins or the nucleotides of DNA sequences. It helps identify homologous sequences, predict functions of unknown genes, and study evolutionary relationships.

FASTA: It is a sequence alignment tool that compares a query sequence to a database of sequences to find regions of similarity. It is used for searching protein

and nucleotide databases, identifying sequence homology, and analyzing sequence alignments.

7.4- SEQUENCE HOMOLOGY

Sequence homology refers to the similarity between DNA, RNA, or protein sequences due to shared ancestry. Homologous sequences have evolved from a common ancestral sequence and can be categorized into two main types: (i) **Orthologs:** Sequences in different species that originated from a common ancestral gene during speciation. Orthologs often retain the same function across species. (ii) **Paralogs:** Sequences within the same species that originated from gene duplication. Paralogs can evolve new functions even if they originally arise from the same ancestral gene.

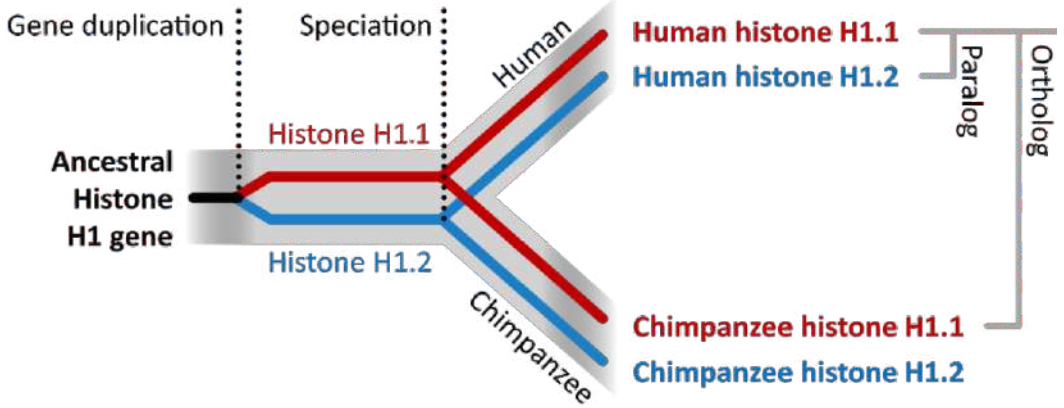


Figure 7.6. Types of Homologous Sequences

Sequence homology provides an insight into the evolutionary relationships between organisms. By comparing homologous sequences, scientists can infer the evolutionary history and divergence of species. Furthermore sequence homology provides a clue about the function of an unknown gene or protein. If an unknown gene/protein is homologous to a gene/protein with a known function, it is likely to have a similar function. Additionally, Identifying homologous genes involved in diseases across different species helps in understanding disease mechanisms and developing treatments. Homologous genes in model organisms can be studied to gain insights into human diseases.

Structural Homology

Structural homology refers to the similarity in the three-dimensional structures of proteins or other macromolecules due to shared ancestry. Proteins with similar structures often perform similar functions, even if their sequences are not highly similar. The three-dimensional structure of a protein provides critical information about its function. Understanding structural homology helps in predicting the function of newly discovered proteins. Furthermore, structural homology is crucial in

drug design, as drugs are often designed to interact with specific protein structures. Understanding the structural relationships between proteins can help in designing more effective drugs. Also studying the structural homology of proteins helps in understanding the evolutionary processes that shape protein functions and interactions.

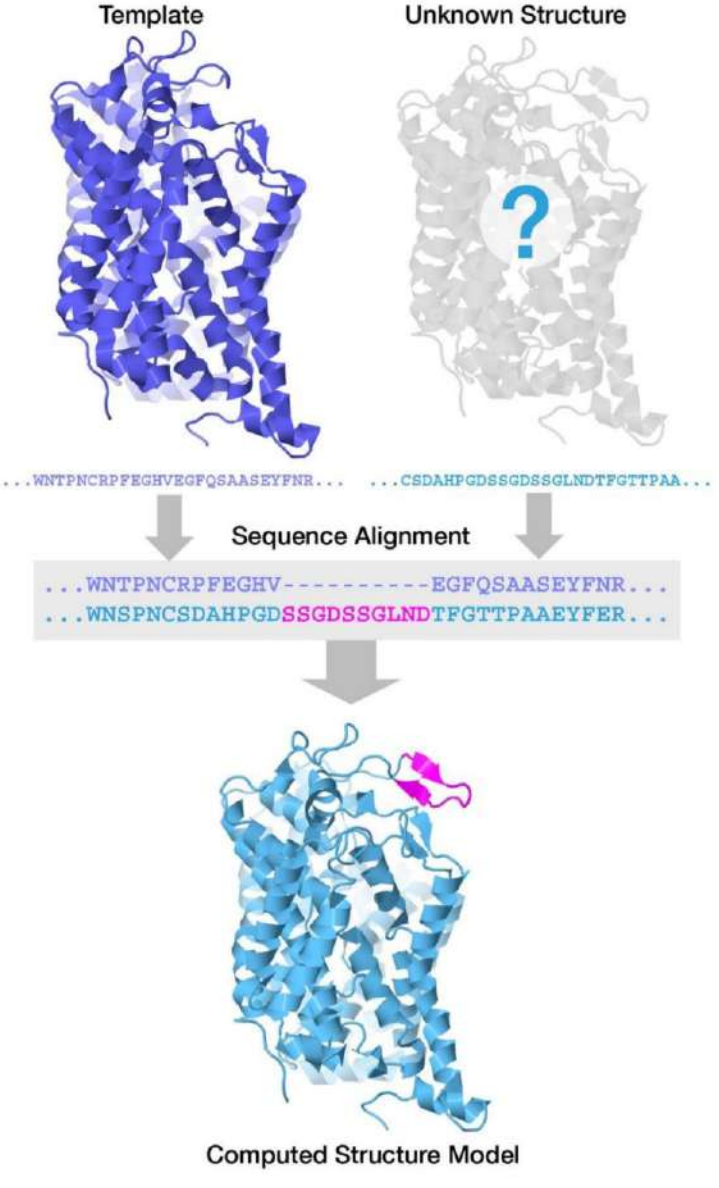


Figure 7.7: Structural homology of protein

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Generally, the function of a protein depends on its:
   (a) One-dimensional structure (b) Two-dimensional structure
   (c) Three-dimensional structure (d) Four-dimensional structure
2. The protein domains are:
   (a) Functional and structural units within protein
   (b) Secondary structural elements
   (c) Linear sequences of amino acids
   (d) Specific regions for post-translational modification
3. The first step in x-ray crystallography experiment is:
   (a) Compute an electron density (b) Build a model of your molecule
   (c) Measure a diffraction pattern (d) Grow a crystal
4. What is primary role of computational biology?
   (a) Using computer algorithms to analyze data
   (b) Identifying genetic mutations
   (c) Studying protein functions
   (d) Analyzing the expression patterns
5. Which computational approach is used to predict protein structure based on amino acid sequence?
   (a) Multiple sequence alignment (b) Homology modelling
   (c) Clustering analysis (d) BLAST searches

SECTION 2:SHORT QUESTIONS

1. Define domains of the protein.
2. How corona virus enters the host cells?
3. Define genomics.
4. Differentiate between genomics and proteomics.
5. What is GenBank. Describe it briefly.
6. Write a short note on protein data bank.

SECTION 3: LONG QUESTIONS

1. Describe the applications of structural biology.
2. Write a note on principle and working of x-ray crystallography.
3. Briefly describe key databases of computational biology.

INQUISITIVE QUESTIONS

1. Consider there is a pandemic of a new unknown disease, and the causative agent is a virus. You also know that virus belongs to X family. How structural biology can be helpful in preventing the disease?
2. Suppose you find an unknown protein and determine amino acid sequence by Edman degradation/mass spectrometry. How you can exploit the computational biology to predict the structure and function of the protein.
3. Homology models of macromolecules differ from experimentally determined structures of the macromolecules. Please comment.
4. Draw a flow chart to describe the steps involved in drug development till its prescription.

Chapter 8

PLANT PHYSIOLOGY

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- List the macro and micronutrients of plants highlighting the role of each nutrient.
- State the examples of carnivorous plants.
- Explain the role of stomata and palisade tissue in the exchange of gases in plants.
- Relate transpiration with gas exchange in plants.
- Describe the structure of xylem vessel elements, sieve tube elements, companion cells, tracheids and relate their structures with functions.
- Describe the movement of water between plant cells, and between the cells and their environment in terms of water potential.
- Describe the movement of water through roots in terms of symplast, apoplast and vacuolar pathways.
- Explain the movement of water in xylem through TACT mechanism.
- Describe the mechanisms involved in the opening and closing of stomata.
- Explain the movement of sugars within plants.
- State movement of water into or out of the cell in isotonic, hypotonic, and hypertonic conditions.
- Explain the osmotic adjustments in hydrophytic (marine and freshwater), xerophytic and mesophytic plants and plants in saline soil.
- List the adaptations in plants to cope with low and high temperatures.
- Explain the turgor pressure and its significance in providing support to herbaceous plants.
- Describe the structure of supporting tissues in plants.
- Explain primary and secondary growth in plants.
- Justify the formation of annual rings.
- Explain influence of apical meristem on the growth of lateral shoots.
- Outline the role of important plant growth regulators.
- Explain the types of movement in plants in response to light, force of gravity, touch and chemicals.
- Define photoperiodism.
- Classify plants with examples on the basis of photoperiodism.
- Describe the mechanism of photoperiodism with reference to the mode of action of phytochrome.
- Explain the role of low temperature treatment on flower production especially to biennials and perennials.

8.1- NUTRITION IN PLANTS

Organisms require nutrition for their survival and maintenance. A **nutrient** is a substance that provides the body with essential ingredients required for metabolism. Specific nutrients, such as carbohydrates, lipids, and proteins, serve as sources of energy. Other nutrients, including water, electrolytes, minerals, and vitamins, are necessary for the metabolic process. **Nutrition** refers to the collective processes involved in the intake and utilization of nutrients for growth, repair, and maintenance of activities in an organism.

Macronutrients and Micronutrients

All autotrophic organisms need carbon dioxide and water, which supply carbon, oxygen and hydrogen. These are the predominant elements which serve as nutrients and are required by plants for the synthesis of organic molecules. There are many other nutrients that plants get from environment. The nutrients of plants can be divided into two groups.

Macronutrients are needed in relatively larger amounts. There are nine macronutrients i.e., carbon, hydrogen, oxygen, nitrogen, potassium, calcium, phosphorus, magnesium and sulphur.

- **Carbon, oxygen and hydrogen** are required for making organic compounds.
- **Nitrogen** is necessary for plant growth as it plays an essential role in energy metabolism and the production of proteins. A deficiency of nitrogen results in leaf loss and stunted growth.
- **Phosphorus** is a part of ATP. It also plays a role in promoting root growth and favours flowering in the aerial zone. A deficiency of phosphorus leads to delayed flowering, as well as the browning and wrinkling of the leaves.
- **Potassium** is involved in water regulation and the transportation of the plant's reserve substances. It enhances the ability of plants to carry out photosynthesis, reinforces cellular tissue, and stimulates the uptake of nitrates. Dark patches are formed on the leaves when there is shortage of potassium.
- **Calcium** provides stability to the cell wall and promotes the development of the cell wall. It also plays a role in cellular proliferation and maturation, and aiding in the development of seeds. Insufficient calcium leads to the development of yellow and brown patches on the leaves.
- **Magnesium** constitutes the core of the chlorophyll molecule and is therefore essential for photosynthesis. It promotes the absorption and transportation of phosphorus and also contributes to the storage of sugars within the plant. Magnesium deficiencies result in weak stalks, loss of greenness in the oldest leaves, and the appearance of yellow and brown spots.
- **Sulfur** is a fundamental element in the metabolism of nitrogen. If there is a shortage of sulfur, the plant becomes lighter in colour.

Micronutrients are needed in very smaller amounts. There are seven micronutrients i.e., iron, manganese, zinc, molybdenum, copper, chlorine, and boron.

Fertilizers are added to the soil to provide macro and micronutrients to the crops.

- **Iron** is essential for the synthesis of chlorophyll. It acts as a cofactor for several enzymes which are involved in energy

Manganese is important for the activity of antioxidant enzymes, such as superoxide dismutase (SOD), which help mitigate

transfer and nitrogen metabolism. Its deficiency results in interveinal chlorosis.

oxidative stress in plants under adverse environmental conditions.

- **Manganese** is involved in the processes of photosynthesis, nitrogen metabolism, carbohydrate metabolism and activation of enzymes. Its deficiency results in the premature falling of the leaf and delayed maturity.
- **Zinc** facilitates chlorophyll synthesis, root development and uptake of nutrients. Deficiency of zinc can lead to stunted growth.
- **Molybdenum** is critical for nitrogen fixation, nitrogen reduction, sulfur metabolism, phosphorus metabolism and iron utilization. Its deficiency can result in chlorosis of older leaves and stunted growth.
- **Copper** is necessary for lignin synthesis providing strength and rigidity to cell wall. It is involved in nitrogen metabolism, reproductive development and also acts as a cofactor for enzymes. Its deficiency can result in chlorosis, twisted leaves and stunted growth.
- **Chlorine** is involved in stomatal regulation, osmotic adjustment and transport of nutrients. Its deficiency can affect the health and growth of plants.

Nutrition in Insectivorous Plants

Some plants supplement organic molecules into their food in addition to inorganic nutrients. These organic chemicals are acquired through the process of capturing and breaking down insects and tiny animals. All insectivorous plants are true autotrophs. However, their development accelerates when they capture prey. Apparently, nitrogenous compounds of animal body are of benefit to these plants. The captured insects are broken down by enzymes that are released by the leaves. Pitcher plant, Venus fly trap and sundew are some of the known insectivorous plants.

Pitcher plant has leaves modified into a sac or a pitcher, partly filled with water **(Fig.8.1).** The leaf's terminal portion is altered to create a hood, which partially covers the exposed opening of the pitcher. It has numerous stiff hairs that prevent little insects from crawling out once they fall inside it.

Figure 8.1: Pitcher plant, insects are entrapped within the leaf.

Venus-fly trap has a "trap" consisting of two lobes that are hinged at the end of each leaf. The inner surfaces of the lobes contain **trichomes**, which are hair-like projections that trigger the lobes to close rapidly upon contact with prey **(Fig.8.2)**. The hinged traps are lined with fine bristles that interlock upon closure, preventing

the prey from escaping. The trapped insect is then digested by the enzymes secreted from the glands on the leaf surface and the products are then absorbed.


Figure 8.2: Venus-fly trap, prey is trapped between the lobes of a leaf.

Sundew catches its prey with shiny drops of "dew," where the plant's common name comes from **(Fig. 8.3)**. The leaves are covered with tiny hairs that look like tentacles. Each leaf has gland and has a single drop of dew at the tip. The insects, attracted by plant's odour are trapped by tentacles. The trapped insects are digested by enzymes and products are absorbed.


Figure.8.3: Sundew, insects are entangled by the tentacles.

8.2- Gas Exchange In Plants

Stomata (singular = stoma) are the tiny openings or pores present within the plant tissues which are necessary for gaseous exchange. These are typically found in leaves but can even be present in some stems. The stomata are surrounded by specialized cells or the guard cells that facilitate the opening and closing of the stomatal pores. Guard cells are bean-shaped and contain chloroplasts. Guard cells can open and close depending on environmental conditions. The opening and closing of stomata control the **transpiration rate** in plants.

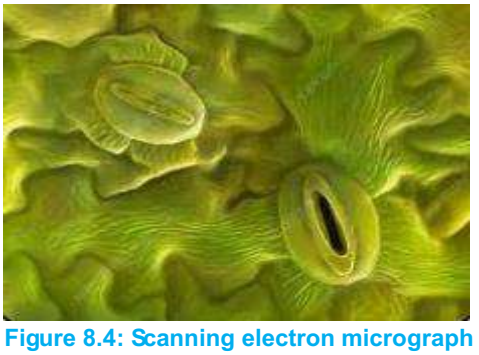


Figure 8.4: Scanning electron micrograph (SEM) of open and closed stomata on a lavender leaf

During daylight, stomata open to allow CO_2 to enter the plant for photosynthesis. The opening of stomata is primarily regulated by guard cells. At night, when photosynthesis ceases due to lack of light, stomata typically close to conserve water. However, plants still respire, taking in O_2 and releasing CO_2. The closure of stomata at night helps minimize water loss through transpiration.

Opening and Closing of Stomata

The guard cells function as multisensory hydraulic valves **(Fig.7.4).** The two hypotheses which may explain the opening and closing of stomata are starch sugar hypothesis and influx of k^+ ion.

Starch sugar hypothesis

In 1856, German botanist H. Van Mohl proposed that guard cells in leaf epidermis are solely responsible for photosynthesis, producing sugars during the day. As sugar concentration increases in guard cells, the water potential drops. Water moves into guard cells causing them to become turgid and open the stomata. At night, photosynthesis ceases, and sugars are converted to insoluble starch or used for respiration, leading to a decline in free sugars. Consequently, water moves out of guard cells and they lose turgor pressure. So, they become flaccid and close the stomata. However, this mechanism does not fully explain the rapid turgor changes in guard cells during stomatal movements.

Influx of K^+ ion

The opening of stomata in plants is facilitated by the active transport of potassium ions (K^+) into guard cells, which reduces their osmotic potential. This influx of K^+ leads to water entering the guard cells through osmosis, causing them to become turgid and open the stomata. Blue light enhances this process by acidifying the surrounding environment, promoting K^+ uptake and subsequent water absorption. At night, K^+ passively diffuses out of the guard cells, resulting in water loss and causing the guard cells to become flaccid, thereby closing the stomata.

Palisade tissue is primarily located just beneath the upper epidermis of the leaf. It consists of elongated, tightly packed cells that are rich in. The arrangement of these cells is organized to maximize light absorption and allowing plants to efficiently convert light energy into chemical energy.

Hormones are involved in stomatal movement in plants. At high temperature when leaf cells start wilting, a hormone called abscisic acid, is released by mesophyll cells. This hormone stops the active transport of K^+ into guard cells, overriding the effect of light and CO2 concentration. So, K^+ pumping stops and stomata close.

Carbon dioxide from the atmosphere diffuses into the leaf through the stomata. Once inside, the gas travels through air spaces within the spongy mesophyll and then into the palisade mesophyll cells, where it is used in photosynthesis. Oxygen produced during photosynthesis diffuses out of

the palisade cells back through the spongy mesophyll and exits the leaf through the stomata.

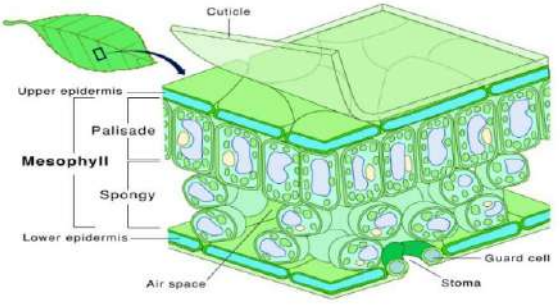


Figure 8.5: Structure of a leaf showing cuticle, epidermis, palisade mesophyll, spongy mesophyll, guard cells and stoma.

8.3- SUPPORT IN PLANTS

Supporting tissues play an important role in maintaining the structural integrity, support and flexibility of plants. These tissues consist of parenchyma, collenchyma, sclerenchyma, xylem and phloem.

1. Parenchyma

The parenchyma tissue provides support to herbaceous plants and parts of larger plants. The parenchyma cells of the epidermis, cortex, and pith absorb water. This water creates an internal hydrostatic pressure known as **turgor pressure** that maintains the rigidity of cells.

Turgor pressure arises from the elevated osmotic pressure within the cell vacuole. The membrane that surrounds the vacuole is called the **tonoplast**. It has many active transport mechanisms that move ions into the vacuole, even when the concentration within is higher than that of the surrounding fluid. Due to the elevated ionic concentration, water is drawn into the vacuole, resulting in turgidity and providing mechanical support to the plant's soft tissues.

2. Collenchyma

Collenchyma cells are specialized cells that are grouped in the form of strands or cylinders. They are found beneath the epidermis of young stems, leaf stalks and along veins in leaves. Collenchyma cells lack secondary walls. Their primary walls are thickened at the corners, due to extra deposition of cellulose. They elongate when stem or leaf grows lengthwise. They provide support to the young parts of plant in which secondary growth has not taken place.

3. Sclerenchyma

This tissue also provides structural support to the plants. Typically, the cells of sclerenchyma tissue possess thick secondary cell walls. These walls are saturated with lignin, an organic compound that confers strength and rigidity to the walls. The

majority of sclerenchyma cells are non-living. The main function of this tissue is to provide support to the various components of the plant. There are three types of sclerenchyma cells which are fibres, sclereids and vessels.

Fibers (Tracheids) are elongated and cylindrical in shape. They can be found either as compact bundles inside the xylem or as bundle caps. **Sclereids** are smaller in size as compared to fibers and are present in the seed coats and shells of nuts. Their function is to offer protection. **Vessels (Tracheae)** are long tubular structures that are joined end to end to form a long water conducting pipe in xylem.

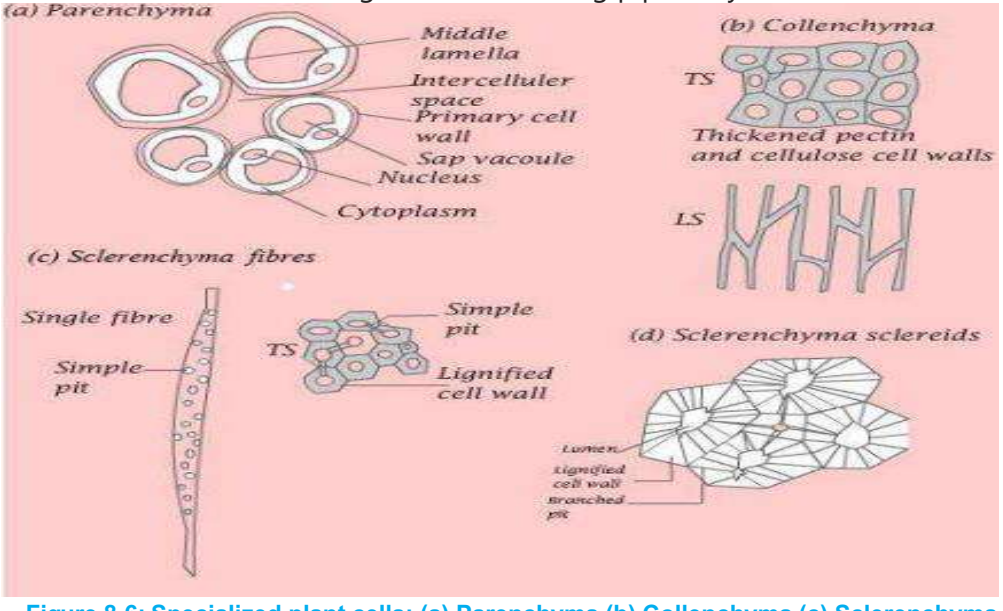


Figure.8.6: Specialized plant cells; (a) Parenchyma (b) Collenchyma (c) Sclerenchyma

8.4- WATER POTENTIAL

Water molecules possess kinetic energy which means that in liquid or gaseous form they move about rapidly and randomly from one place to another. So, greater the concentration of the water molecules in a system the greater is the total kinetic energy of water molecules. This is called water potential (symbolized by Greek letter psi = Ψ_w). In plant cells, two factors determine water potential i.e., Solute potential (Ψ_s) and Pressure potential (ΨP).

Pure water has maximum water potential which by definition is zero. Water moves from a region of higher Ψ_w to lower Ψ_w. All solutions have lower Ψ_w than pure water and so have negative value of Ψ_w (at atmospheric pressure and at a defined temperature). So, the **osmosis** can be defined as the movement of water molecules from a region of higher water potential to a region of lower water potential through a partially permeable membrane.

Solute Potential (Ψs)

The solute potential or osmotic potential is a measure of the change in water potential (Ψ_w) of a system due to the presence of solute molecules. Ψ_s is always a negative value, so if more solute molecules are present, lower (more negative) is the Ψ_s.

Pressure Potential (ΨP)

It is the part of water potential which is due to the pressure exerted by water. If pressure greater than atmospheric pressure is applied to pure water or a solution, its water potential increases. When water enters plant cells by osmosis, pressure may be built up inside the cell making the cell turgid and increasing the pressure potential.

Thus, the total water potential (Ψ_W) is sum of solute potential (Ψ_s) and pressure potential (Ψ_P):

$$\Psi_W = \Psi_S + \Psi_P$$

If we use the term water potential, the tendency for water to move between any two systems can be measured; not just from cell to cell in a plant but also from soil to root, from leaf to air and from soil to air. The steeper the potential gradient the faster is the flow of water along it.

8.5- TRANSPORT OF WATER IN PLANTS

Uptake of Water by Roots

Roots of plants provide large surface area for absorption by their extensive branching systems. You know that roots have tiny root hairs, which are actually extensions of epidermal cells of roots. Most of the uptake of water and minerals in roots takes place through root hairs.

From soil, water and minerals enter the root epidermal cells by active and passive transport. From root epidermis, they move to cortex, and then into the xylem tissue in the centre of root. Inside roots, water and minerals move in three different pathways to reach the xylem.

1. The Apoplast Pathway

It is a continuous pathway that involves a system of adjacent cell walls in the plant roots. The apoplast pathway becomes discontinuous in the endodermis in the roots due to the presence of Casparian segments.

2. The Symplast Pathway

In symplast pathway, water and minerals move through interconnected protoplasts of root cells. The protoplasts of neighbouring cells are interconnected through **plasmodesmata**, which are cytoplasmic strands that extend through pores in adjacent cell walls. The symplast pathway is less important, except for minerals in the region of endodermis.

3. The Vacuolar Pathway

In vacuolar pathway, water and minerals move through cell membranes, cytoplasm and tonoplast (membranes of vacuoles) and vacuoles. They move from vacuole to vacuole and bypass the symplast and apoplast pathways. Movement in vacuolar pathway is negligible.

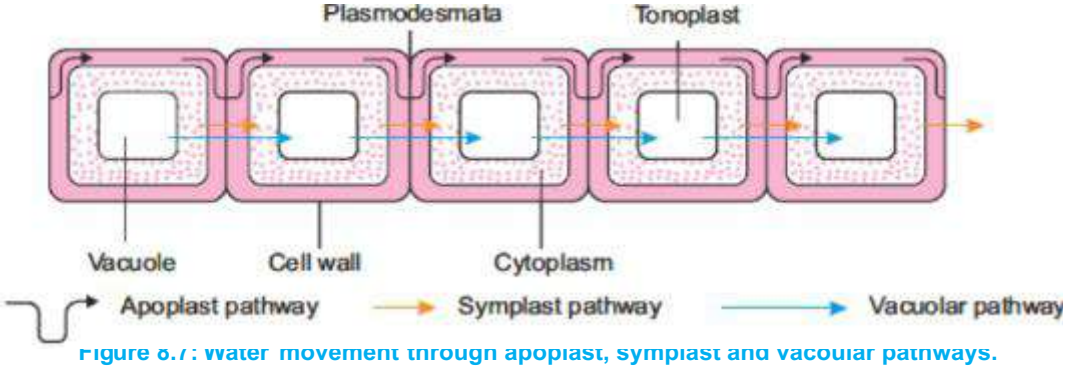


Figure 8.7: Water movement through apoplast, symplast and vacuolar pathways.

Structure of Xylem Tissue

Xylem is the vascular tissue in plants that carries water and dissolved minerals from the roots to the stem and leaves. It is also a key structural component which provides mechanical support to the plant body.

Xylem comprises of tracheids, vessels, xylem fibres and xylem parenchyma **(Fig. 8.7).**

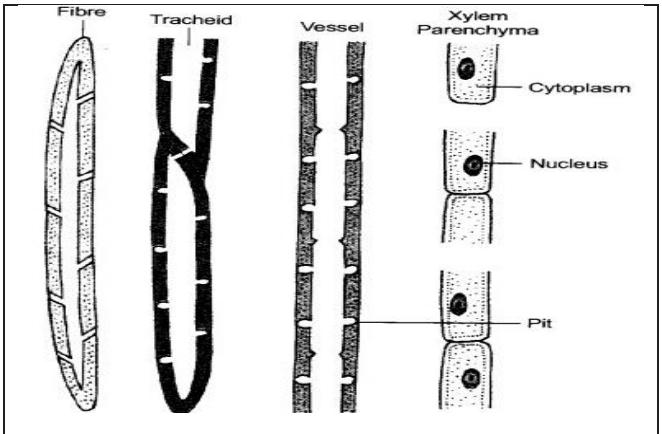


Figure 8.8: Different components of xylem tissue

Tracheids are elongate and thin cells that have thick walls made of lignin. The ends of the cells are tapered and they are linked to each other by bordered pits, which enable the lateral movement of water between cells. **Vessels** are shorter and broader compared to tracheids. They are arranged in a linear fashion, forming continuous channels. Perforation plates are present at the outer edges of these structures, enabling efficient movement of water. **Xylem fibres** are elongated cells with thickened lignified walls. At maturity, they are dead and enhance the structural integrity of the xylem. They offer additional structural support to the plant. **Xylem parenchyma** are living cells with thin walls that have the ability to retain and hold nutrients and water. Xylem parenchyma cells participate in the lateral translocation of water and nutrients and can also contribute to the healing and regeneration of xylem tissue.

The Movement of Water through Xylem

The movement of water within plants, from roots to leaves, occurs primarily through specialized vascular tissue known as xylem. The TACT (Transpiration, Adhesion, Cohesion, Tension) mechanism is a widely accepted model explaining how water moves against gravity through the xylem to reach all parts of the plant. This mechanism depends on both physical and chemical properties of water and the plant's interaction with its environment.

Transpiration is the process by which water evaporates from the surface of plant leaves, specifically through stomata. As water vapour exits the leaf, a **negative pressure** is generated within the leaf tissue. This negative pressure creates a pulling force, drawing water upward from the roots through the stem and toward the leaves. Transpiration, therefore, act as the primary driving force behind water transport in the xylem.

Adhesion is the attraction between water molecules and the walls of the xylem vessels. Due to this attraction, water molecules stick to the walls of xylem vessels as they move upward. This property prevents any break in the water column within xylem. Adhesion thus play a crucial role in maintaining the continuity of the water column, especially in tall plants where gravity exerts a significant downward force on the water column.

Cohesion refers to the attractive force between water molecules themselves, caused by hydrogen bonding. Water molecules within the xylem stick together, forming an unbroken column from the roots to the leaves. This cohesive property of water ensures that the **"pull"** initiated by transpiration at the leaf level extends down through the entire water column.

Tension is the negative pressure created by the pulling force of the transpiration at the leaf level. As water evaporates from the leaf surface, it creates a low-pressure area that extends through the xylem. This tension pulls the cohesive water column upwards. Tension is therefore vital for the continuous ascent of water within the xylem.

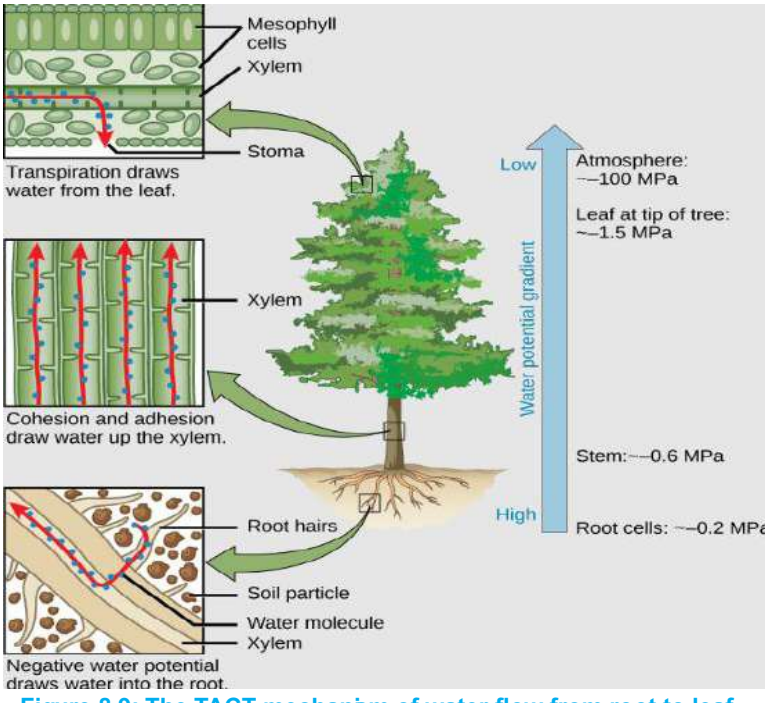


Figure 8.9: The TACT mechanism of water flow from root to leaf.

8.6- TRANSLOCATION OF FOOD IN PLANTS

Structure of Phloem

Phloem is a vascular tissue in plants responsible for the transport of organic nutrients, particularly the products of photosynthesis, from the leaves to other parts of the plant where they are needed or stored. The phloem is generally found on the outer side of both primary and secondary vascular tissue in plants with secondary growth. The phloem constitutes the inner bark.

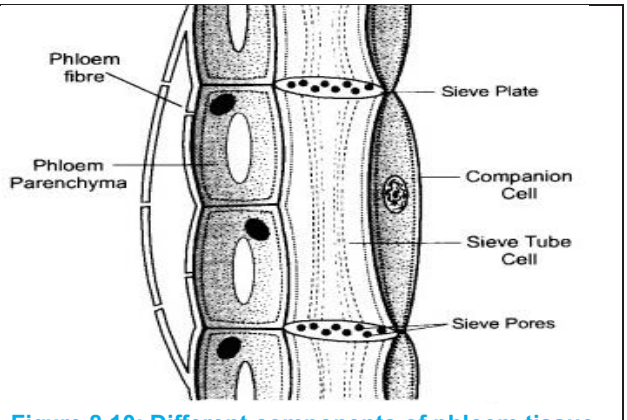


Figure 8.10: Different components of phloem tissue.

Phloem comprises of sieve elements, companion cells, phloem fibres and phloem parenchyma **(Fig. 8.10).**

The cells of phloem that transport sugars and other organic material throughout the plant are called **sieve tube elements or cells**. Sieve tube elements have **'sieve areas'**, which are the portions of the cell wall where pores interconnect

the sieve tube elements. Some of the sieve areas are generally formed in end walls of sieve tube elements where the individual cells are joined together to form a longitudinal series called a **sieve tubes**. Each sieve tube element is associated with one or more companion cells. Sieve tube elements and companion cells are in communication with each other by plasmodesmata. Companion cells supply ATP and proteins to sieve tube elements. **Phloem parenchyma** stores substances, such as sugars, resins, latex, and mucilage, which are important for plant defence and moisture retention.

Mechanism of Translocation

The transport of sugars in plants takes place through phloem tissue. Passive theories of phloem transport include:

Diffusion is far too slow, to account for the velocities of sugar movement in phloem, which on the average is 1 meter per hour, while the rate of diffusion is 1 meter per eight years.

Pressure flow theory: The pressure-flow theory, also known as the mass-flow hypothesis, is the most widely accepted explanation for the transport of sugars in plants through the phloem. This process of translocation moves sugar from the **source** (where they are synthesized) to the **sink** (where they are consumed or stored). This theory was proposed by **Ernst Munch** in 1930. This theory relies on the principle of osmotic pressure differences between source and sink regions. Following steps explain the pressure-flow theory.

1. The glucose formed during photosynthesis in mesophyll cells, is used in respiration. The excess of glucose is converted into non-reducing sugar i.e., sucrose.
2. Sucrose is actively transported from mesophyll cells to the companion cells of phloem. From here, sucrose diffuses to sieve tubes, through plasmodesmata. So, the concentration of sucrose in sieve tubes increases.
3. Due to higher sucrose (solute) concentration in sieve tubes, water moves into them by osmosis from the nearby xylem of leaf. It results in an increase in the water potential at the source end of sieve tubes.
4. At the sink end, sugar is actively unloaded from sieve tubes and water also follows by osmosis. The exit of water lowers the water potential at the sink end. So, there is a higher water potential at the source end while a lower water potential at the sink end.
5. The difference in water potential causes water to flow from source to sink. Since sucrose is dissolved in water, it is carried along from source to sink along with water.

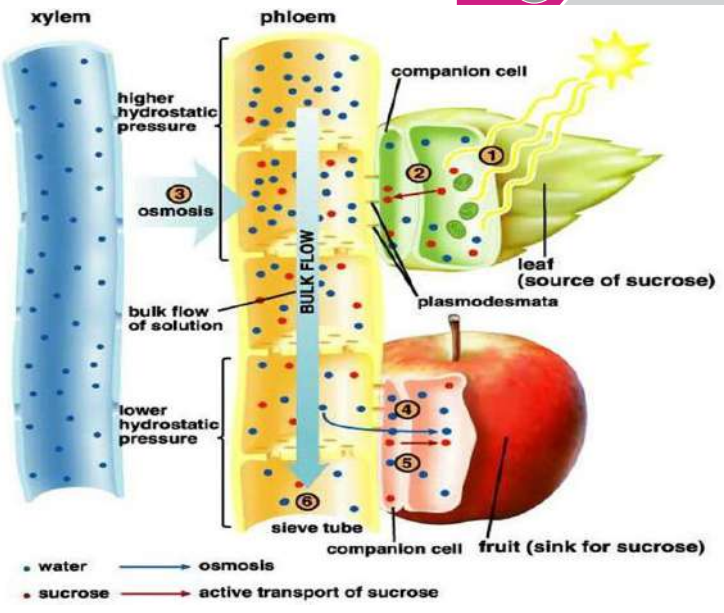


Figure 8.11: The pressure-flow theory

8.7- GROWTH IN PLANTS

Growth in plants refers to a permanent increase in size, which can occur in various dimensions such as height, width, and mass. Throughout life, the plant adds organs such as branches, leaves, and roots. Its organs increase in size from the tips but the rate of growth is not uniform throughout the body. In lower plants, the entire plant body is capable of growing, but in higher plants, growth is limited to certain regions known as **growing points**. These growing points consist of groups of cells, called **meristems**, that are capable of continuous cell division.

Types of Meristems

There are three types of meristems in plants i.e., apical meristems, intercalary meristems and lateral meristems **(Fig.7.13)**.

Apical meristems are found at the tips of roots and shoots. They are primarily responsible for the extension of the plant body. These are perpetual growth zones found and are responsible for the increase in the number of cells at the tips of roots and stems. They play an important role in primary growth.

Intercalary Meristems are separated from the apex by permanent tissues. They are situated at the bases of internodes in many plants such as grasses and play an important role in the production of leaves and flower. These are temporary.

Lateral meristems are cylinders of dividing cells present along the peripheral regions. They are responsible for growth in thickness of stems and roots. They are found in woody plants and are crucial for secondary growth. There are two main forms of lateral meristems; vascular cambium and cork cambium. **Vascular cambium** is

located between the xylem and phloem and is responsible for production of secondary xylem and secondary phloem. **Cork cambium** is formed in the outer layer of stems and roots. This tissue produces cork cells which replace the epidermis and forms the outer protective bark.

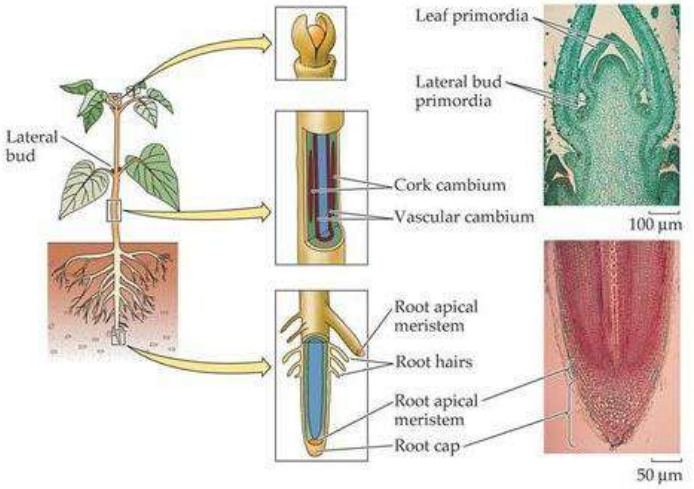


Figure 8.12: Apical meristem produces the primary plant body and lateral meristem produces the secondary plant body.

Types of Growth

In plants, there are two types of growth i.e., primary growth and secondary growth **(Fig.7.14)**.

Primary Growth

Primary growth is responsible for an increase in the length of the plants. It is facilitated by the activity of apical meristems. Herbaceous plants generally display primary growth with little secondary growth as compared to woody plants.

The process of primary growth in plants occurs in three phases.

1. **Cell Division:** The cells of apical meristems undergo divisions and the number of cells is increased. It happens at the tips of apical meristems of root and shoot. The area of apical meristem where cell division occurs, is called **zone of cell division** In this zone, cells are non-vacuolated and small. These cells have spherical nuclei in the centre of cytoplasm.
2. **Cell Elongation:** After the formation of new cells, their volume increases due to uptake of water. Plasticity of cell wall increases and wall pressure is reduced. It happens at a little distance from the tips of apical meristems. The area where cell elongation occurs, is called **zone of cell elongation**. In this zone, cells are vacuolated and large. They have nuclei in the peripheries of cytoplasm. During this phase, different cells elongate in different dimensions and the final size of cells is attained. For example, the cells which are determined to develop into pith, cortex

etc. do not elongate much length-wise while the cells which are determined to develop into xylem tissue elongate more length-wise.

3. **Cell Differentiation:** After the cells have got their final size and shape, elongation stops and cells are specialized to perform specific functions. Their cell walls become thicker and many new structural features develop. It happens in the area next to the zone of elongation. This area is called zone of cell differentiation. In this zone, cells are fully differentiated and each type of cell performs specific function.

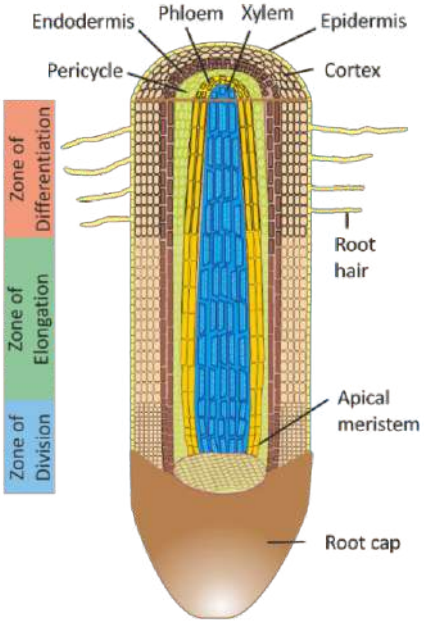


Figure 8.13: Primary growth in a root

Secondary Growth

Secondary growth refers to the increase in thickness or girth of stems and roots. It is due to the activity of lateral meristems, specifically the vascular cambium and cork cambium. It is more prominent in woody perennial plants, while herbaceous plants show only primary growth.

The cells of vascular cambium divide and produce new cells on both of its outer and inner margins. Cells produced on outer margins of vascular cambium make secondary phloem while the cells produced on its inner margins make secondary xylem. Secondary tissues (particularly secondary xylem) cause increase in plant's thickness. Division in cork cambium produces cells on both outer and inner sides. These cells make new cork. The region of mature stem outside of the vascular cambium, which contains secondary phloem, cork cambium and cork, is collectively called bark.

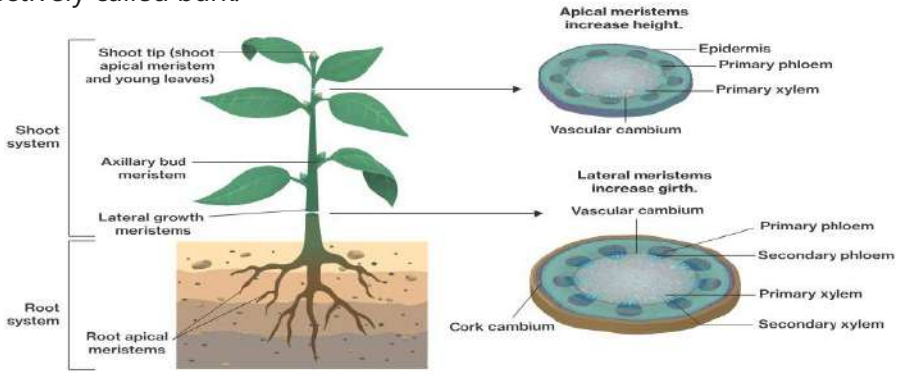


Figure 8.14: Primary and secondary growth in a plant.

Annual rings are formed due to the seasonal activity of the cambium layer in trees. This process is influenced by environmental factors and results in the production of two distinct types of wood each year: **spring wood** (early wood) and **autumn wood** (late wood). These rings provide valuable information about the age of the tree and the environmental conditions experienced during each growing season.

The cambium is a meristematic tissue that generates new vascular tissues i.e., xylem and phloem. In spring, when conditions are favourable, the cambium is highly active, producing a large volume of xylem with wider vessels, resulting in lighter-coloured spring wood. As the season changes to autumn, the cambium's activity decreases. It produces fewer xylem elements, which are narrower and denser, leading to the formation of darker autumn wood. The combination of spring wood and autumn wood forms a complete annual ring. Each year, a new ring is added, allowing for the determination of a tree's age through dendrochronology.

Dendrochronology is the scientific method of dating and studying tree rings to analyse past climate conditions and events.

The transition between these two types of wood is gradual from spring to autumn, but the shift from autumn back to spring in the following year is abrupt, marking a clear distinction between the growth periods. This data is valuable for studying long-term climate variability and changes.

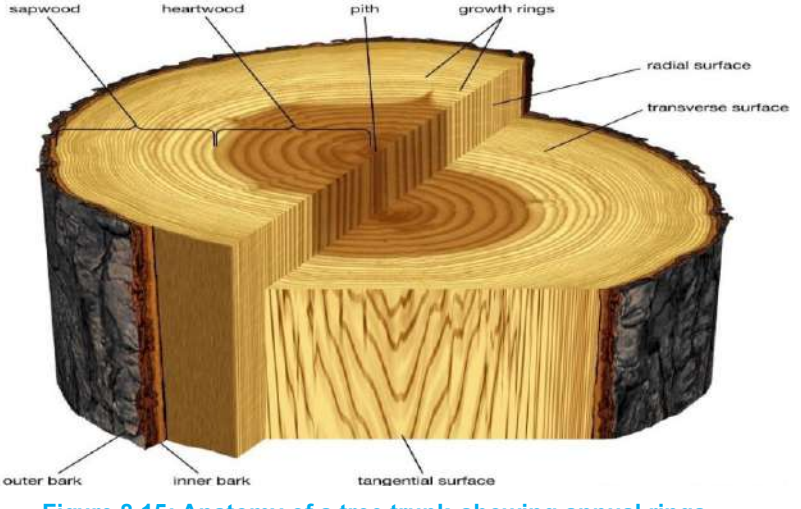


Figure 8.15: Anatomy of a tree trunk showing annual rings

Plant Growth Regulators

Plants regulate the rates of growth and the rate of metabolism in their cells. Special chemical messengers, called plant growth regulators or **plant hormones** regulate their growth. There are five major groups of plant growth regulators i.e., auxins, cytokinins, gibberellins, abscisic acid, and ethylene.

Auxins

These are indole acetie acid (IAA) or its variants. These regulate following activities:

- In stem, promote cell enlargement in region behind apex.
- Promote cell division in cambium.
- In root, promote growth at very low concentrations. Inhibit growth at higher concentrations, e.g., geotropism. Promote growth of roots from cuttings and calluses.
- Promote bud initiation in shoots but sometimes antagonistic to cytokinins and is inhibitory.
- Promote apical dominance and fruit growth. They can sometimes induce parthenocarpy.
- Cause delay in leaf senescence (aging) in a few species.
- Inhibit abscission.

Gibberellin

Gibberellins are produced in the apical portions of roots and shots, and transported to other parts. Gibberellins contain Gibberellic acid and there are more than 110 different gibberellins. They preform following activities:

- Promote cell enlargement in the presence of auxins. Also promote cell division in apical meristem and cambium.
- Promote 'bolting' of some rosette plants.
- Promote bud initiation in shoots of chrysanthemum callus.
- Promote leaf growth and fruit growth. May induce parthenocarpy.
- In apical dominance, enhance action of auxins.
- Break bud and seed dormancy.
- Sometimes may substitute for red light. Therefore, promote flowering in long-day plants, while inhibit in short-day plants.
- Cause delay in leaf senescence in a few species.

Cytokinins

They are usually produced in roots, young fruits, and in seeds. Cytokinins promote cytokinesis during cell division. They increase the rate of DNA replication and the rate of RNA and protein synthesis. They perform the following:

- Promote stem growth by cell division in apical meristem and cambium.
- Inhibit primary root growth.
- Promote lateral root growth.
- Promote bud initiation and leaf growth.
- Promote fruit growth but can rarely induce parthenocarpy.
- Promote lateral bud growth, also break bud dormancy.
- Cause delay in leaf senescence.

- Promote stomatal opening.

Abscisic acid

Abscisic acid (ABA) is synthesized mainly in mature green leaves, fruits, and root caps. It performs the following functions:

- Inhibits stem and root growth notably during physiological stress, e.g., drought, and waterlogging.
- Promotes bud and seed dormancy.
- Promotes flowering in short day plants, and inhibits in long day plants (antagonistic to gibberellins).
- Sometimes promotes leaf senescence.
- Promotes abscission.
- Promotes closing of stomata under conditions of water stress (wilting).

Ethylene

It is a natural product of the metabolism of plants. Inhibits stem growth, notably during physiological stress.

- Inhibits root growth.
- Breaks dormancy of bud.
- Promotes flowering in pineapple.
- Promotes fruit ripening.

8.8- OSMOREGULATIONIN PLANTS

Osmoregulation refers to the process by which an organism maintains a stable internal equilibrium of water and dissolved substances, irrespective of the surrounding environmental conditions. Many marine organisms undergo osmosis without the requirement for regulatory systems since their cells have the same osmotic pressure as that of the sea. However, some organisms must actively acquire, retain, or eliminate water or salts in order to regulate their internal water and mineral balance.

Types of Solutions

Hypotonic solution: A solution having reduced solute concentration relative to the intracellular environment of a cell. As a result, water enters the cell by osmosis resulting in the swelling.

Hypertonic solution: A solution having high solute concentration relative to the intracellular environment of a cell. As a result, water moves out of the cell which causes the cell to shrink due to loss of water, a condition called **plasmolysis**

Isotonic solution: A solution whose solute concentration resembles to the intracellular environment of the cell. Net movement of water between the cell and its environment is zero in this case.

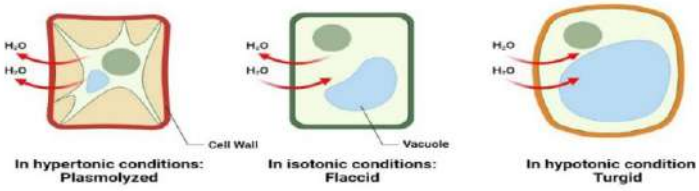


Figure 8.16: Effect of Hypertonic, Hypotonic and isotonic solution to plant cell.

Osmotic Adjustments in Plants

Plants are distributed in different habitats of aquatic, moderate, severely dry terrestrial and saline nature, thus termed as hydrophytes, mesophytes, xerophytes and halophytes, respectively.

Hydrophytes are adapted to aquatic environments, including marine and freshwater ecosystems, through specialized osmotic adjustment mechanisms. **Marine hydrophytes** thrive in saline (hypertonic) conditions, where water tends to leave their cells. They excrete excess salts using specialized salt glands and synthesize organic solutes like proline, glycine betaine, and sugars to retain water by increasing their internal osmotic potential. They have thick cuticles which further reduce water loss, and they exhibit halophytic traits to tolerate high salinity. **Freshwater hydrophytes** grow in hypotonic environments, where water continuously enters their cells. These plants expel excess water through structures like hydathodes or vacuoles to avoid overhydration. They actively absorb essential ions, such as potassium and calcium, to maintain osmotic balance and compensate for the dilute surroundings. With thin or absent cuticles, these plants facilitate water exchange and often have reduced root systems, relying on direct nutrient and water absorption from their environment. Examples of hydrophytes are water lilies, lotus, seaweeds and tape grass **(Fig. 8.17).**

Figure 8.17: (a) Waterlily floating in freshwater. (b) Tape grass in freshwater lake.

Mesophytes live in moderate environments that are neither too dry nor too wet. They prefer soil that is not waterlogged and has a moderate salt content and humidity. Mesophytes have well-developed roots and shoots with a fully formed vascular system. They do not require any special adaptations to survive. Their leaves

are flat, broad, and green with stomata on the surface. Examples of mesophytes include rose, tomatoes, and daisies **(Fig.8.18)**.

Figure 8.18: Examples of mesophytes, left (rose) and right (daisy).

Xerophytes are plants that are adapted to survive in dry conditions. They have special adaptations to minimize water loss and store water. Plants that store water are known as **succulents** They possess fleshy stems that can store water and used when needed. Other adaptations in xerophytes include waxy coatings on leaves to reduce water loss, leaf dropping during dry periods, and leaf folding or repositioning to absorb sunlight efficiently. Examples of xerophytes include thorn trees, desert marigold, and blue agave **(Fig. 8.19)**.

Figure 8.19: A xerophytic plant

Halophytes inhabit saline soil with high concentrations of salts like NaCl, $MgCl_2$, $MgSO_4$, or saline water. On such a substratum, only such plants can grow which can tolerate a relatively high concentration of these salts. These plants have succulent leaves and sometimes the stem is also succulent. In certain cases, leaves are modified into spines. Examples of halophytes are sea arrowgrass and sea lavender.

Figure 8.20: Sea Arrowgrass

Halophytes growing in marshy places near seashore form a special vegetation known as the mangrove or tidal woodland. These are also called Helophilous halophytes.

7.9- THERMOREGULATION IN PLANTS

Thermoregulation is a homeostasis in which organisms maintain their body temperature despite variations in environmental temperature. **High temperature** denatures the enzymes and damages the metabolism. Plants use evaporative cooling to cope with high temperature. Hot and dry weather, however, causes water deficiency resulting in closing of stomata, thus plants suffer in such conditions. Most plants have adapted to survive in heat stress as the plants of temperate regions face the stress of 40°C and higher temperature. The cells of these plants synthesize large quantities of special proteins called **heat-shock proteins** These proteins embrace enzymes and other proteins thus help to prevent their denaturation.

Low temperature, on the other hand alters the fluidity of the cell membrane, because lipids of the membrane become locked into crystalline structures, which affects the transport of the solutes. The structure of the membrane proteins is also affected. Plants respond to cold stress by increasing proportion of unsaturated fatty acids, which help membrane to maintain structure at low temperature by preventing crystal formation. This adaptation requires time. Because of this reason, rapid chilling of plants is more stressful than gradual drop in air temperature. Freezing temperature causes **ice crystal formation**. The confinement of ice formation around cell wall does not affect as badly and plants survive. However, formation of ice crystals within protoplasm perforates membranes and organelles hence killing the cells. The plants native to cold region such as oaks, maples, roses and other plants have adapted to bring changes in solutes composition of the cells, which causes cytosol to super cool without ice formation, although ice crystals may form in the cell walls.

7.10- MOVEMENTS IN PLANTS

Organisms react to both external and internal stimuli. Animals may exhibit locomotion in reaction to stimuli but the plants are fixed, hence they can only alter their growth pattern.

Tropic movements: The growth movements in plants that are triggered by a stimulus, are collectively called tropic movements or tropisms. Such movements occur as a curvature of whole organ towards or away from stimuli such as light, touch, chemical, water and gravity. Following are the major types of tropic movements in plants:

1. **Phototropism**: It is the movement of part of plant, in response to stimulus of light and is caused by the differential growth of part of a plant like stem or root. The tips of shoots usually show positive phototropism while roots show negative phototropism.
2. **Geotropism**: It is the movement of plant parts in response to gravity. Roots display positive geotropism and shoots negative geotropism.
3. **Thigmotropism**: It is the movement in response to stimulus of touch, for example climbing vines. When they come in contact with some solid object, the growth on the opposite side of contact increases and the tendril coils around the support.
4. **Chemotropism**: The movement in response to some chemicals is called chemotropism. The hyphae of fungi are chemotropic.

7.11 - PHOTOPERIODISM

The response to changes in day length that enables plants to adapt to seasonal changes in their environment is termed as **photoperiodism**. Simply, it is response of plants to the length of day and night.

Effect of photoperiodism was first studied in 1920 by Garner and Allard. They studied that tobacco plant flowers only after exposure to a series of short days. Tobacco plant naturally flowers under same conditions, in autumn, but flowering could be induced by artificially exposing to short days. With further studies they were able to classify flowering plants into **long-day plants**, which require long days for flowering, **short-day plants**, which require short days for flowering and **day-neutral plants** which flower without being influenced by photoperiod. Later on, further studies indicated that it is really the length of the dark period which is critical. Thus, short-day plants are really long-night plants. If they are grown in short days, but the long night is interrupted by a short light period, flowering is prevented. Long-day plants will flower in short days if the long night period is interrupted.

Mechanism of Flower Induction

Phytochrome, a photoreceptor protein exists in two forms i.e., P_{660} and P_{730}. P_{660} is a quiescent form. It absorbs red light at a wavelength of 660 nm and is converted to active P_{730} which absorbs far red light at 730 nm and is converted to P_{660}. In nature, the P_{660} to P_{730} conversion takes place in day light and P_{730} to P_{660} conversion occurs in the dark. The rate at which P_{730} is converted to P_{660} provides the plant with a **"clock"** for measuring the duration of darkness.

It has been found that red light inhibits flowering in short-day plants but promotes flowering in long-day plants, under conditions during which flowering normally takes place. This observation led to the hypothesis that the P_{730}-P_{660} interconversion might be the plant time-regulator for flowering. According to this hypothesis, P_{730}, converted from P_{660} by the absorption of red light, would inhibit flowering in short day plants but promote flowering in long day plants. Because P_{730} accumulates in the day and diminishes at night, short day plants could flower only if the night were long enough, during which a great amount of P_{730} would not be completely inactivated, so that enough P_{730} would remain at the end of night to promote flowering. But now it is generally agreed that the time measuring phenomenon of flowering is not totally controlled by the interconversion of P_{660} to P_{730}. Other factors, like presence or absence of light and length of dark or light period also play an important role in flowering. The biological clock once stimulated causes production of **florigen** hormone in leaves, which travels through phloem to the floral buds, initiating flowering.

Table7.2: Classification of plants according to photoperiodic requirements for flowering

Short-day plants (SDPs)	Long-day plants (LDPs)	Day-neutral plants (DNPs)
Flowering induced by dark periods longer than a critical length, e.g., cocklebur 8.5 h; tobacco 10-11h.	Flowering induced by dark periods shorter than a critical length, e.g., henbane 13h.	Flowering independent of photoperiod.
Examples include cocklebur (Xanthium), chrysanthemum, soyabean, tobacco, strawberry.	Examples include henbane (Hyoscyamus niger), snapdragon, cabbage, spring wheat, spring barley	Examples include cucumber, tomato, garden pea, maize, cotton.

7.12- VERNALISATION

Biennial and perennial plants are stimulated to flowering by exposure to low temperature. This is called **vernalisation**. The low temperature stimulus is received by the shoot apex of a mature stem or embryo of the seed but not by the leaves as in photoperiodism.

For some plants, vernalisation is an absolute requirement while in some cases it simply assists in inducing flowering. The duration of low temperature (chilling) treatment required varies from four days to three months. Temperature around 4°C is found to be very effective in this regard. It stimulates the production of a hormone "**vernalin**" which induces vernalisation. Photoperiodism and vernalisation serve to synchronise the reproductive behaviour of plants with their environment, ensuring reproduction at favourable times of year. They also ensure that members of the same species flower at the same time, encouraging cross pollination for genetic variability.

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Process by which water evaporates from surface of leaf primarily through stomata:
   (a) Transpiration (b) Guttation (c) Imbibition (d) Cohesion
2. Through which structure does most of transpiration occurs?
   (a) Root hairs (b) Phloem (c) Xylem (d) Stomata
3. The TACT theory primarily explains
   (a) The movement of nutrients in the plants
   (b) The transport of water in plants
   (c) The absorption of minerals
   (d) The process of photosynthesis
4. Which of the following is not a function of xylem?
   (a) Transport of water (b) Transport of minerals
   (c) Transport of food (d) Mechanical support
5. Which of the following has a perforated cell wall?
   (a) Vessel (b) Fibre (c) Tracheid (d) Sclereid
6. Exposure to low temperature stimulates the process of flowering in biennial or perennial plants:
   (a) Dormancy (b) Photoperiodism (c) Vernalization (d) All of above
7. Plants that are adapted to survive in dry conditions:
   (a) Xerophhytes (b) Hydrophytes (c) Mesophytes (d) Halophytes
8. When sugar content in a cell increases the concentration of solute increases, what happens to the water potential?
   (a) Raises (b) Drops (c) Unchanged (d) None of these
9. In higher plant, transport of food materials occurs through;
   (a) Companion cells (b) Sieve tubes
   (c) Vessel elements (d) Tracheids
10. The plant hormone which inhibits the stem and root growth is
    (a) Auxin (b) Ethylene (c) Cytokinin (d) Gibberellin
11. The leaves of some hydrophyte float on the surface of water. In such a leaf, stomata are found in;
    (a) Lower epidermis (b) Upper epidermis
    (c) Sides of leaf (d) Deep depressions in leaf

12. Mesophytes are adapted to survive in:

(a) Moderate environments (b) Dry conditions

(c) Water environments (d) All of above

SECTION 2:SHORT QUESTIONS

1. Differentiate between macronutrients and micronutrients?
2. What is water potential?
3. What are the main three pathways for the movement of water between plant cells?
4. Differentiate between hypertonic and hypotonic solution?
5. What are halophytes?
6. Differentiate between long day plants and short day plants?
7. Write down the phases of plant growth?
8. Differentiate between Vernalin and Florigen.
9. Differentiate between Thigmotropism and Geotropism.
10. How intercalary meristem is different from apical meristem?

SECTION 3: LONG QUESTIONS

1. Describe osmoregulation in Hydrophytes and Halophytes?
2. Describe the Physiological adaptation of plants to extreme conditions. How do plants adjust their cell membrane composition and protein structures to survive high and low temperatures?
3. What is the role of meristem in the growth of plants?
4. Describe the mechanism of opening and closing of stomata?
5. Explain the concept of photoperiodism and its influence on plant flowering. How do short-day, long-day and day-neutral plants differ in their flowering responses, and what role does phytochrome plays in this process?

INQUISITIVE QUESTIONS

1. Can you explain the hypothesis regarding the opening and closing of stomata?
2. What mechanisms enable carnivorous plants to supplement their nutrient uptake despite being autotrophs?
3. How can you say that parenchyma and schlerenchyma provide support to plants?
4. How do the annual rings depict climatic variability?
5. How does Pressure Flow Theory explain the movement of sugars through a plant?
6. What strategies would you adopt to induce flowering in a plant?

Chapter 9

HUMAN DIGESTIVE SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Describe the mechanical and chemical digestion in the oral cavity
- Explain swallowing and peristalsis.
- Illustrate with a diagram the structure of the stomach and relate each component with the mechanical and chemical digestion in the stomach.
- Identify the role of the nervous system and gastrin hormone on the secretion of gastric juice.
- Describe the major actions carried out on food in the three regions of the small intestine.
- Trace the absorption of digested products from the small intestine lumen to the blood capillaries and lacteals of the villi.
- Describe the component parts of large intestine with their respective roles.
- Correlate the involuntary reflex for egestion in infants and the voluntary control in adults.
- Explain the storage and metabolic role of the liver.
- Describe composition of bile and relate the constituents with respective roles.
- Outline the structure of pancreas and explain its function as an exocrine gland.
- Relate the secretion of bile and pancreatic juice with the secretin hormone.

Digestion is the process by which the body breaks down food into smaller, absorbable components. Digestion is crucial for converting food into energy and raw materials required for growth, repair and maintenance of body functions. It supports the immune system, provides essential nutrients and ensures overall health. Efficient digestion prevents nutrient deficiencies, supports metabolism and maintains energy levels, making it vital for sustaining life.

9.1- ANATOMY & PHYSIOLOGYOF DIGESTIVE SYSTEM

The human digestive system is composed of the **gastrointestinal** (GI) tract and accessory digestive organs. The GI tract is a continuous tube that extends from mouth to anus. It includes oral cavity, pharynx, oesophagus, stomach, small intestine and large intestine. The accessory digestive organs include the salivary glands, liver, gallbladder and pancreas.

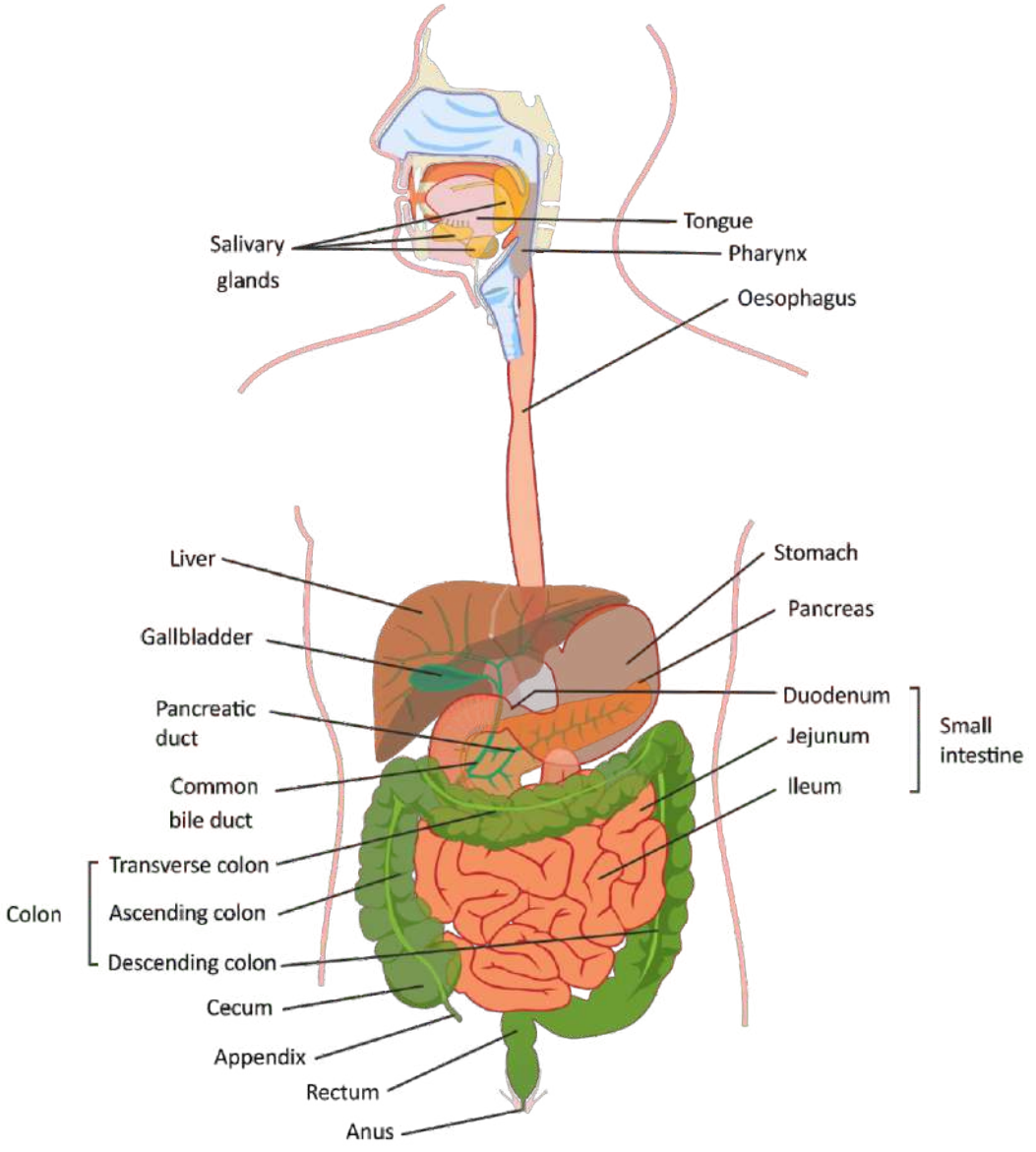


Figure 9.1: Human digestive system

Oral Cavity

It is a cavity immediately after the opening of mouth. **Lips** are made of highly vascularized, skeletal muscle tissue with many sensory nerve endings. Lips help to retain food as it is being chewed. They also play a role in phonation (the modification of sound). The important functions performed by oral cavity are as follows:

Selection of food: The muscular tongue is plays role in the selection of food through its taste buds. When food enters the oral cavity, it is tasted and physically felt. If the

taste or smell is unpleasant or if hard objects like bone or dirt are present in the food, it is rejected. The senses of smell and sight also play role in the selection of food.

Mechanical digestion of food: The ingested food is physically broken down by the teeth through a process called **mastication** (chewing). Chewing reduces food into smaller and more manageable pieces, increasing the surface area for enzymatic action.

Chemical digestion of food: As the chewing of food goes on, the salivary glands pour their secretion, **saliva**, into oral cavity. Palate, tongue and cheeks help in the mixing of chewed food with saliva. There are three pairs of salivary glands which pour saliva into oral cavity. These three pairs are; **sublingual** glands situated below tongue, **submaxillary** glands located behind jaws, and **parotid** glands located in front of ears.

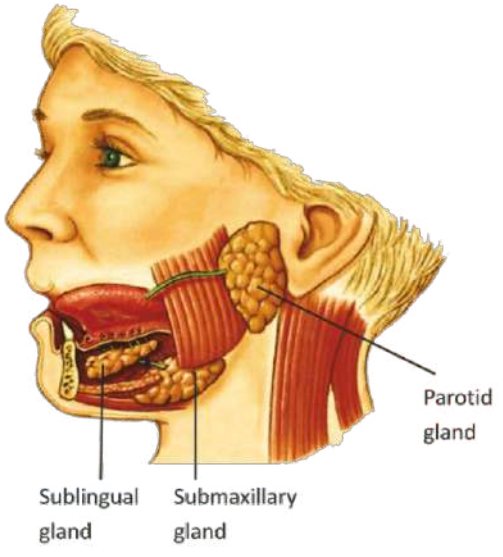


Figure 9.2: Location of salivary glands

Saliva contains water and mucus that moisten and lubricate the food. Saliva also contains bicarbonate ions, which buffer chemicals in the oral cavity, and thiocyanate ions, which kill microorganisms. Fresh saliva is alkaline (pH: 8) but it quickly loses CO_2 and gets pH 6. Saliva also contains an enzyme, **salivary amylase** It partially digests the polysaccharides (starch and glycogen) to disaccharides (maltose). After the mechanical and chemical digestive processes in the oral cavity, food mass is in the form of a small moist mass called a **bolus**.

Pharynx

The pharynx is a cavity behind the mouth. It is the common passageway for both the digestive and respiratory tracts. The bolus is pushed to the back of the mouth and is swallowed through the pharynx.

Swallowing of food: During swallowing, the tongue moves upwards and backwards against the roof of the mouth. Due to it, the bolus is forced to the back of oral cavity. The soft palate is also raised against the back wall of pharynx. These movements close the passage between nasal cavity and pharynx. At the same time, the larynx moves upward and it lowers the **epiglottis** (a flap of cartilage) and closes the opening of trachea. In this way, the bolus passes over the trachea and enters oesophagus.

The beginning of the swallowing action is voluntary, but once the food reaches the back of the mouth, swallowing becomes automatic.

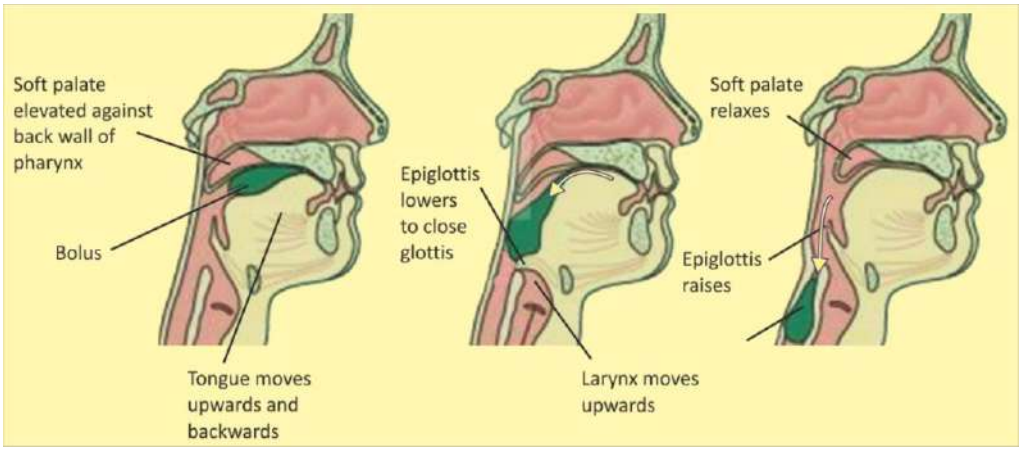


Figure 9.3: Swallowing of food

Oesophagus

After being swallowed, the food enters the tube called oesophagus. It connects the pharynx to the stomach. The previous digestive actions of saliva continue in oesophagus. In adult human, the oesophagus is about 25 cm long and its lower end opens in stomach. Food moves down through the oesophagus to the stomach by **peristalsis** The exit of food from the oesophagus to the stomach is controlled by the **lower oesophageal sphincter** or **cardiac sphincter**, which opens in response to the pressure exerted by food. It also prevents the backflow of stomach contents into the oesophagus.

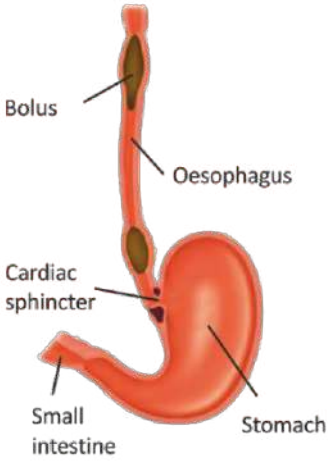


Figure 9.4: Oesophagusand its connections

Motility of Alimentary Canal

The following two types of movements occur in alimentary canal.

Peristalsis: It is the rhythmic sequence of waves of contraction in the smooth-muscles of the walls of alimentary canal. Peristalsis squeezes the food down along oesophagus and other parts of the alimentary canal.

Segmentation: The small and large intestines also have rings of smooth-muscles, which contract and relax repeatedly. These contractions and relaxations create a back-and-forth movement in the same place, called segmentation. This movement mixes the food with digestive secretions and increases the efficiency of absorption.

Antiperistalsis

Occasionally, the peristaltic movements may reverse in a process called **antiperistalsis**, pushing food from the intestines back into the stomach and oral cavity, leading to **vomiting**. In contrast, **hunger contractions** are peristaltic movements triggered by low blood glucose levels, creating the uncomfortable sensation known as **hunger pangs**.

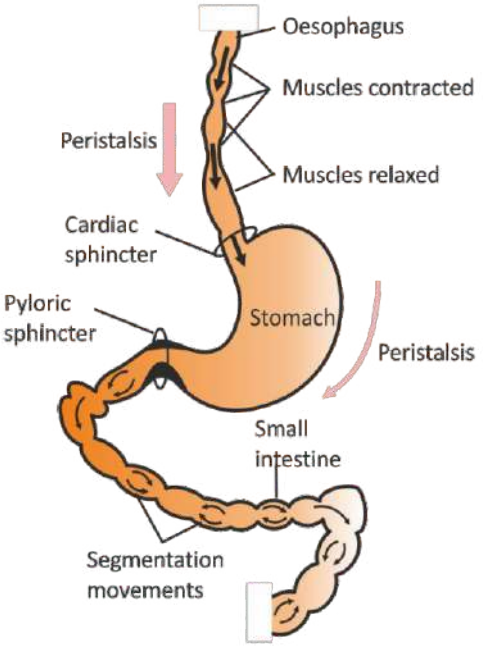


Figure 9.5: Peristalsis and Segmentation

The Stomach

The stomach is an elastic muscular bag (J-shaped) situated after oesophagus and before duodenum. It is located in the left side in abdominal cavity, right below the diaphragm. Its has three portions. The **cardiac portion** is present immediately after oesophagus. **Fundus portion** is present on a side of the cardiac portion. **Pyloric portion** is located beneath the cardiac portion. The cardiac sphincter opens when a wave of peristaltic contractions coming down the oesophagus reaches it and allows food to enter the stomach.

Mechanical digestion of food: The stomach wall is made of the same layers, as the other parts of alimentary canals. The outermost layer is **serosa**, the middle layer is made of **smooth muscles** In stomach, there are three layers of muscles i.e., outer longitudinal muscles, middle circular muscles and the inner oblique muscles. The inner two layers are **submucosa** and **mucosa** The muscular walls of stomach contract and vigorously and help in churning of food (mechanical digestion) and mixing the food with stomach secretions. These contractions also generate enough heat that melts the solid fats.

Sometimes there is a back flush of acidic chyme from stomach into the oesophagus. It causes a painful burning sensation in the chest and this condition is known as **pyrosis** or **heartburn**.

Chemical digestion of food: The mucosa of stomach possesses numerous tubular **gastric glands** These glands open in the mucosa wall through deep depressions, called **gastric pits**. Each gastric gland contains epithelial cells and three secretory cells:

i. The **mucous cells** which secrete mucous – a

In infants, the gastric juice contains large amounts of **rennin** enzyme. This enzyme coagulates milk proteins and delays the passage of milk into the small intestine. The delay enables other enzymes to digest the milk proteins.

thick secretion that covers the inside of the stomach and protects it from HCl and digestive enzymes.

ii. The **parietal (oxyntic) cells** which secrete Hydrochloric acid. It adjusts the pH of stomach contents to about 2-3. HCl also softens the food, activates the pepsinogen and kills microorganisms.

iii. The **chief cells** which secrete enzyme, pepsinogen.

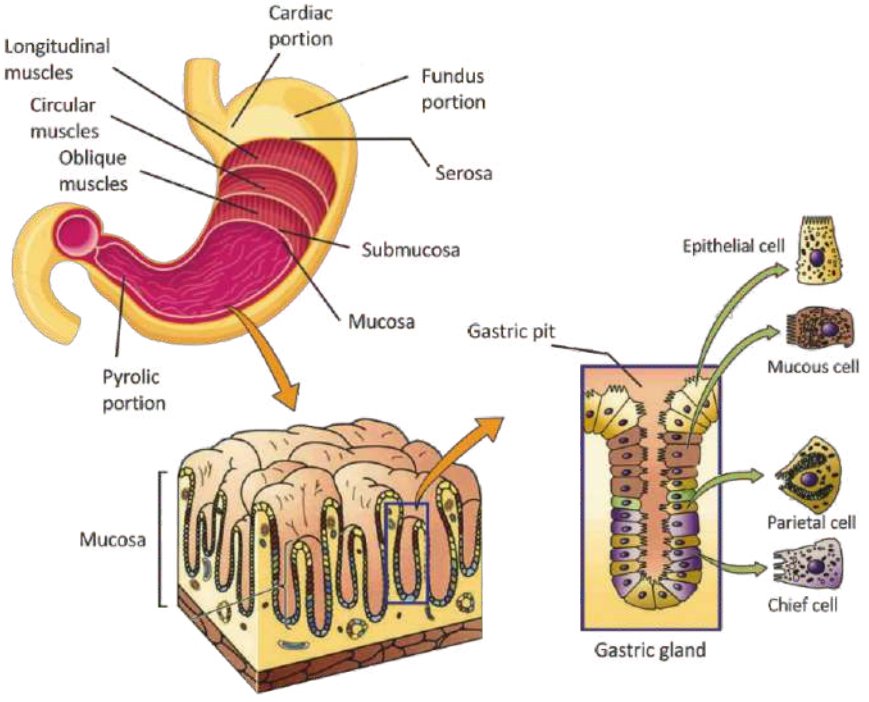


Figure 9.6: Stomach; external and internal structure

All the secretions of gastric glands are collectively called **gastric juice** When the bolus enters the stomach, the gastric glands secrete gastric juice. The H^+ ions of the HCl activate pepsinogen into pepsin. Pepsin catalyses the breakdown of proteins to yield polypeptides and peptides. About three to four hours after a meal, the stomach contents have been sufficiently mixed and are semi-liquid acidic mass called **chyme**. The **pyloric sphincter** regulates the release of the chyme into the small intestine.

Regulation of Secretion of Gastric Juice

The secretion of gastric juice is regulated by both the nervous system and hormonal mechanisms. In reaction to the smell, sight, or thought of food, the medulla of brain sends message to the gastric glands

The mucosa of stomach is susceptible to damage from acid and pepsin if it had no protection. Protection of the mucosa is provided in two ways; viscous mucous and bicarbonate, which neutralizes acid.

to secrete small amounts of gastric juice. When food arrives in stomach, the distension of stomach and decrease in the pH of the gastric contents stimulate more secretion and powerful contractions.

The presence of proteins in food stimulate special endocrine cells present in the mucosa of stomach to release a hormone called **gastrin**. Gastrin is carried by blood to the gastric glands where it stimulates them to produce and secrete more gastric juice. When food moves from stomach to small intestine, a hormone called **somatostatin** stops the release of hydrochloric acid.

The Small Intestine

It is the longest part of alimentary canal. It starts after the stomach and ends at the large intestine. In adult man it is about 2-3 cm in diameter and 6 m in length. Small intestine is responsible not only for the final digestion of all kinds of food but also for the absorption of digested food into blood and lymph. Small intestine consists of three parts i.e., duodenum, jejunum and ileum.

Duodenum

The first 20 – 25 cm long portion is the duodenum. It is concerned with the digestion of food. It also contains glands, which produce an alkaline secretion containing bicarbonate. Two main secretions are poured into duodenum.

a- Pancreatic juice It is the secretion of pancreas and is poured into duodenum. It is slightly alkaline (pH: 8) due to the presence of bicarbonate. It neutralizes the acidity of chyme. The important enzymes in pancreatic juice are:

i. **Pancreatic amylase,** which digests polysaccharides into maltose and even glucose)
ii. **Trypsinogen,** which is in inactive form. Another enzyme **enterokinase** (secreted by the walls of duodenum) activates trypsinogen into trypsin, which digests proteins into polypeptides.
iii. **Chymotrypsin and carboxypeptidase,** which digest proteins into smaller peptides and then into amino acids.
iv. **Pancreatic lipase,** which digests lipids to glycerol and fatty acids.
v. **Pancreatic nucleases,** which digest DNA and RNA into nucleotides.

Fats are insoluble in water. So, they cannot be attacked readily by lipase enzymes of pancreatic juice. Bile salts act as detergent molecules. They break fats into droplets and keep them separate from one another.

b- Bile: It is the secretion of liver. Before its release, it is stored in gallbladder. It contains salts which emulsify fats and break them into small droplets (emulsion). These droplets provide large surface areas for effective action of lipids-digesting enzymes.

If bile pigments are prevented from leaving digestive tract, they may accumulate in blood, causing a condition known as jaundice.

Jejunum and Ileum

Jejunum is 2.4 meters long part, next to duodenum. Ileum is the last three fifth i.e., about 3.5 metres long part of small intestine. These parts carry out the rest of digestion and absorption of food. The walls of jejunum and ileum contain glands which secrete intestinal juice. It contains various enzymes; for example, aminopeptidase digests polypeptides into dipeptides, erypsin digests dipeptides into amino acids, lipase digests fats into fatty acids and glycerol, maltase digests maltose into glucose, sucrase digests sucrose into glucose and fructose, and lactase digests lactose into glucose and galactose. After the action of enzymes of intestinal juice, the chyme is converted into an alkaline emulsion, called **chyle**.

Absorption of Digested Food and Water

The absorption of digested food, water, and dissolved minerals occurs in jejunum and ileum. The inner wall of jejunum and ileum contains large circular folds. These folds have numerous finger-like projections called **villi**

Each villus is richly supplied with blood capillaries and a vessel of lymphatic system, called **lacteal**. The blood capillaries and lacteal are covered by a single-cell thick epithelium. The epithelial cells of villi have countless cytoplasmic projections, called **microvilli**. The total surface area of absorption becomes extraordinarily large due to villi and microvilli.

Due to the presence of folds and numerous villi, the internal surface of jejunum and ileum appears velvety.

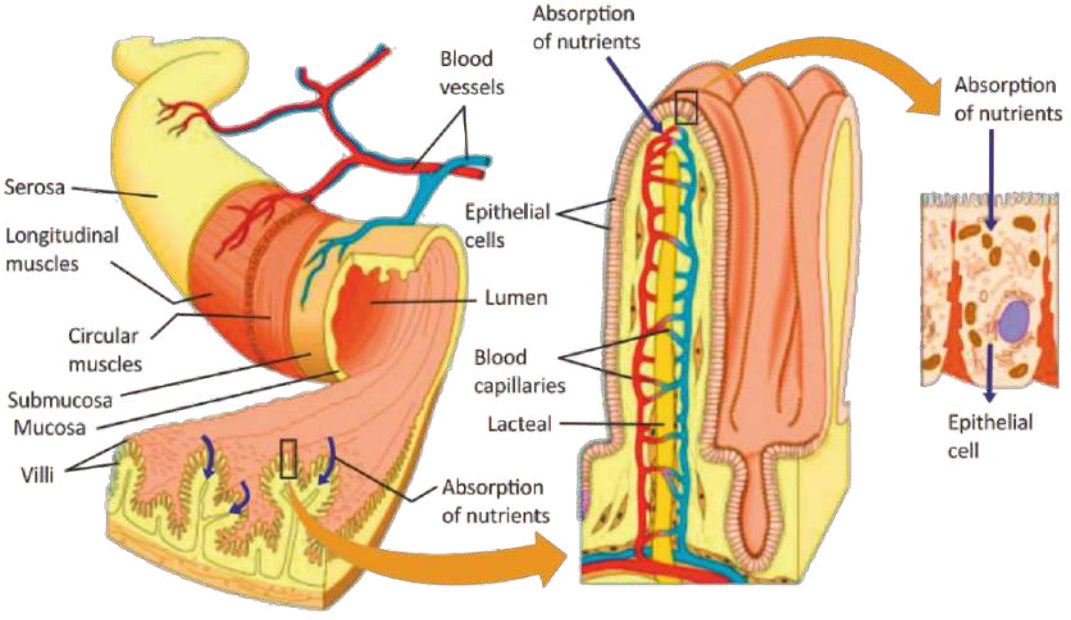


Figure 9.7: Intestinal wall and detailed structure of villi

Absorption of simple sugars and amino acids Simple sugars (e.g., glucose) and amino acids are absorbed by diffusion or active transport into the epithelial cells of villi. From here, these molecules enter the blood capillaries of villi. Blood capillaries of villi join to form **hepatic portal vein** which carries sugars and amino acids to liver. Liver stores extra glucose and amino acids in the form glycogen and proteins respectively. From liver, the required amounts of these products pass to heart via hepatic vein.

Absorption of Fatty acids and glycerol: The products of fat digestion i.e., fatty acids and glycerol are absorbed by passive transport into the epithelial cells of villi. Inside villi, they combine to form triglycerides. The triglycerides are coated with proteins. In this way small droplets, called **chylomicrons** are formed. The chylomicrons enter the lacteals of villi. From the lacteals, the chylomicrons move into thoracic lymphatic duct, from where they enter in bloodstream. Blood plasma has enzymes which hydrolyse chylomicrons back into fats and proteins. Fats are ultimately hydrolysed into fatty acids and glycerol and enter body cells.

The Large Intestine

It is the last part of the alimentary canal. It is much shorter than small intestine, occupying about the last metre of the intestinal tract. It is involved in the absorption of water and salts and vitamin 'K' from the lumen of intestine into the blood. The large intestine is not convoluted and its inner surface area does not possess villi. It consists of three parts.

Cecum

It is a blind sac that projects from the area of large intestine between ileum and colon. From the blind end of caecum there arises a finger-like process called vermiform appendix. In human digestive system, appendix performs no function so is vestigial.

Appendicitis is the inflammation of the appendix. It is usually due to bacterial infection. The infected appendix must be removed surgically otherwise it may burst and the inflammation may spread in the entire lining of the abdomen. The surgical removal of appendix is called **appendicectomy**.

Colon

Next to cecum is the colon. It has an ascending, a transverse and a descending limb. Its main function is to absorb water from the alimentary canal. As the water is absorbed, the remaining material becomes more solid. These wastes products, called faeces, consist of a large number of bacteria, indigestible plant fibres (e.g., cellulose), other undigested food stuff, sloughed off mucosal cells, bile pigments and water.

Rectum

It is the last part of large intestine where faeces are temporarily stored. At its distal end, the rectum opens out through anus. Anus is surrounded by two sphincters; the internal sphincter is made of smooth muscles and the outer is made of striated

muscles. Under normal conditions when the rectum is filled up with faeces, it gives rise to a defecation reflex. The defecation reflex is consciously inhibited in adults but in infants it is controlled involuntarily. During growth, the child learns to bring this reflex under voluntary control.

Many bacteria, for example E. coli, live and actively divide within colon. During their metabolism, they produce amino acids and vitamin K. Vitamin K is necessary for man for the coagulation of blood. It is absorbed from the large intestine into the blood.

Control of Egestion

The involuntary reflex for **egestion** in infants and the voluntary control in adults represent two stages of neurological and muscular development. In infants, egestion is an involuntary reflex mediated by the spinal cord, where rectal distension triggers automatic relaxation of the internal anal sphincter and expulsion of waste. This occurs because the higher brain centres responsible for voluntary control are not yet fully developed. In adults, egestion becomes voluntary as the **cerebral cortex** matures, allowing conscious regulation of the external anal sphincter to delay or initiate defecation. This transition reflects the integration of reflex pathways with cognitive control, adapting to social and environmental demands.

Accessory Digestive Organs

1. Liver and Gallbladder

The liver plays a vital role in digestion by producing **bile**, which is essential for fat digestion. Bile emulsifies fats, making them easier to digest. Liver also processes nutrients absorbed from the small intestine, detoxifies harmful substances, synthesizes proteins and stores glycogen for energy.

Cholesterol, secreted by the liver, may precipitate in the gall bladder to produce gall stones, which may block release of bile.

The gallbladder stores and concentrates bile produced by the liver. When food enters the small intestine, the gallbladder releases bile through the bile duct.

2. Pancreas

Pancreas is a large gland situated just ventral to the stomach. It has exocrine and endocrine portions. The **exocrine** (ducted) portion secretes its secretion i.e., pancreatic juice into pancreatic duct. The pancreatic duct joins with the common bile duct from the liver and enters the duodenum. Pancreatic juice contains enzymes for the digestion of all groups of food. Its major enzymes include trypsin, chymotrypsin, lipases, amylases, nucleases etc. The **endocrine** (ductless) portion of pancreas secretes its secretion i.e., insulin and glucagon hormones into extracellular fluid from where they diffuse into nearby capillaries.

Hormonal Control of the Secretions of Pancreas and Liver

We have studied the regulation of gastric secretions through nervous system and hormones. The release of secretions from pancreas and liver is also controlled by hormones. When chyme enters duodenum from stomach, its acidity stimulates duodenal walls to release a hormone, **secretin** Similarly, the partially digested proteins and fats present in chyme stimulate the duodenal walls to secrete another hormone, **cholecystokinin**(CCK). Both these hormones stimulate pancreas to release pancreatic juice, and gallbladder to release bile.

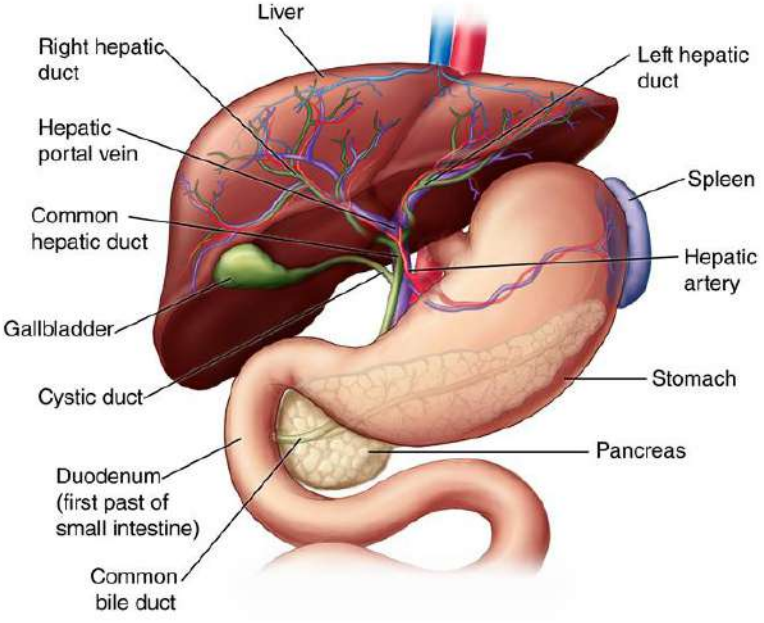


Figure 9.8: Accessory Digestive Organs

Storage and Metabolic Role of the Liver

The liver performs many important functions, especially in storing nutrients and regulating metabolism. It stores excess nutrients from the food and releases them when the body needs energy or building materials. These nutrients stored in the liver include glucose (stored as glycogen), vitamins (like A, D, B12, and K), minerals (e.g., iron and copper), and fats and fat-soluble substances. It also plays a central role in metabolism. It helps in breaking down, building up, and converting substances in the body. For example, it converts excess glucose into glycogen and back when needed, It also breaks down fats to produce energy and forms cholesterol and lipoproteins. It converts amino acids and removes harmful ammonia by turning it into urea, which is excreted in urine. It breaks down and removes toxins, drugs, and alcohol from the blood. The liver also helps in breaking down and regulating hormones

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Where does chemical digestion of carbohydrates begin?
   (a) Stomach (b) Oesophagus (c) Small intestine (d) Mouth
2. Which enzyme in saliva starts breaking down starch?
   (a) Lipase (b) Amylase (Ptyalin) (c) Trypsin (d) Pepsin
3. What prevents food from entering the trachea during swallowing?
   (a) Epiglottis (b) Oesophageal sphincter
   (c) Uvula (d) Tongue
4. Why does the enzyme activity drops in the stomach when pH rises?
   (a) Acid blocks food entry (b) Enzymes denature in low pH
   (c) Enzymes need acidic pH to work (d) Saliva dilutes gastric juice
5. Which change would most affect protein digestion?
   (a) Blocking bile release (b) Inhibiting salivary glands
   (c) Inhibiting pepsin production (d) Slowing peristalsis
6. Why is lipase not active in the stomach?
   (a) It is destroyed by acid (b) It needs alkaline pH to work
   (c) It is secreted by the liver (d) It digests only proteins
7. Which stomach secretion activates pepsin and kills bacteria?
   (a) Bile (b) Hydrochloric acid (HCl)
   (c) Sodium bicarbonate (d) Mucus
8. Why is segmentation important in the small intestine?
   (a) It absorbs bile (b) It breaks down enzymes
   (c) It mixes food with digestive juices (d) It pushes food to the rectum
9. What is the function of villi and microvilli in the small intestine?
   (a) Produce enzymes (b) Increase surface area for absorption
   (c) Store bile (d) Neutralize stomach acid
10. Which best explains the liver's role in digestion?
    (a) It produces insulin (b) It stores undigested food
    (c) It produces bile for fat digestion (d) It secretes enzymes into the colon

SECTION 2: SHORT QUESTIONS

1. What is the main function of the digestive system?
2. What is the mode of action of saliva in mouth?
3. What is role of tongue in the mouth?
4. What role does the epiglottis play during swallowing?
5. What is the composition of gastric juice?
6. Why is hydrochloric acid (HCl) important in the stomach?
7. What is the difference between bolus and chyme?

8. Which organ produces bile, and what is its function?
9. Differentiate between physical and chemical digestion.
10. What do you understand by emulsification of fats?
11. What is role of the role of the pyloric sphincter in digestion?
12. How do villi and microvilli help in nutrient absorption?
13. What are the main functions of the large intestine?
14. What causes jaundice in the digestive system?
15. How does stress negatively impact digestion?

SECTION 3: LONG QUESTIONS

1. Explain the complete process of digestion, starting from ingestion in the mouth to egestion in the large intestine. Include the roles of mechanical and chemical digestion at each stage.
2. Describe the structure and function of the stomach in digestion.
3. Compare and contrast the roles of the small intestine and large intestine in digestion.
4. Explain the absorption of food from the small intestine?
5. Discuss accessory organs (liver, gallbladder and pancreas) and their contributions in digestion.
6. Describe the hormonal and nervous regulation of gastric acid secretion.

INQUISITIVE QUESTIONS

1. Why does the small intestine need both peristalsis and segmentation?
2. How does the liver help digestion without using enzymes?
3. Why do we need bile if we already have enzymes for fat digestion?
4. How does the pancreas “know” when to release its enzymes?
5. Why are pancreatic secretions alkaline, not acidic?

Chapter 10

HUMAN RESPIRATORY SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Define the respiratory surface and list its properties
- Describe the main structural features and functions of the components of human respiratory system.
- Explain the ventilation mechanism in humans.
- Describe the transport of oxygen and carbon dioxide through blood.
- Outline the role of respiratory pigments.
- State the causes, symptoms and treatment of upper Respiratory Tract Infections (sinusitis, otitis media) and lower Respiratory Tract Infections (pneumonia, pulmonary tuberculosis).
- Describe the disorders of lungs (emphysema and COPD).

Recalling

Our cells obtain oxygen from the blood. The blood obtains this oxygen from air present in our lungs. Oxygen diffuses across the wet membranes of the lungs, which are filled with air in the process of breathing.

You have studied in your previous class how organisms get energy out of food molecules. For this purpose, organisms carry out catabolic processes in their cells, collectively called cellular respiration (glycolysis, Krebs cycle, and electron transport chain). These processes use oxygen and produce carbon dioxide. The term **external respiration** is used for the uptake of oxygen from the environment and the disposal of carbon dioxide into the environment at the body system level. It involves breathing and the exchange of oxygen and carbon dioxide in the capillaries. The organs which carry out these processes constitute the respiratory system. The theme of this chapter is to explain the respiratory system of humans and important respiratory disorders.

10.1- RESPIRATORY SYSTEM OF MAN

It consists of the organs that carry out external respiration (uptake of oxygen and disposal of carbon dioxide) at the body system level. The main organs of respiratory systems are the lungs which provide suitable respiratory surface for this gaseous exchange.

Properties of the Respiratory Surface

Respiratory surface means the area where actual gas exchange occurs between the environment and the blood. This gaseous exchange occurs through diffusion. In humans and other vertebrates which breathe in air, oxygen from the air diffuses into the blood and carbon dioxide diffuse from the blood to air. The following properties enable respiratory surfaces for effective diffusion of gases across them.

1. It is moist and permeable – so that gases may pass through it.
2. It is thin – so that gases have to travel minimum distance.
3. It has a blood supply – so that gases can diffuse in and out of blood.
4. It has structural support– so that it remains open and does not collapse.
5. It is located internally – so that its moist surface does not lose water to the atmosphere.
6. Air ventilates over it i.e., moves towards and away from it.
7. Air reaches to it after passing a branched tubular way – so that air becomes saturated with water vapour before reaching it.

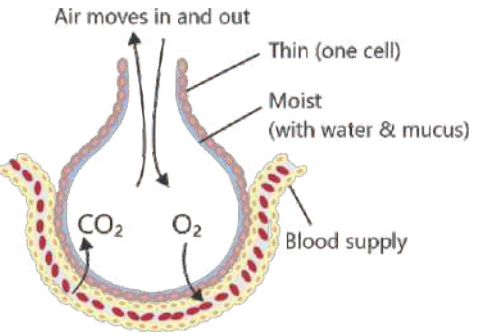


Figure 10.1: Some properties of respiratory surface

Components of Human Respiratory System

The organs of the respiratory system form a continuous system of passages, called the **respiratory tract**, through which air flows into and out of the body. The respiratory tract has two major divisions: the upper respiratory tract and the lower respiratory tract.

Upper Respiratory Track

It consists of nasal cavity, pharynx and larynx. These organs are involved in the movement of air into and out of the body. They also clean, humidify, and warm the incoming air. No gas exchange occurs in these organs.

1- Nasal cavity

The external openings of nose, called **nostrils**, lead to a **nasal cavity**. It is a large, air-filled space behind the nose and partitioned by a **nasal septum** (a part of the nasal bone). As inhaled air flows through the nasal cavity, it is warmed and humidified by blood vessels present very close to its surface. Hairs in the nose and mucous produced by mucous membranes trap larger foreign particles in the air before they go deeper into the respiratory tract. In addition to its respiratory functions, the nasal cavity also contains chemoreceptors needed for sense of smell, and contribution to the sense of taste.

2- Pharynx

It is a tube-like structure that connects the nasal cavity and oral cavity to larynx and oesophagus. Both air and food pass through it. So, it is part of both the respiratory and the digestive systems. Air passes from the nasal cavity through the pharynx to the larynx (as well as in the opposite direction). Food passes from the mouth through the pharynx to the esophagus.

3- Larynx

The larynx connects the pharynx and trachea. It is composed of muscles and cartilages. It is also called the voice box, because it contains two bands of smooth muscles called **vocal cords** The vocal cords vibrate when air flows over them and so produce sound.

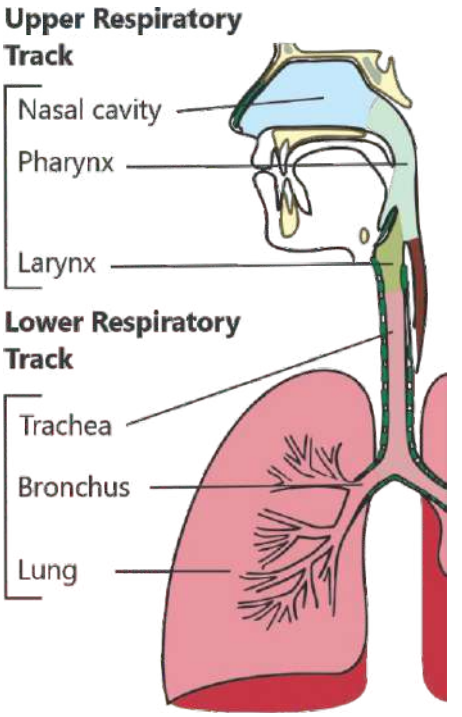
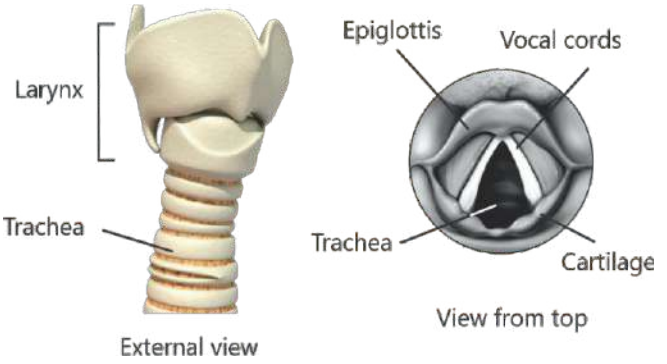


Figure 10.2: Respiratory track

Epiglottis is a cartilaginous flap that extends in front and above the opening of larynx called glottis. When air enters the larynx, the epiglottis keeps standing upwards to give way to air. When we swallow something, the backward motion of the tongue raises the larynx. Due to it, the epiglottis is forced downwards to close the glottis. It prevents swallowed material from entering the larynx.

Muscles in the larynx move the vocal cords apart to allow breathing. Other muscles in the larynx move the vocal cords together to allow the production of vocal sounds. The latter muscles also control the pitch of sounds and help control their volume.



If swallowed material does start to enter the larynx, it irritates the larynx and stimulates a strong cough reflex. This generally expels the material out of the larynx, and into the throat.

Figure 10.3: Larynx and Trachea

Lower Respiratory Track

The trachea and other passages of the lower respiratory tract conduct air between the upper respiratory tract and the lungs. These passages make a tree-like shape, with repeated branching. There are an astonishing 2,414 kilometres of airways conducting air through the human respiratory tract! It is only in the lungs, however, that gas exchange occurs between the air and blood.

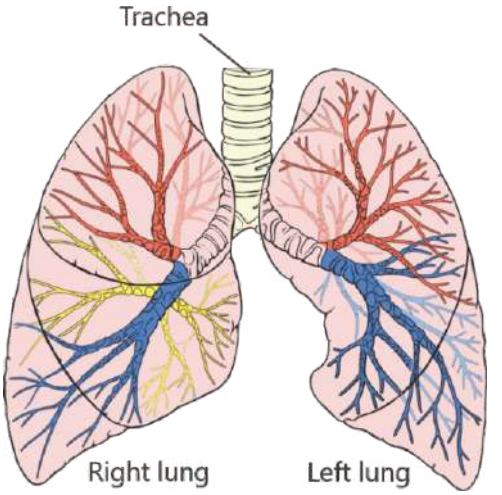


Figure 10.4: Tree-like branching of the lower respiratory tract

1- Trachea

The trachea, or windpipe, connects the larynx to the lungs for the passage of air. It is the widest passageway in the respiratory tract. It is about 1 inch wide and 4–6 inches long. Its walls are made of smooth muscles and C-shaped rings of cartilage. The trachea is lined with mucus and cilia. The cilia propel foreign particles trapped in the mucus toward the pharynx. The C-shaped cartilage provides strength and support to the trachea to keep the passage open. The trachea branches at the bottom to form two bronchi.

2- Bronchi, Bronchioles, and Alveoli

There are two primary bronchi (singular, bronchus). The right and left bronchi enter the lungs and branch into smaller, **secondary bronchi** There are two secondary bronchi in left lung while three in right lung. In secondary bronchi, the C-shaped cartilages are replaced with cartilage plates. The secondary bronchi branch into still smaller **tertiary bronchi**, which branch further into very small **bronchioles**. The bronchioles do not have cartilage plates. They divide many times and make **terminal bronchioles**. The terminal bronchioles end in **alveolar ducts**, which terminate in clusters of tiny air sacs, called **alveoli** (singular, alveolus), in the lungs.

3- Lungs

The lungs are the largest organs of the respiratory tract. The outside of each lung is covered by two membranes. First membrane, **visceral pleura,** lines the lungs while the second membrane, **parietal pleura,** lines the inner wall of thoracic cavity. The small space between these two membranes, called **pleural cavity**, is filled with fluid. This fluid allows the lungs to expand and contract freely during breathing. Each lung is divided into **lobes**. The right lung is larger and contains three lobes. The left

lung is smaller and contains two lobes. The smaller left lung allows room for the heart, which is just left of the centre of the chest.

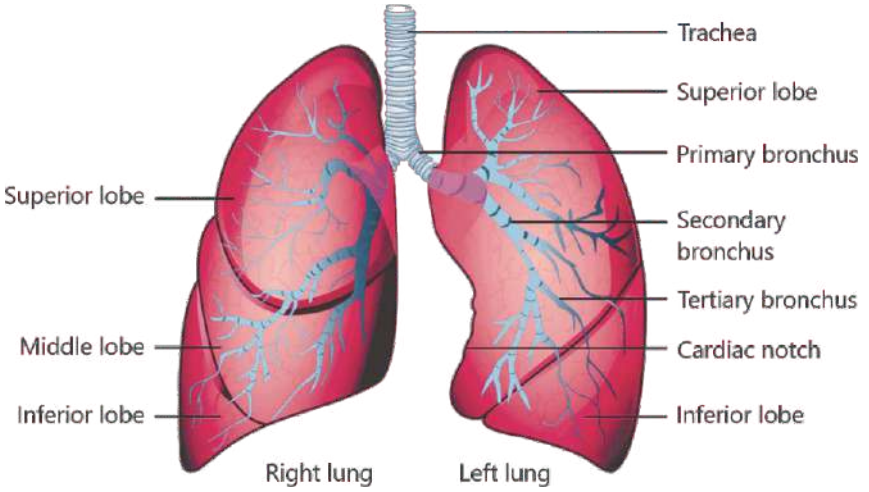


Figure 10.5: Right and left lungs

As mentioned previously, the terminal bronchi end in alveolar ducts. Each alveolar duct opens in a cluster of alveoli. These clusters make the bulk of the lung and are surrounded by blood capillaries. Each cluster contains 20-30 alveoli. An alveolus is made of moist epithelial tissue (only 0.1 micrometre thick). So, they provide the respiratory surface where gas exchange takes place between the air and blood.

Some epithelial cells of alveoli secrete a liquid called surfactant, which lines the inside of alveoli. It prevents the alveoli from collapsing and sticking together when air moves out of them. In healthy lungs, surfactant is constantly secreted and reabsorbed.

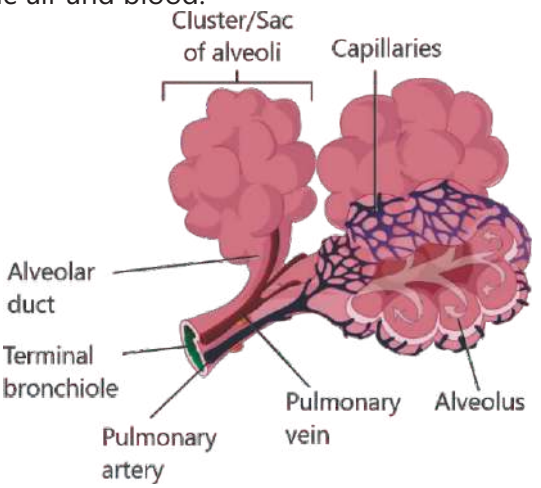


Figure 10.6: Clusters of alveoli

Recalling

You have studied that pulmonary arteries carry deoxygenated blood to the lungs. This blood absorbs oxygen in the lungs and pulmonary veins carry the oxygenated blood back to the heart to be pumped throughout the body. The lungs also receive oxygenated blood from the heart that provides oxygen to the cells of the lungs for cellular respiration.

The alveoli are the functional units of the lungs where gas exchange takes place. The two lungs may contain as many as 700 million alveoli. They provide a huge total surface area for gas exchange. When we breathe in, the alveoli fill with air, making the lungs expand. Oxygen in the air inside the alveoli is absorbed by the blood via diffusion in the network of tiny capillaries that surround them. The blood in these capillaries also releases carbon dioxide (also by diffusion) into the air inside the alveoli. When we breathe out, air leaves the alveoli and rushes into the outside atmosphere, carrying carbon dioxide with it.

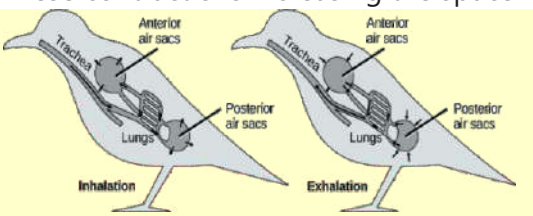
Mechanism of Breathing or Ventilation

The movement of the air in and out of the body is called breathing or ventilation. Our lungs do not draw in air or push it out. Rather, it is done by creating negative and positive pressures in the lungs. This role is played by two sets of muscles i.e., (i) **diaphragm** (dome-like large skeletal muscle that separates thoracic cavity and abdomen) and (ii) the **intercostal muscles** (present between each pair of ribs).

Atmospheric pressure is lower at high altitudes. It means a greater increase in thorax is required to make the pressure in lungs lower than the atmospheric pressure. That is why it is harder to breathe at high altitudes. The body adapts mechanisms to improve oxygen uptake under these conditions, which is why athletes often undertake high altitude training prior to competitions.

Inspiration: Taking in of air is called inspiration or inhalation. For this purpose, the diaphragm contracts. It causes the diaphragm to lower and take a more flattened shape. At the same time, the intercostal muscles contract.

It raises the ribs and expands the rib cage. These contractions increasing the space in the thorax. As a result, lungs expand because of the adherence of the visceral and parietal pleural membranes. The expansion of lungs lowers the air pressure inside them. The pressure in lungs becomes lower than the atmospheric pressure and the air enters the lungs.



Birds have lungs as well as air sacs in their body. Air flows in one direction. It flows from outside to posterior air sacs. For here, the air goes to the lungs, then to anterior air sacs, and then outside. The flow of air is in the opposite direction from blood flow. So, gas exchange takes place much more efficiently. This type of breathing enables birds to obtain the required oxygen, even at high altitudes where oxygen concentration is low.

Expiration: Moving the air out of lungs is called expiration or exhalation. Expansion of the thorax and lungs during inspiration places these structures under elastic tension. This elastic tension is relieved by the relaxation of the intercostal muscles and diaphragm. When diaphragm relaxes, it assumes its dome-like shape. Similarly, when intercostal muscles relax, the ribs lower

and rib cage moves inward. These movements decrease the space in thorax and allow the lungs to recoil. So, the pressure inside lungs becomes more than the atmospheric pressure and the air moves out of the lungs.

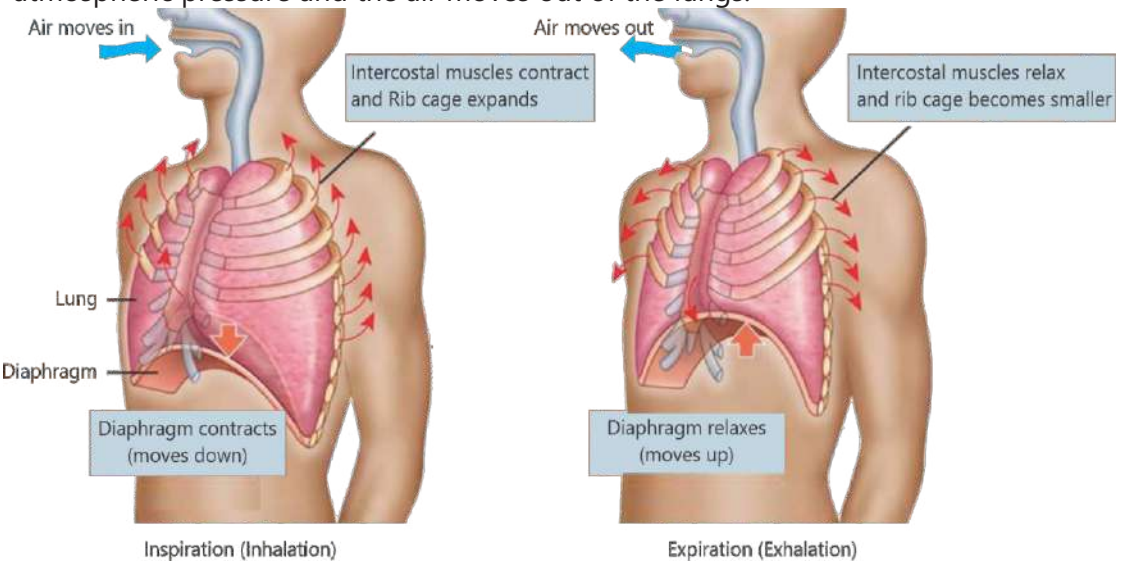


Figure 10.7: Mechanism of breathing

Control of Breathing

Each breath is initiated by neurons in a respiratory centre located in the medulla oblongata i.e., a part of the brain stem. These neurons send impulses to the diaphragm and intercostal muscles, stimulating them to contract., causing inspiration. When these neurons stop producing impulses, the diaphragm and intercostal muscles relax and expiration occurs.

10.2- TRANSPORT OF GASES

The process known as gas transport is an essential component of respiration. Oxygen is transported from lungs to all tissues and, at the same time, carbon dioxide is transported from tissue to the lungs. The following is a brief description of the mechanisms by which gases are transported in human body.

Transport of Oxygen

The partial pressure of oxygen in alveoli allows to diffuse through alveoli into pulmonary capillaries. Inside the blood, small amount of oxygen dissolves in the blood plasma. Blood plasma can dissolve a maximum of only about 3 mL O_2 per litre. Yet whole blood carries almost 200 mL O_2 per litre! The reason is that most of the oxygen is not dissolved in blood plasms but is bound to molecules of haemoglobin inside the RBCs.

Oxyhaemoglobin is bright red while deoxyhaemoglobin is dark red. But deoxyhaemoglobin imparts a bluish tinge to tissues. Because of these colour changes, vessels that carry oxygenated blood are always shown with a red colour, and vessels that carry oxygen-depleted blood are indicated with a blue colour.

The partial pressure of oxygen in alveoli (at sea level) is approximately 105 mm Hg, which is less than the partial pressure of oxygen in the atmosphere. So, about 97% of the haemoglobin within RBCs combines with oxygen and becomes **oxyhaemoglobin**. This molecule has a bright red, tomato juice colour. As the blood travels through the blood capillaries, some of the oxyhaemoglobin releases oxygen and becomes a dark red coloured **deoxyhaemoglobin**. Consequently, when blood leaves the tissue in the veins, it has a low partial pressure of oxygen (40 mm Hg). Here, 75% of haemoglobin is saturated in the form of oxyhaemoglobin. It means that 22% (97% minus 75%) of the oxyhaemoglobin has released its oxygen to the tissues, leaving 78% oxyhaemoglobin in the blood as a reserve. This large reserve of oxygen enables the blood to fulfil the body's oxygen needs during exercise as well as at rest.

Factors affecting Oxygen Transport

During exercise, the muscles use more oxygen from the capillary blood. It decreases the venous blood partial pressure of oxygen to 20 mm Hg. In this case, the percent saturation of haemoglobin drops from 75% to 35%. Because arterial blood still contains 97% oxyhaemoglobin, the amount of oxygen unloaded is now 62% (97% minus 35%), instead of the 22% at rest.

The oxygen reserve also ensures that the blood contains enough oxygen to maintain life for four to five minutes if breathing is interrupted or if the heart stops pumping.

The CO_2 produced by tissues lowers the pH of blood. This lowered pH reduces haemoglobin's affinity for oxygen and thus causes it to release oxygen more readily. The effect of pH on haemoglobin's affinity for oxygen is known as the Bohr effect. Increasing temperature has a similar effect on haemoglobin's affinity for oxygen. During exercise, skeletal muscles produce more heat, haemoglobin unloads a higher percentage of the oxygen.

Transport of Carbon dioxide

Blood capillaries deliver oxygen to the tissues and remove carbon dioxide from tissues. The partial pressure of CO_2 is higher in tissues than in blood. It causes the carbon dioxide to enter from tissues into blood. While, the process reverses in lungs where the partial pressure of CO_2 is lower in alveoli than in blood. Blood transports carbon dioxide from tissues to lugs in three ways.

1- As bicarbonate ions

Approximately 72% of carbon dioxide is carried in the blood as bicarbonate ions. CO_2 enters the RBCs and combines with water to form carbonic acid (H_2CO_3) in the presence of enzyme carbonic anhydrase. Carbonic acid

The formation of carbonic acid is important in maintaining the acid-base balance of the blood, because bicarbonate serves as the major buffer of the blood plasma.

(H_2CO_3) disassociates to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The hydrogen ion readily associates with oxyhaemoglobin and oxygen of oxyhaemoglobin is released to the tissue. While the bicarbonate ions (HCO_3^-) moves out from RBCs into plasma. The movement of bicarbonate ions (HCO_3^-) is facilitated by a transporter that exchanges one chloride ion (Cl^-) for a bicarbonate ion (this is called the "chloride shift" or "Hamburger phenomenon").

2- As Carboxyhaemoglobin

About 20% of CO_2 is carried as carboxyhaemoglobin. When partial pressure of CO_2 is higher in blood than tissues, CO_2 combines with the globin chains of haemoglobin and forms carboxyhaemoglobin.

CO_2 binds to the protein portion of haemoglobin while O_2 binds to the haem irons. So, both do not compete for attachment to haemoglobin.

3- As dissolved CO_2 in Plasma

When CO_2 enters blood, a little amount dissolves in the water of blood plasma. About 8% of CO_2 is carried this way.

The blood carries CO_2 in these three forms to the lungs. The lower PCO_2 of the air inside the alveoli causes the conversion of H_2CO_3 into H_2O and CO_2. The CO_2 diffuses out of blood into the alveoli, so that it can leave the body in the next exhalation.

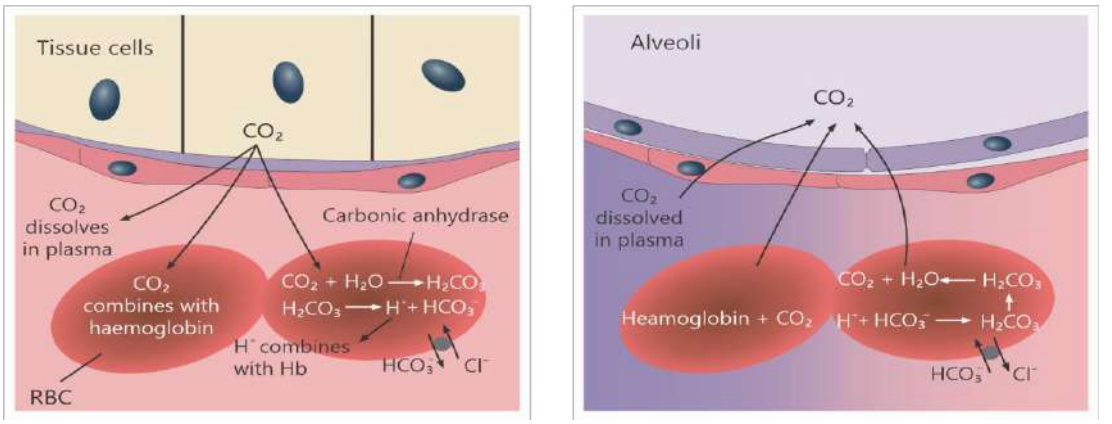


Figure 10.8: Transport of Carbon dioxide by blood

Carbon Monoxide Poisoning

Incomplete combustion of fuels such as wood, gasoline, propane, or natural gas produces CO gas. If gas heaters are left burning overnight in closed environments, CO accumulates in the room. It enters the body through inhalation and binds to haemoglobin with a much higher affinity than oxygen. This binding reduces the amount of haemoglobin available to transport oxygen to the body's tissues, leading to tissue hypoxia (oxygen deprivation). It leads to CO poisoning. Symptoms of CO poisoning may include headache, dizziness, weakness, nausea, confusion, shortness of breath, chest pain, and loss of consciousness. In severe cases, it can cause permanent brain damage, and even death.

10.3- RESPIRATORY PIGMENTS

Respiratory pigments are special proteins in blood or tissues and are involved in transporting oxygen throughout body. They also serve other purposes e.g., O_2 storage, CO_2 transport, and transport of substances other than respiratory gases. The two well-known respiratory pigments are haemoglobin and myoglobin.

Haemoglobin

Haemoglobin is a protein present in RBCs. A haemoglobin molecule is composed of four globin (globular) polypeptide chains (two α chains and two β) and four haem groups. There are 141 and 146 amino acids in the α and β chains, respectively. Each polypeptide chain is folded in such a way that it contains a pocket where the heme group binds. So, each chain is associated with a haem group. A haem group consists of an iron ion held in a porphyrin ring. The iron ion is attached with four nitrogen atoms of the polypeptide chain. Under higher partial pressure of oxygen, iron ion attaches a molecule of O_2. In this way, one haemoglobin molecule can carry up to four O_2molecules.

The four polypeptide chains of haemoglobin are bound to each other by salt bridges, hydrogen bonds, and hydrophobic effect.

Myoglobin

Myoglobin is the oxygen-binding protein in skeletal and cardiac muscle cells of vertebrates. It gives a distinct red or dark gray colour to muscles. It is a monomer, composing of a single polynucleotide chain (made of 153 amino acids) and contains a single haem group. Therefore, it is capable of binding with a single O_2 molecule. The binding affinity of myoglobin is high as compared to that of haemoglobin. As a result, myoglobin serves as the oxygen-storing protein in muscles. It releases oxygen when the partial pressure of oxygen is below 20 mm Hg. In this way, myoglobin provides oxygen to the muscles when they need.

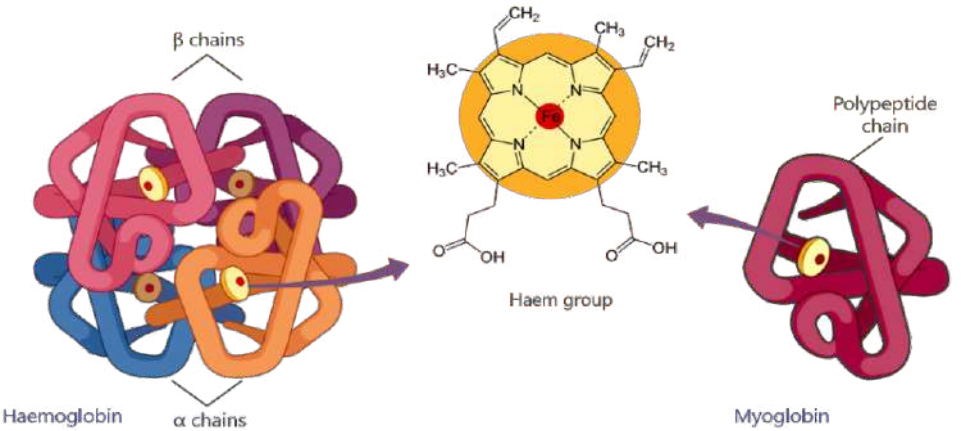


Figure 10.9: Structure of haemoglobin and myoglobin

Table10.1: Differences between Haemoglobin and Myoglobin		
	Haemoglobin	**Myoglobin**
1	Consists of four polypeptide chains.	Consists of one polypeptide chain.
2	Possesses four haem groups.	Possesses one haem group.
3	Found in blood (RBCs).	Found in skeletal and cardiac muscles.
4	Can attach four O_2 molecules.	Can attach one O_2 molecule.
5	Transports oxygen.	Stores oxygen.
6	Has less affinity with oxygen.	Has more affinity with oxygen.
7	Loses oxygen at PO_2 60 mm Hg.	Loses oxygen at PO_2 20 mm Hg.

10.4- Respiratory Disorders

A range of disorders can affect the respiratory system and interfere with respiration. These respiratory disorders can range from mild and self-limiting conditions such as the common cold to more severe diseases such as sinusitis, otitis media, pneumonia, pulmonary tuberculosis, emphysema and COPD.

Upper Respiratory Tract Infections

Upper Respiratory-tract Infections (URIs) affect the nose, throat, sinuses, and larynx and can be easily transmitted from person to person through respiratory droplets.

1. Sinusitis

It is the inflammation of the lining of the sinuses (four paired air-filled spaces that surround the nasal cavity i.e., under the eyes; above the eyes; between the eyes and behind the eyes). It may be acute (lasts for 7 to 10 days) or chronic (lasts longer than 12 week). Most case of sinusitis are due to viral infections; some may be due to bacterial infections and rare cases may also involve fungal infections.

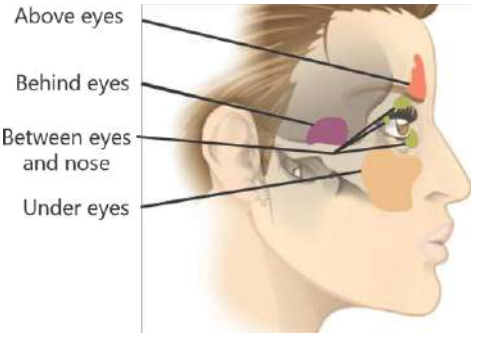


Figure 10.10: Sinuses

Symptoms of sinusitis include fever, plugged nose, pus-like nasal discharge, loss of sense of smell, facial pain, a feeling that phlegm is falling from the back of nose into throat, and headache that is sometimes aggravated by bending over.

Treatment: Most cases are caused by viruses and resolve without antibiotics. If it is due to a bacterial infection, antibiotics or sulpha drugs are usually prescribed. Beside it, the physician may also prescribe nebulization which can be useful in reducing inflammation in the sinuses and nose and to accelerate recovery. For chronic or recurring sinusitis, treatment may include nasal surgery in which the pathogens and mucous are removed.

2. Otitis media

It is the inflammation of the middle ear. Otitis may be acute (rapid onset) or chronic (lasts more than six weeks). The common cause of otitis media accumulation of fluid in Eustachian tube, which cannot be drained from the middle ear. When this fluid is not drained, it allows the growth of bacteria and viruses in the middle ear that lead to otitis media.

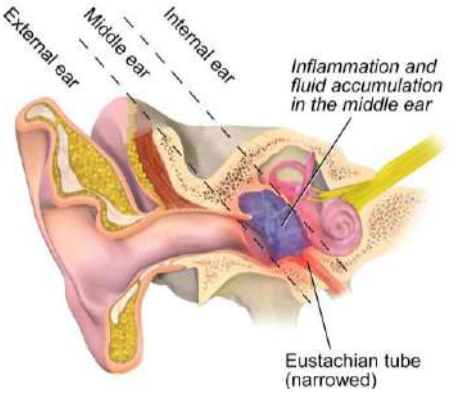


Figure 10.11: Otitis media

Symptoms of otitis media include severe ear pain, pulling at one or both ears, fever, fluid draining from ear(s), loss of balance, and hearing difficulties.

Treatments include oral and topical pain killers and antibiotics (if caused by bacterial infection).

Lower Respiratory Tract Infections

Lower Respiratory-tract Infections include pneumonia, pulmonary tuberculosis, lung abscess and bronchitis.

1. Pneumonia

Pneumonia is a form of acute respiratory infection. It can cause mild to life-threatening illness. In pneumonia, the alveoli of one or both lungs are inflamed and are filled with pus and fluid. It makes breathing painful and limits oxygen intake. Pneumonia is most commonly caused by viruses or bacteria. It is the single largest infectious cause of death in children worldwide.

Pneumonia killed more than 808 000 children under the age of 5 in 2017, accounting for 15% of all deaths of children under 5 years.

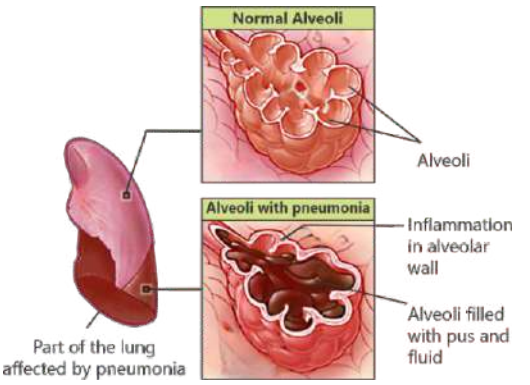


Figure 10.12: Pneumonia

A variety of organisms, primarily bacteria (particularly *Streptococcus pneumoniae*) or viruses (e.g., human rhinovirus) and less commonly fungi, can cause pneumonia.

Symptoms: Its symptoms include cough with phlegm, shortness of breath, chest pain, fever, blueness of skin, loss of appetite, high heat rate, and fatigue.

Treatment: Specific antibiotics are used to treat bacterial pneumonia. Analgesics, also used to reduce fever and pain. Vaccination prevents against certain bacterial and viral pneumonias both in children and adults.

2. Pulmonary Tuberculosis

Tuberculosis (TB) is a chronic infection caused by bacteria *Mycobacterium tuberculosis* It can affect many parts of the body but it generally affects the lungs. The tuberculosis of the lungs is called pulmonary tuberculosis. It is highly contagious and spreads through cough or sneezes. The bacteria enter the lungs, multiply and cause inflammation and damage to the lung tissue, including the alveoli. The damage to the alveoli can lead to the formation of small cavities or holes in the lung tissue, which can make it difficult for the lungs to function properly. In advanced stages, the alveoli are so damaged that the lungs may become unable to supply the body with enough oxygen. This can lead to a condition called respiratory failure, which is a medical emergency.

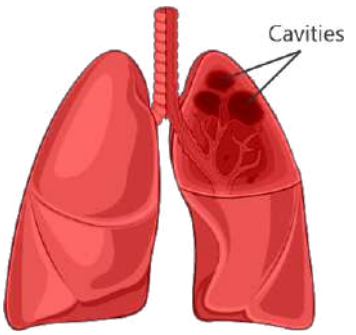


Figure 10.13: A lung affected with TB

Symptoms: Major symptoms of pulmonary tuberculosis are cough-with blood, intermittent intermittent fever usually in the evening, night sweats, weight loss, anorexia, depression, weakness and dry cough, chest pain due to Inflammation of the pleura of the lungs.

Treatment: includes the use of multiple antibioticsover a long period of time (for 9 months) regularly.

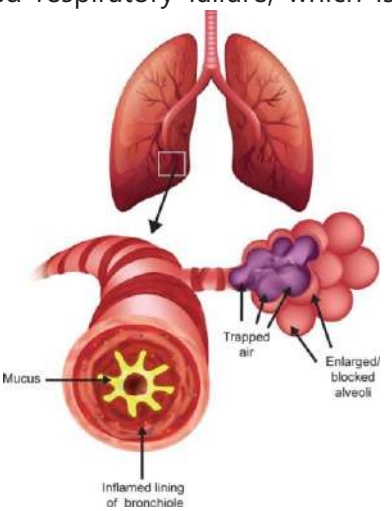


Figure 10.14: A lung affected by COPD

Disorders of the Lungs

Chronic obstructive pulmonary disease (COPD) is an important disorder of the lungs.

1. Chronic Obstructive Pulmonary Disease (COPD)

Chronic obstructive pulmonary disease (COPD) is a chronic inflammatory disease of lungs. The common causes of COPD are tobacco smoking, long terms exposure to harmful pollutants and chemical fumes etc., A small percentage genetic predisposition (protein alpha-1 antitrypsin deficiency) can also develop COPD, even without smoking or significant exposure to pollutants.

Symptoms: The symptoms of COPD are persistent cough with mucus (sputum), shortness of breath, wheezing, chest, fatigue and frequent respiratory tract infections.

Treatment: COPD is incurable but by minimizing exposure to smoke, pollutants, and chemicals, this disease can slow its progression. Others therapies include bronchodilators, inhaled corticosteroids, pulmonary rehabilitation, and oxygen therapy. In some severe cases, surgery such as lung transplantation may be considered.

Chronic bronchitis is a type of COPD. It involves inflammation and narrowing of the bronchial tubes in the lungs. It leads to increased mucus production, which can further block the airways and make breathing difficult. This disease lasts for three months to two years. It is caused by long-term exposure to irritants such as cigarette smoke, air pollution, or industrial dusts **Symptoms** of chronic bronchitis are almost same as of COPD such as wheezing, shortness of breath, chest tightness, and frequent respiratory infections.. Chronic bronchitis can be managed by quitting smoking. Other **treatments** are bronchodilators, pulmonary rehabilitation, and in some cases oxygen therapy.

Emphysema

Emphysema is a type of COPD. In emphysema, the inner walls of alveoli are damaged, causing them to eventually rupture. This creates one larger air space instead of many small ones and reduces the surface area available for gas exchange. The primary cause of emphysema is smoking. It can also be caused by long-term exposure to air pollution, dust, or chemical fumes. Emphysema disease can also be caused by a genetic deficiency of a protein called alpha-1 antitrypsin.

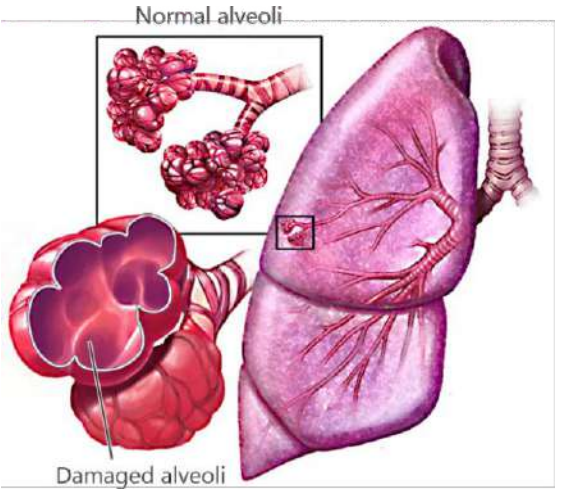


Figure 10.15: Emphysema

Symptoms: The symptoms of emphysema include shortness of breath, coughing, wheezing, fatigue, and chest tightness.

Treatment: Quitting smoking is the most important step in managing emphysema, as continued smoking can speed up the progression of disease. Other treatments include bronchodilators, inhaled steroids, oxygen therapy, and pulmonary rehabilitation.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. During inhalation, diaphragm;
   (a) Contracts and moves upward (b) Contracts and moves downward
   (c) Relaxes and moves upward (d) Relaxes and moves downward
2. Which part of the respiratory system acts as the respiratory surface?
   (a) Larynx (b) Trachea (c) Bronchi (d) Alveoli
3. How many oxygen molecules can attach with a haemoglobin molecule?
   (a) 1 (b) 2 (c) 3 (d) 4
4. What is TRUE about respiratory pigments?
   (a) Transport oxygen from lungs to tissues
   (b) Transport oxygen and carbon dioxide in equal amounts
   (c) Transport less oxygen and more carbon dioxide
   (d) Regulate the pH of blood
5. Which respiratory pigment is found in muscle tissue?
   (a) Haemoglobin (b) Melanin (c) Myoglobin (d) Chlorophyll
6. What is the maximum amount of air that can be inhaled or exhaled during a respiratory cycle?
   (a) Tidal volume (b) Vital capacity
   (c) Inspiratory reserve volume (d) Expiratory reserve volume
7. In what form is carbon dioxide primarily transported in the bloodstream?
   (a) Dissolved in plasma (b) Bound to haemoglobin
   (c) Converted to bicarbonate ions (d) None of the above
8. Which of the following treatments is commonly used to manage pulmonary TB?
   (a) Antibiotics (b) Cough syrup (c) Surgery (d) Chemotherapy
9. Which of the following is a common cause of pneumonia?
   (a) Bacterial infection (b) Viral infection
   (c) Fungal infection (d) All of these

10. Emphysema is characterized by:
    (a) Inflammation of airways (b) Narrowing of airways
    (c) Destruction of the alveoli in lungs (d) Fluid build-up in lungs

SECTION 2: SHORT QUESTIONS

1. Define respiratory surface and list its properties.
2. How nasal cavity functions in filtering the inhaled air?
3. Trace the path of air through different parts of the respiratory system.
4. Describe the structure and function of alveoli.
5. What is the role of diaphragm during inhalation and exhalation?
6. What the three ways of the transport of carbon dioxide in blood?
7. What are the advantages of having millions of alveoli rather than a pair of simple balloon-like lungs?
8. Differentiate between:
    - Internal and external respiration
    - Upper and lower respiratory tract
    - Bronchi and bronchioles
    - Haemoglobin and myoglobin

LONG QUESTIONS

1. Describe the mechanism of inhalation and exhalation.
2. Describe the transport of oxygen through blood.
3. Describe the transport of carbon dioxide through blood.
4. Describe the structure and function of haemoglobin.
5. Describe the causes, symptoms and treatment of sinusitis.
6. Describe the causes, symptoms and treatment of pneumonia and pulmonary tuberculosis.
7. Describe causes, symptoms and treatment of emphysema.

INQUISITIVE QUESTIONS

1. How does the structure of the alveoli optimize the exchange of gases like oxygen and carbon dioxide?
2. How do diseases like chronic obstructive pulmonary disease (COPD) affect gaseous exchange efficiency?
3. Can you explain the process of external respiration versus internal respiration in the context of gaseous exchange?
4. How does the transport of like oxygen in the bloodstream support cellular respiration?
5. What are the environmental factors that can influence gaseous exchange in humans?

Chapter 11

HUMAN CIRCULATORY SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- State the location of heart in the body and define the role of pericardium.
- Describe the structure of the walls of heart and rationalize the thickness of the walls of each chamber.
- Trace the flow of blood through the heart as regulated by the valves.
- State the phases of heartbeat.
- Explain the role of SA node, AV node and Purkinje fibers in controlling the heartbeat.
- List the principles and uses of Electrocardiogram.
- Describe the detailed structure of arteries, veins and capillaries.
- Describe the role of arterioles in vasoconstriction and vasodilation.
- Describe the role of precapillary sphincters in regulating the flow of blood through capillaries.
- Trace the path of the blood through the pulmonary and systemic circulation (coronary, hepatic-portal and renal circulation).
- Compare the rate of blood flow through arteries, arterioles, capillaries, venules and veins.
- Define blood pressure.
- State the role of baroreceptors and volume receptors in regulating the blood pressure.
- Define the term thrombus and differentiate between thrombus and embolus.
- Identify the factors causing atherosclerosis and arteriosclerosis.
- Categorize Angina pectoris, heart attack, and heart failure as the stages of cardiovascular disease development.
- State the congenital heart problem related to the malfunctioning of cardiac valves.
- Describe the principles of angiography.
- Outline the main principles of coronary bypass, angioplasty and open-heart surgery.
- Define hypertension and describe the factors that regulate blood pressure and can lead to hypertension and hypotension.
- List the changes in lifestyles that can protect man from factors that regulate blood pressure and can
- lead to hypertension and hypotension.
- List the changes in lifestyles that can protect man from hypertension and cardiac problems.
- Describe the formation, composition and function of intercellular fluid.
- Compare the composition of intercellular fluid with that of lymph.
- State the structure and role of lymph capillaries, lymph vessels and lymph trunks.
- Describe the functions of lymph nodes and state the role of spleen as containing lymphoid tissue.

Humans have two systems for the transport of different materials in different parts of body i.e., blood circulatory system and lymphatic system. The closed blood circulatory system of humans

Recalling:
Blood is the medium in which dissolved nutrients, gases, hormones, and wastes are transported throughout the body. It is composed of two main components (i) plasma and (ii) cells or cell-like bodies (white blood cells, red blood cells, platelets). In a healthy person, plasma constitutes about 55% by volume of the blood, and cells or cell-like bodies about 45% by volume of the blood.

consists of blood, heart, and blood vessels (arteries, capillaries and veins).

11.1- Structure And Functioning Of Heart

Human heart is a hard-working pump that moves blood through body. It is situated in the middle of chest cavity (between the lungs). Its back surface is near vertebral column while its front surface is behind sternum and rib cartilages.

The heart is usually felt to be on the left side because the left side of heart is stronger and larger, since it pumps to all body parts.
Because the heart is between the lungs, the left lung is smaller than the right lung and has a cardiac notch in its border to accommodate the heart.

Pericardium

Heart is enclosed in a sac called **pericardium** (Figure 11.1). Pericardium separates heart from surrounding organs. It is composed of the following two layers;

1. Outer layer of pericardium is called **fibrous pericardium**. It is made of strong connective tissue. It protects heart against external pressure and shocks. It also prevents excessive dilation of heart.
2. Inner layer of pericardium is called **serous pericardium** It is a sac, made of two layers i.e.,
   a) Outer **parietal** pericardium - present beneath fibrous pericardium.
   b) Inner **visceral** pericardium (also called epicardium) - closely attached to the underlying heart.

The space between parietal and visceral pericardium is called **pericardial cavity**. It contains up to 50 mL pericardial fluid. It lubricates heart and protects it from infections.

Wall of the Heart

The wall of heart is composed of three layers. The inner layer of pericardium i.e., epicardium makes the outer lining of heart wall. Beneath epicardium, there is the thickest layer of heart wall i.e., **myocardium**. Myocardium is made of cardiac muscles. **Endocardium** is present beneath myocardium. It is a single layer of epithelial cells and make 1 .

the inner linings of heart chambers (Figure 1 .1)

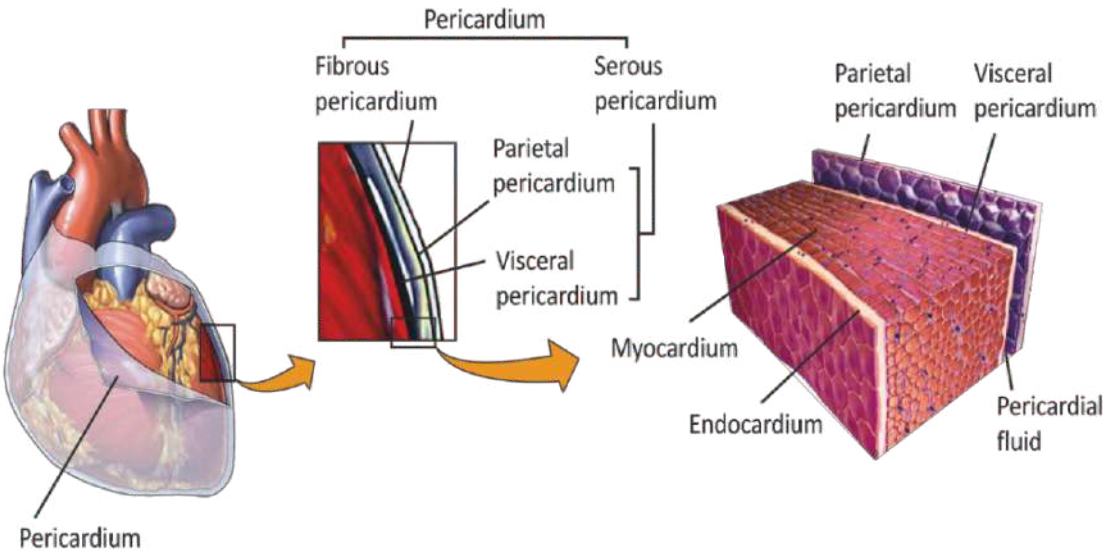


Figure 11.1: Pericardium and heart wall

Chambers and Valves of Heart

There are four chambers of heart i.e., two upper thin-walled **atria** and two lower thick-walled **ventricles**. Atria receive blood from body and pass it to ventricles, which distribute blood to body. Atria and ventricles are separated by **atrioventricular septum**. The left and right atria are separated from each other by an **interatrial septum**. Similarly, the left and right ventricles are separated from each other by an **interventricular septum**. It is much thicker than the interatrial septum.

At the entrance points of ventricles (in atrioventricular septum), there are two atrioventricular valves i.e., a tricuspid valve and a bicuspid valve. **Tricuspid valve** (made of three cusps) is present between right atrium and right ventricle. **Bicuspid (mitral) valve** (made of two cusps) is present between left atrium and left ventricle. When ventricles contract, tricuspid and bicuspid valves close and prevent the back flow of blood into atria.

At the exit points of ventricles, there are two **semilunar valves** (with shapes like a half-moon). These are called pulmonary valve and aortic valve. **Pulmonary valve** is located at the base of pulmonary artery while **aortic valve** is present at the base of aorta. When ventricles relax, pulmonary and aortic valves close. So, they prevent back flow of blood from pulmonary artery and aorta into ventricles.

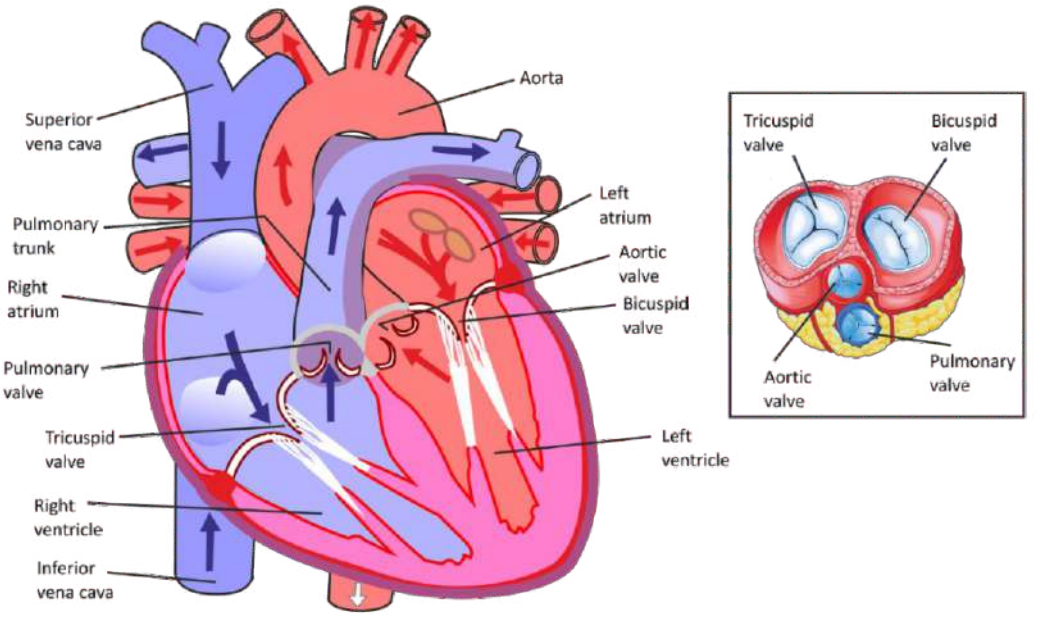


Figure 11.2: Human Heart and valves

Circulation of Blood through HEART

Human heart functions as a **double pump**. It carries out pulmonary circulation (supply of blood to lungs) and systemic circulation (supply of blood to all organs of body – except lungs). Complete separation of deoxygenated (right side) and oxygenated (left side) blood is maintained in heart.

The right atrium receives deoxygenated blood from body via two veins i.e., superior vena cava and inferior vena cava. Right atrium passes this blood to right ventricle via tricuspid valve. When right ventricle contracts, deoxygenated blood is passed to pulmonary trunk via semilunar pulmonary valve. The pulmonary trunk divides into left and right pulmonary arteries which carry this blood to lungs.

The oxygenated blood from lungs is brought to left atrium by pulmonary veins. Left atrium passes this blood to left ventricle via bicuspid (or mitral) valve. When left ventricle contracts, oxygenated blood is passed to aorta via semilunar aortic valve. Aorta carries this blood to all parts of body (except lungs).

The wall of left ventricle is thicker (about 3 times) than that of the right ventricle because it has to push the blood to all over body.

Cardiac Cycle Heartbeat

Heart works in continuous cycles. Its chambers relax and are passively filled with blood from large veins. Then, its chambers contract and propel the blood throughout body. Its alternating relaxations and contractions are collectively called a cardiac cycle or one **heartbeat**.

While atria are relaxed and being filled with blood, the ventricles are also relaxed. This relaxed period of heart chambers is called **diastole**. During diastole, both atria are filled with blood. As blood accumulates in atria, their blood pressure rises, due to which both of them contract. This is called **atrial systole** It passes the blood through tricuspid and bicuspid valves into the two relaxed ventricles. When ventricles are filled with blood, both of them contract. This is called **ventricular systole** and it pumps the blood to pulmonary arteries and aorta. During ventricular systole, tricuspid and bicuspid valves close while pulmonary and aortic valves open.

In one complete heartbeat, diastole lasts about 0.4 sec, atrial systole takes about 0.1 sec, and the ventricular systole lasts about 0.3 sec. In one's life, heart beats about 2.5 billion times, without stopping.

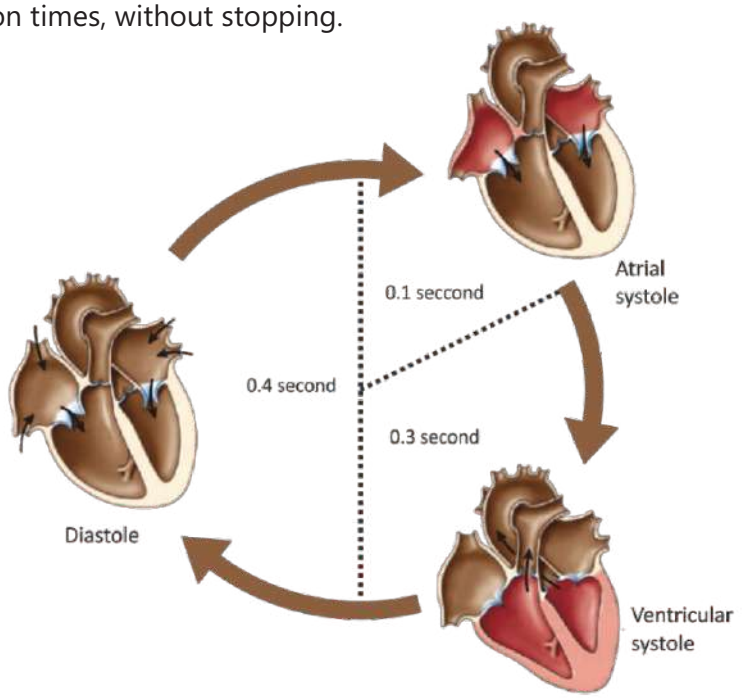


Figure 11.3: Cardiac cycle (one heartbeat)

Sounds of a Heartbeat

When both ventricles contract simultaneously to pump the blood to pulmonary arteries and aorta, the tricuspid and bicuspid valves close and **"lubb"** sound is made. Similarly, when ventricular systole ends and both ventricles relax simultaneously, the pulmonary and aortic semilunar valves close and **"dubb"** sound is made. —Lubb-dubb|| can be heard with the help of a stethoscope.

Most cases of heart murmurs are not serious, and those that prove serious can be corrected by replacing the damaged valves with artificial ones or with valves taken from an organ donor.

If the valves are not closing fully, or if they open narrowly, turbulence is created within the heart. This turbulence can be heard as a heart murmur. A murmur sounds like a hiss.

Control of Heartbeat (Heart Excitation and Contraction)

The pumping of heart is initiated by the **Sinoatrial Node** (SA node) or **pacemaker**. The sinoatrial node consists of a small cluster of cardiac muscle cells. It is embedded in the upper wall of right atrium. Heartbeat starts when SA node sends electrical impulses to the walls of atria. It causes both atria to contract simultaneously. The impulses then travel to an **atrioventricular node** (AV node). It is also made of small cluster of cardiac muscle cells. It lies at the lower portion of interatrial septum.

From AV node, the impulses reach an **atrioventricular bundle** or **bundle of His**. It is a network of fibres present in interventricular septum. AV bundle divides into left and right branches, which end at the **Purkinje fibres** in the walls of the ventricles. Stimulation of these fibres causes the ventricles to contract almost simultaneously (Figure 11.4). There is a delay of about 0.15 second in conductance of impulses from the SA node to AV node, permitting atrial systole to be completed before ventricular systole begins.

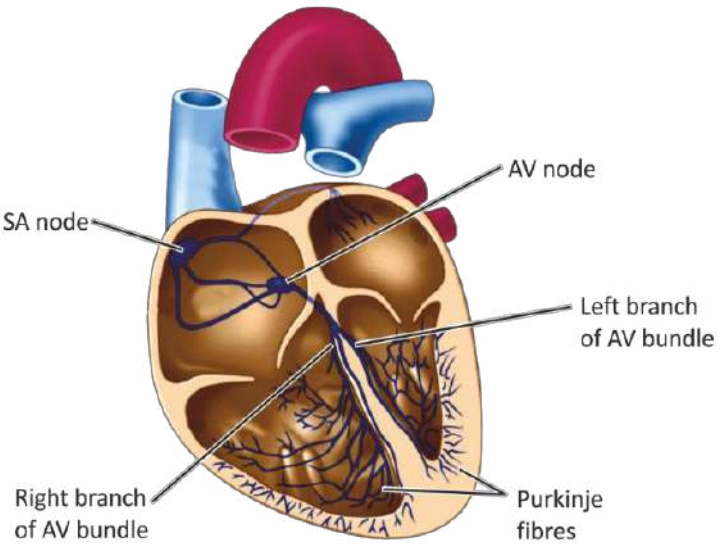


Figure 11.4: Pacemaker and its connections

If there is some block in the flow of the electrical impulses, or if the impulses initiated by SA node are weak; it may delay the rhythmicity of heartbeat or stop it. In such patients of weak SA node, **artificial pacemaker** is used. It is a battery- operated device that is surgically transplanted near the AV node. It emits electrical signals that trigger normal heartbeats.

Rate of Heartbeat

In an adult, about 8,000 litres of blood move through 96,000 km of blood vessels every day.

The heart of an average adult beats about 70 times per minute. It pumps the entire blood volume (about 5 litres) every minute. The normal speed of heartbeat is made and maintained by pacemaker and AV node. Brain also exerts some influence on heart rate. For example, during fever and exercise, the control centre in brain sends nerve signals to both the pacemaker and the AV node, making them to increase the heart rate. It is to cope with the situation. In contrast, when we are asleep or at rest, the brain's control centre slows down the activity of pacemaker and AV node.

Electrocardiogram

The recording of electrical potentials, generated by the currents of cardiac impulses, is known as electrocardiogram (ECG). When cardiac impulse passes over the surface of heart, a minute electrical current is generated. This current spreads into the tissues surrounding heart. This minute electrical current also travels to the surface of body. In ECG, the electrical potentials generated by this current are measured and recorded. For this purpose, electrodes are placed on skin on the opposite sides of heart. The electrodes are attached to a machine called **electrocardiograph** that records electrical potentials generated by this current. ECG helps to diagnose the abnormalities in conduction system of heart. ECG shows the following waves of electrical impulses produced at specific events of cardiac cycle. (Figure 11.5).

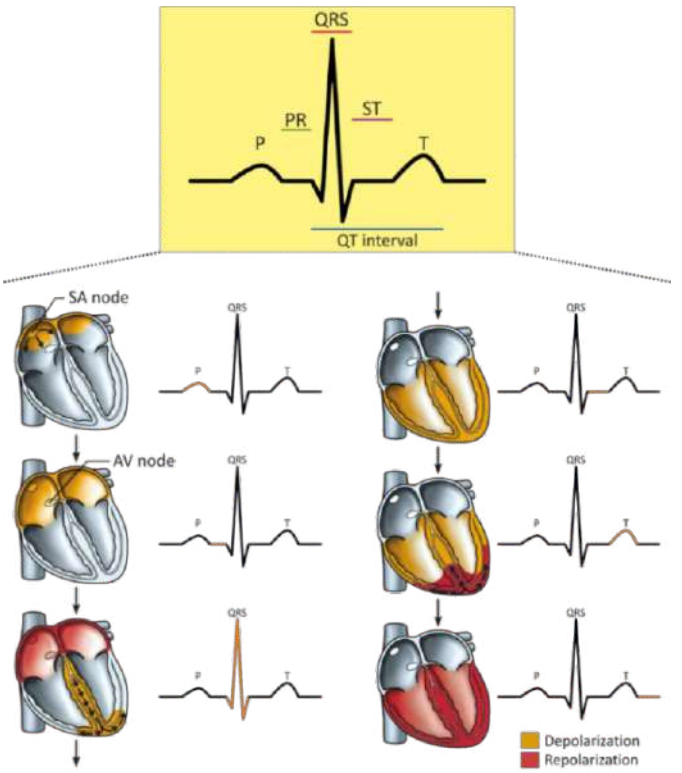


Figure 11.5: ECG reading of a single heartbeat

P wave: It shows beginning of atrial depolarization, initiated by SA node. It causes atrial contraction. Irregular or absent P waves may indicate arrhythmia (lack of rhythmicity).

PR segment: It shows the completion of atrial depolarization. It is usually 0.12 to 0.20 seconds. A prolonged PR indicates a first-degree heart block.

QRS: It shows the beginning of depolarization of ventricles. Atrial re-polarization also occurs during this phase. Abnormalities in the QRS complex may indicate bundle branch block, ventricular tachycardia (faster rate of contraction), or other ventricular abnormalities.

Some abnormal babies may have blueness (cyanosis) of skin. They are called blue babies. It is due to the mixing of oxygenated and deoxygenated blood between two atria. Mixed blood is supplied to the body of new born babies resulting in blueness of skin. Cyanosis results due to the failure of **interatrial foramen** to close, during development. Interatrial foramen is a temporary opening in the embryonic heart between right and left atria. Normally, it is closed during development. Cyanosis may also happen due to failure of **ductus arteriosus** to fully constrict, during development. Ductus arteriosus is a temporary channel between the embryonic pulmonary artery and aorta. Normally, it constricts during development.

ST segment: It shows the completion of depolarization of ventricles. It can be depressed in ischemia (decreased flow of blood and oxygen to heart muscles) and elevated in myocardial infarction. This segment ordinarily lasts about 0.08 second.

T wave: It represents the beginning of repolarization of ventricles. T wave abnormalities may indicate electrolyte disturbance. The hyper-acute T wave shows the earliest findings of acute myocardial infarction.

QT interval: The QT interval is from the beginning of the QRS complex to the end of the T wave. A normal QT interval is usually about 0.40 seconds.

11.2- Blood Vessels

Arteries, veins, and capillaries are the main blood vessels in human circulatory system.

1. Arteries

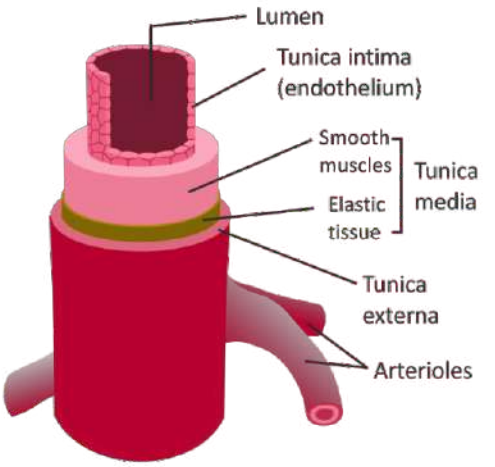


Figure 11.6: Structure of artery

Arteries are the blood vessels which carry blood away from heart to different parts of body. All arteries carry oxygenated blood, except pulmonary arteries. The central core of artery is **lumen**. The walls of arteries are made up of three layers. Outer layer i.e., **tunica externa** or adventitia is made of connective and elastic tissue. Middle layer i.e., **tunica media** is made of thick muscular tissue and elastic fibres. Inner layer i.e., **tunica intima** is made of thin layer of endothelial cells. Middle layer is important and it can withstand higher blood pressure during ventricular systole. Arteries divide into smaller vessels called **arterioles**. Arterioles divide repeatedly until they form a dense network of very fine branches i.e., capillaries.

2. Capillaries

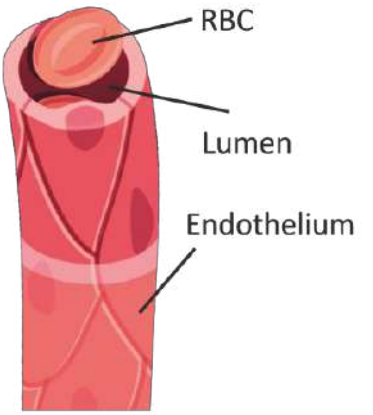


Figure 11.7: Structure of capillary

These vessels are formed by the division of arterioles. Capillaries join to form venules. Capillaries penetrate all tissues and have approach to the cellular level. The walls of capillaries are made of a single layer of **endothelial** cells. The internal diameter of a capillary is about 8 micrometres. Capillaries are the sites where materials are exchanged between blood and body tissues by diffusion or active transport. Water and diffusible substances can pass through capillary walls. Materials pass through the endothelial cells or through the intercellular spaces of capillary wall. Some materials are also taken up by capillary wall cells by endocytosis. The capillary wall cells then pass these materials to the other side by exocytosis.

No cell of the body is more than 100 micrometres away from a capillary. Capillaries are so narrow that RBCs must pass through them in single line. It is estimated that the total length of capillaries in an adult human is over 80, 600 kilometres, enough to encircle the globe twice!

The pressure within capillaries causes a continuous leakage of fluid from the blood plasma into tissues. This fluid, known as **interstitial fluid** consists of water with dissolved nutrients, hormones, gases, wastes and small proteins. Large proteins, RBCs and platelets remain within capillaries. But some WBCs can squeeze out through the intercellular spaces of capillary wall.

3. Veins

These blood vessels carry blood from different parts of the body towards heart. All veins carry deoxygenated blood, except pulmonary veins. The wall of veins has same three layers as are present in arteries. The outer layer i.e., **tunica externa (adventitia)** is made of connective and elastic tissue. The middle layer i.e., **tunica media** is relatively thin and only slightly muscular, with few elastic fibres. The inner layer i.e., **tunica intima** is made of thin layer of endothelial cells.

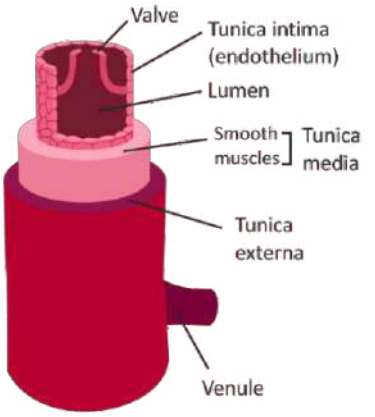


Figure 11.8: Structure of vein

The middle layer of veins is relatively thinner than that of arteries because veins do not have to withstand high blood pressure. An empty artery is still a hollow tube but an empty vein collapses like an empty balloon. **Semilunar valves** are present in veins to prevent the back flow of blood, as it is moving towards heart. The pressure generated by the contraction of surrounding muscles presses veins and assists in the return of blood towards heart.

Smaller veins join to form larger veins and ultimately from vena cavae (inferior vena cava and superior vena cava), which pour blood into the right atrium of heart. Pulmonary veins from lungs empty in left atrium.

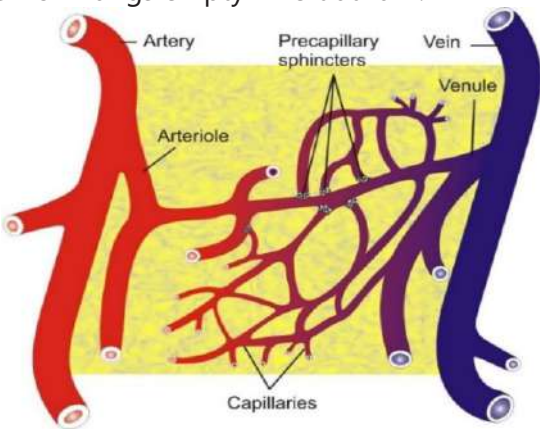


Figure 11.9: Relationship of arterioles, capillaries & venules

Regulation of Blood Flow in Capillaries

The amount of blood flowing in capillaries is controlled by constricting or dilating the capillaries. Nervous stimulation can constrict capillaries and certain chemicals such as histamine can dilate them. Some capillaries are connected with arterioles and venules through loops of other capillaries. The entry of each loop is guarded by a ring of muscles called a **pre-capillary sphincter**. These sphincters regulate the amount of blood flowing through capillaries.

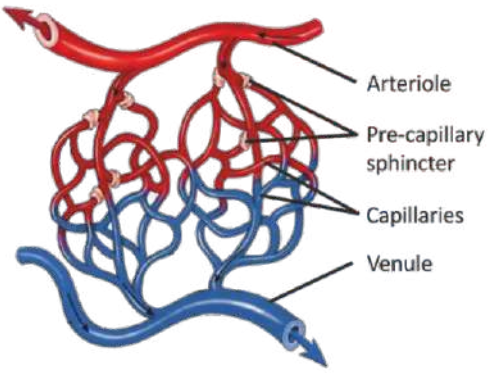


Figure 11.10: Pre-capillary sphincters

Vasoconstriction and Vasodilation inArterioles

In the walls of arterioles, there are more circular muscles than elastic tissue. The contraction of the circular muscles of arterioles is under the control of nervous and endocrine systems. When these muscles contract, arterioles are constricted. It is called **vasoconstriction** and it reduces the flow of blood in arterioles. When these muscles are relaxed, arterioles are dilated. It is called **vasodilation** and it increases blood flow in them.

Vasoconstriction and vasodilation happen in response to changes in metabolic activity of tissues. For example, when metabolic activity in a tissue rises, oxygen decreases and carbon dioxide increases in its interstitial fluid. In its response, the circular muscles of the arterioles in that tissue relax (vasodilation). It increases blood flow in these arterioles and also in capillaries. The increased blood flow supplies more oxygen and removes more carbon dioxide. Similarly, decreased metabolic activity causes vasoconstriction od arterioles.

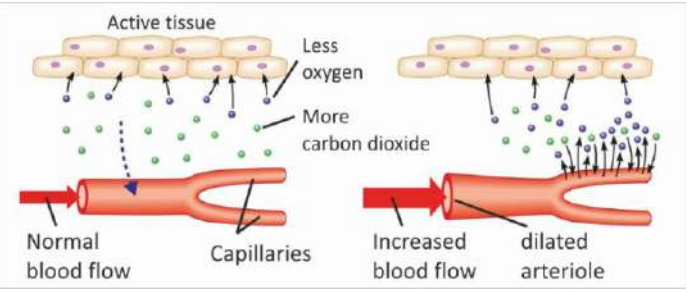


Figure 11.11: Vasodilation

Rate of Blood Flow

The velocity of blood flow is different in different vessels. It is highest in aorta (450-500 mm/sec) and tends to fall along the network of arteries, arterioles and becomes lowest in capillaries (01 mm/sec). It rises again in venules, veins and vena

cavae (250-300 mm/sec). These changes in the velocity of blood result from changes in the total cross section of the vessel system.

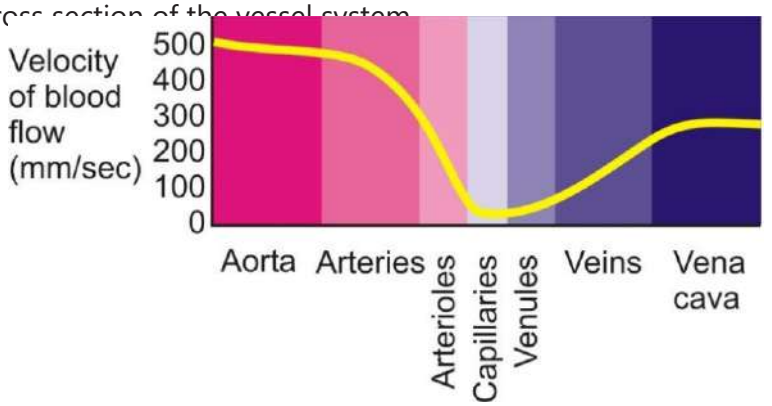


Figure 11.12: Velocity of blood, moving in different vessels

Circulatory Pathways

In humans (and in all mammals and birds), blood circulates throughout body in two main pathways. These are called pulmonary circulation (to and from lungs) and systemic circulation (to and from the other body parts).

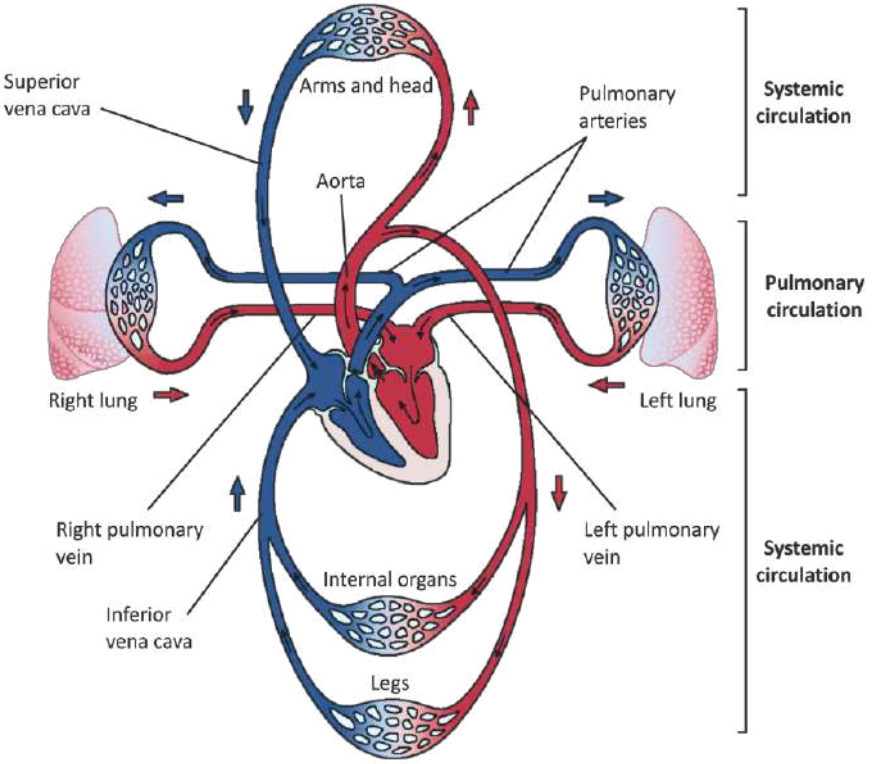


Figure 11.13: Pulmonary and systemic circulations

Pulmonary Circulation

Pulmonary circulation supplies deoxygenated blood to lungs and returns oxygenated blood to heart. A big artery i.e., pulmonary trunk carries deoxygenated blood from the right ventricle of heart. Pulmonary trunk divides into right and left pulmonary arteries, which carry deoxygenated blood to the right and left lungs. Inside each lung, the pulmonary artery divides and makes pulmonary arterioles and lung capillaries. In lung capillaries, blood is oxygenated. Lung capillaries join to form pulmonary venules, which join to form pulmonary vein. Left and right pulmonary veins from lungs open in left atrium.

SystemicCirculation

The systemic circulation supplies oxygenated blood to all the cells, tissues, and organs of the body (except lungs) and returns deoxygenated blood to heart. It consists of the following components:

1. Coronary Circulation

The heart walls are supplied with blood through a small portion of the systemic circulation. Two **coronary arteries** i.e., right and left coronary arteries arise from aorta, near its origin. These arteries divide into many smaller arteries, arterioles and then into capillaries. After supplying oxygenated blood to heart muscles, the capillaries unite to form venules which make many **coronary veins** The coronary veins join to form a **coronary sinus** which opens in right atrium. Small coronary veins drain directly into right atrium

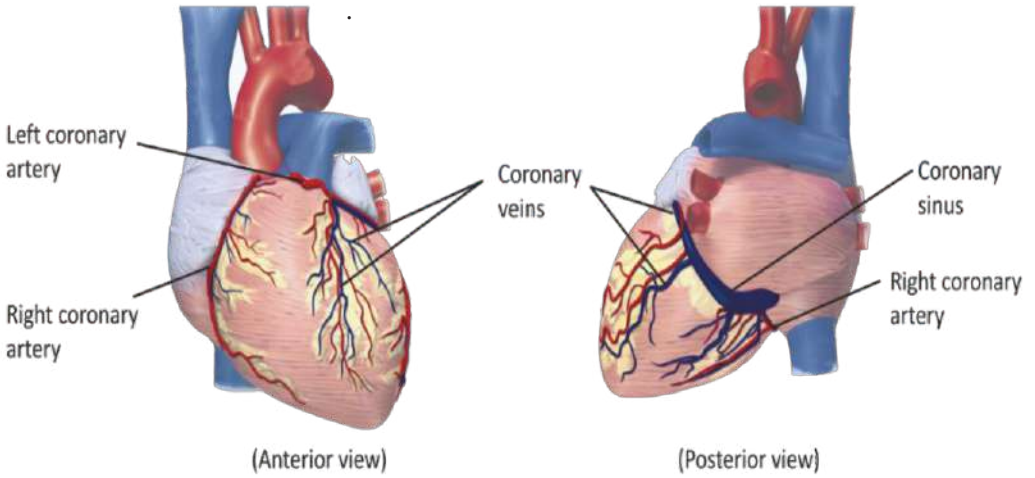


Figure 11.14: Coronary circulation

2. Hepatic Portal Circulation

A portal system is a circulation in which veins end in capillaries. In hepatic portal system, a large **hepatic portal vein** collects blood from spleen and alimentary canal and take it to liver. The blood from liver is taken to heart through **hepatic veins**.

The blood that comes from alimentary canal to liver contains substances that are absorbed from small intestine. These substances pass through liver before going to heart. Liver removes harmful substances from blood and absorbs nutrients for storage before sending this blood to heart. Hepatic portal system extends from the lower portion of oesophagus to the upper part of anal canal.

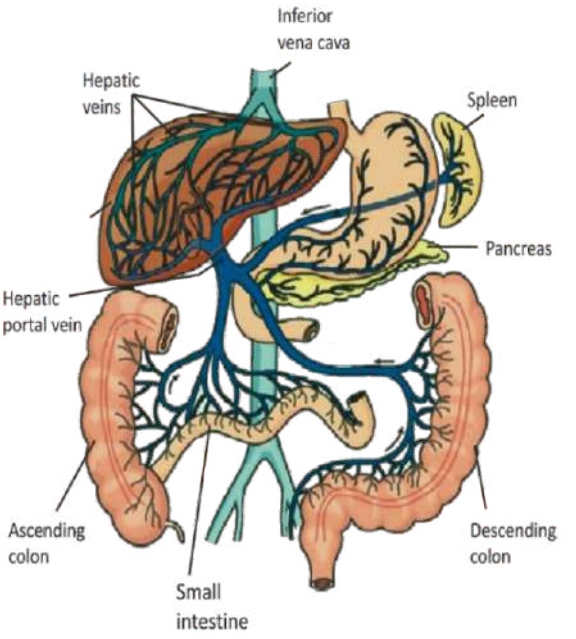


Figure 11.15: Hepatic portal system

3. Renal Circulation

It is another important component of the systemic circulation. Right and left renal arteries carry oxygenated blood to the right and left kidneys. Inside the kidney, each renal artery divides repeatedly to make smaller arteries. The smaller arteries branch into several **afferent arterioles**, which supply blood to nephrons (units of kidney). Each afferent arteriole divides to make the capillaries of **glomeruli**.

The capillaries of glomeruli unite to make **efferent arteriole**, which divides to make two sets of capillaries i.e., (i) **peri-tubular capillaries** (around nephron tubule in cortical portion of kidney), and (ii) **vasa recta** (around nephron tubule in the medulla of kidney). These capillaries unite to form venules that converge and make smaller veins. The smaller veins unit to form a renal vein.

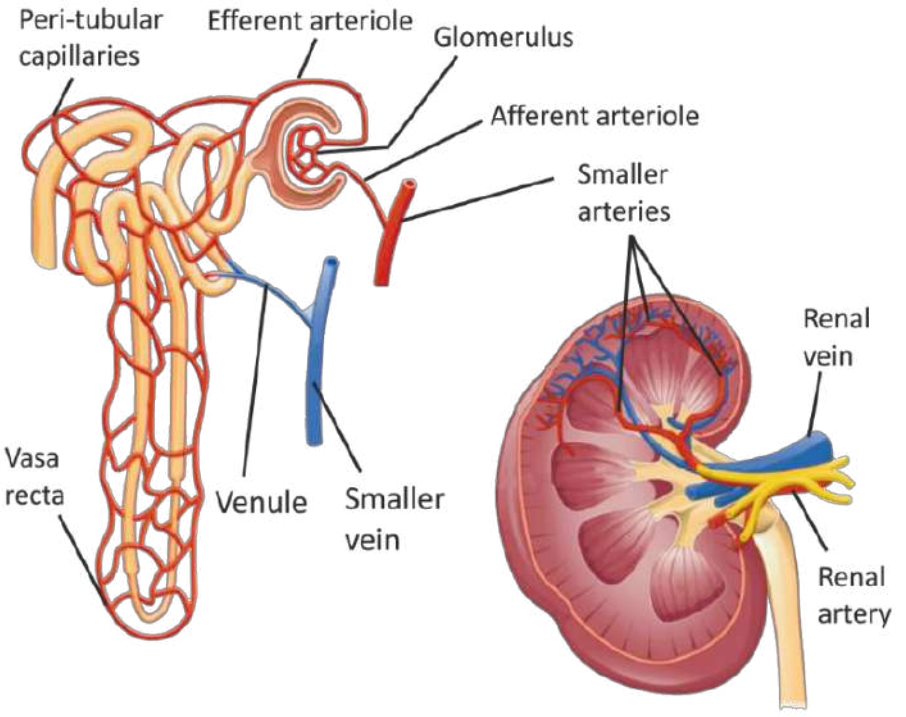


Figure 11.16: Renal portal system

11.3- Blood Pressure

Blood pressure is the measure of force exerted by blood against the inner walls of blood vessels. This force keeps blood flowing from heart to the entire capillary network in body. Although such a pressure occurs throughout the vascular system, the term blood pressure most commonly refers to **systemic arterial blood pressure** Blood pressure is highest in aorta and then gradually reduces in systemic arteries. The walls of arteries are elastic. The flow of blood creates rhythmical throbbing of arteries, which is called as **pulse.**

Arterial blood pressure rises and falls corresponding to the phases of cardiac cycle. When ventricles contract (ventricular systole), heart forces blood into pulmonary arteries and aorta. As a result, the pressure in these arteries rises sharply. The maximum pressure during ventricular systole is called **systolic pressure** Systolic pressure in a normal young adult is **120 mm Hg**. When ventricles relax (diastole), the arterial pressure drops. The lowest pressure that remains in arteries before the next ventricular contraction is called **diastolic pressure** Diastolic pressure in a normal young adult is **75-85 mm Hg**.

Conventionally, the readings of blood pressure are expressed as 120/80. The instrument sphygmomanometer is used for the manual measurement of systolic and diastolic blood pressures. In this instrument, rise and fall in mercury column shows the readings of blood pressure.

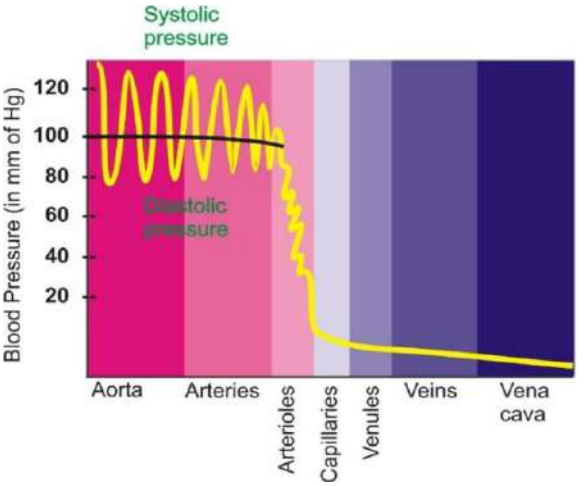


Figure 11.17: Systolic & diastolic blood pressures

Regulation of Blood Pressure

Pressure receptors, known as baroreceptors, are present in carotid arteries (arteries that supply blood to the head region and brain) and aortic arch (portion of artery that bends between the ascending and descending aorta). When blood pressure falls, baroreceptors activate sensory neurons that send information to brain. The control centre in brain reacts by increasing the rate and force of contraction of heart, and by causing vasoconstriction in arterioles. Both these changes restore blood pressure to normal.

The long-term regulation of blood pressure is done through hormones. Certain hormones regulate the volume of blood by effecting the reabsorption of water and salt in kidneys. When there is a decrease in blood volume and blood pressure, special receptors present in brain create thirst. They also stimulate posterior pituitary gland to secrete **antidiuretic hormone (ADH)**. ADH stimulates kidneys to retain more water in blood, excreting less in urine. It restores the blood volume and ultimately blood pressure. ADH also constricts arterioles, which raises arterial blood pressure.

The walls of right atrium contain endocrine cells that secrete **atrial natriuretic hormone (ANH)**. When there is stretching of the atrium by an increased blood volume, the right atrium secretes ANH. It speeds up the excretion of salts and water through urine, which lowers the blood volume and pressure.

11.4- Cardiovascular Disorders

Cardiovascular disorders are the leading cause of death in developed and developing countries. These involve the disorders of blood vessels and heart. Atherosclerosis and arteriosclerosis are the major contributors to cardiovascular disorders.

Atherosclerosis means ~~–d~~eposition within arteries||. Various materials may accumulate in arteries e.g., fatty materials, abnormal amounts of smooth muscle cells, cholesterol, fibrin, and cellular debris of various kinds. All these build-ups impair the

proper functioning of arteries. The accumulation of cholesterol is thought to be the prime contributor to atherosclerosis. Atherosclerosis can lead to heart attacks, because it causes the narrowing of arteries and increases the risk of the formation of thrombus.

Arteriosclerosis means ―hardening of arterial walls‖. It occurs when calcium is deposited in arterial walls. The blood flow through these arteries is restricted and arteries cannot expand normally. This forces the heart to work harder. Severe atherosclerosis usually leads to arteriosclerosis.

Various diagnostic tests are performed on cardiovascular patients to locate the exact problem and to measure the severity of disease. The important tests are ECG and angiography. You have learnt about the readings of ECG, and here you would go through the basic learning of angiography.

Angiography

Coronary angiography is an X-ray examination of blood vessels or chambers of heart. In order to create the X-ray pictures, a physician guides a small tube-like device called **catheter** through the large arteries of body. When the tip of catheter reaches the opening of coronary arteries, a special fluid (called a **contrast medium** or dye) is injected in catheter. This fluid is visible in X-ray machine. Pictures (**angiograms**) of fluid in coronary artery are obtained. If clots are present in the lumen of a coronary artery, the artery appears narrow.

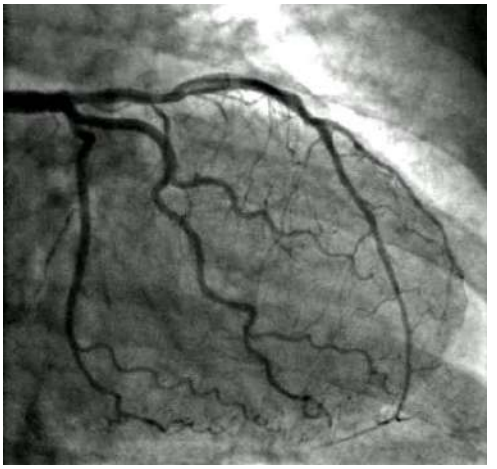


Figure 11.18: An angiogram, showing blood flow in coronary arteries

By changing the **diagnostic catheter** to a **guiding catheter**, physicians can also pass an instrument into coronary artery through the catheter. The most commonly used instruments are guide wires and balloon dilation catheters (see angioplasty).

Thrombosis

Thrombosis is the formation of thrombus. Thrombus is a solid mass or plug of blood constituents (clot) in a blood vessel. This mass may block (wholly or only in part) the vessel. Thrombus formation may be due to; (i) irritation or infection of lining of blood vessels, (ii) reduced rate of blood flow, due to long periods of inactivity, or (iii) pneumonia, tuberculosis, emphysema etc.

Formation of thrombus in a blood vessel and then its carriage to any other location is called **thromboembolism**.

Thrombosis blocks the blood flow to organs. A thrombosis in coronary arteries causes heart attack. Similarly, a thrombus in the vessels of brain causes stroke. A thrombus may be dislodged and carried to some other locations in the circulatory system. Such a thrombus is called **embolus**.

Heart Problems and Treatments

We know that coronary arteries supply oxygen and nutrients to cardiac muscles. If blood flow is blocked in coronary arteries, it results in insufficient supply of blood to one or more parts of cardiac muscle. If heart muscles die due to no supply of oxygen and nutrients, the condition is known as **myocardial infarction** (heart attack).

Heart disease and coronary artery disease are the leading causes of death in developed countries.

Blockage of coronary arteries is usually due to gradual build-up of lipids (especially **cholesterol**) in the inner wall of coronary artery. If such conditions persist, chest pain, called **angina pectoris**, can result during periods of stress or physical exertion. Angina indicates that oxygen demands are greater than its delivery and a heart attack may occur in future.

Recovery from a heart attack is possible if the damaged portion of heart is small enough that the other blood vessels in heart can enlarge their capacity and resupply the damaged tissues.

If lifestyle changes and medication haven't relieved the symptoms or if the narrowed coronary arteries are at imminent risk of a heart attack, coronary bypass surgery or angioplasty is performed.

Coronary Bypass Surgery

The open or beating-heart surgery is done when heart is still beating.

It is one of the most common and effective procedures to compensate the blockage of blood to cardiac muscles. In this surgery, surgeon takes a healthy blood vessel from leg, arm, chest or abdomen of the patient. He attaches the ends of blood vessel above and below the blocked coronary artery. So, blood is bypassed around the damaged or blocked area.

Coronary bypass surgery doesn't cure the underlying disease process i.e., atherosclerosis or coronary artery disease. Lifestyle changes — especially smoking cessation

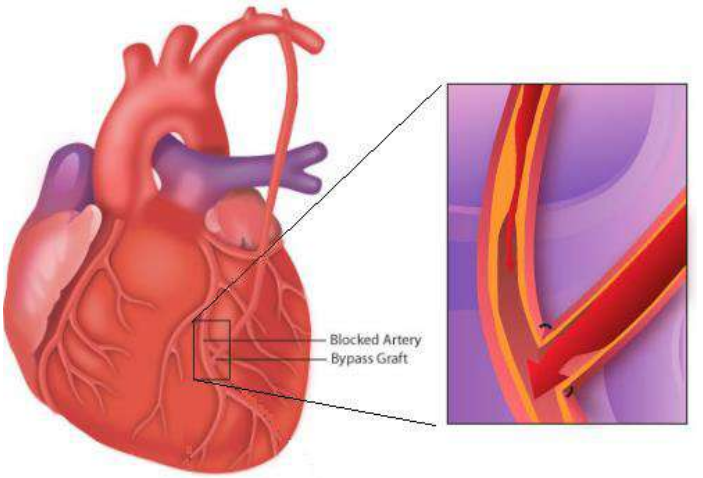


Figure 11.19: Coronary bypass

— are crucial to reduce the chance of future blockages and heart attacks, even after successful bypass surgery. In addition, patients need to make other lifestyle changes, such as reducing certain types of fat in diet, increasing physical activity, and controlling high blood pressure, diabetes and other risk factors for heart disease.

Angioplasty and Stenting

Angioplasty is a procedure that opens a blocked or narrowed artery. During an angioplasty, a small wire called a catheter, under x-ray guidance, is passed through the narrowed coronary artery. A small sausage-shaped balloon is then advanced over the wire into the narrowed section of artery. The balloon is then inflated to dilate the narrowed section of the artery. Once the artery is dilated, a small amount of dye is injected to confirm the successful dilatation.

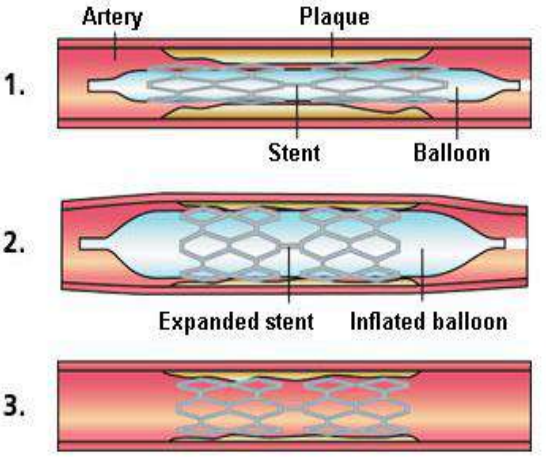


Figure 11.20: Angioplasty and stenting

Stenting may also be done during angioplasty. A **stent** is an expandable stainless steel mesh tube, mounted on a balloon catheter. When the stent/balloon is positioned within the narrowed artery, the balloon is inflated. The inflated balloon expands the stent and the artery. The balloon is removed and the stent remains in place. The stent supports the artery walls and keep the artery open and dilated.

Hypertension

A chronic (long lasting) elevation in blood pressure is called hypertension. It occurs when blood pressure consistently remains above 140/90. Any abnormality in nervous or hormonal mechanisms of blood pressure regulation may cause hypertension. Other causes of hypertension include stress, obesity, high salt intake, and smoking. There may also be hereditary reasons of hypertension.

Whenever blood pressure is chronically elevated, there is an increased chance of the rupture of blood vessels. When this occurs in brain, it is called **brain haemorrhage**. It damages the delicate structure of brain. Hypertension also weakens cardiac muscles. If hypertension is prolonged, heart is unable to pump effectively and blood flow cannot be maintained to meet needs of tissues. In such conditions, blood may be retained in heart and lungs. It is called **congestive heart failure**. Hypertension can also damage the nephrons of kidneys. It leads to further retention of salts and water in blood and therefore further hypertension.

Chest pain, including angina, does not occur during congestive heart failure.

11.5- LYMPHATIC SYSTEM OF HUMAN

In human, in addition to the blood circulatory system, there is another system responsible for the transport of materials. It also returns the materials from tissues to blood. This system is called lymphatic system. It consists of lymph vessels, lymphoid masses, lymph nodes and lymph-the fluid which flows in the system.

Lymph Vesselsand Lymph

Recalling:
The branches of lymph capillaries in villi, are called lacteals. Fatty acids and glycerol are absorbed into the epithelial cells of villi where they form triglycerides. The triglycerides are coated with proteins to form chylomicrons, which enter the lacteals of villi.

Lymphatic system begins with small vessels called **lymph capillaries**, which have blind endings in extracellular fluid (interstitial fluid). Pressure of the interstitial fluid forces it to enter into lymph capillaries. Lymph capillaries are more permeable than blood capillaries. So, larger molecules can also enter lymph capillaries. When interstitial fluid enters lymph capillaries, it is called **lymph**. Lymph capillaries join to form larger **lymphatic vessels** (or lymphatics or lymph vessels). Lymph vessels join to form larger lymph ducts. There are two main lymph ducts i.e., **right lymphatic duct** and **thoracic duct** These vessels open into right and left subclavian veins (veins that drain blood from the arms and shoulders to the heart), respectively. The flow of lymph is always from body tissues towards thoracic duct. It is maintained by the activity of skeletal muscles, movement of viscera and breathing movements. The valves present in lymph vessels prevent the back flow of lymph.

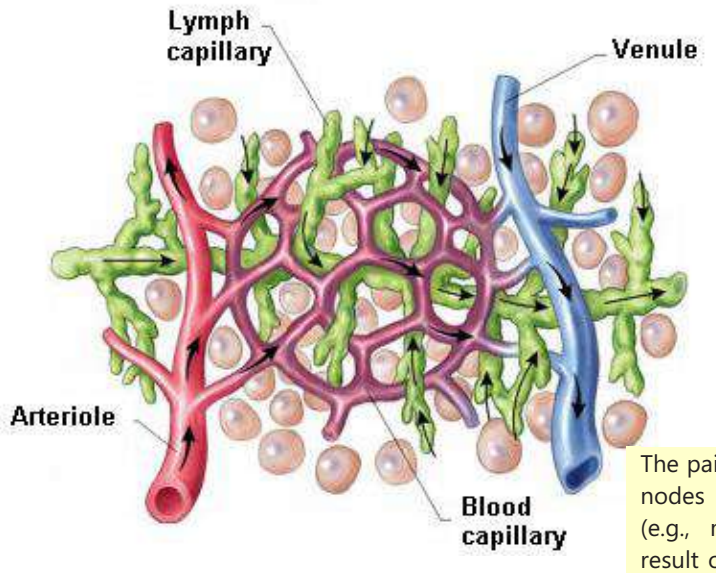


Figure 11.21: Formation of lymph

The painful swelling of lymph nodes in certain diseases (e.g., mumps) is largely a result of the accumulation of dead lymphocytes and macrophages.

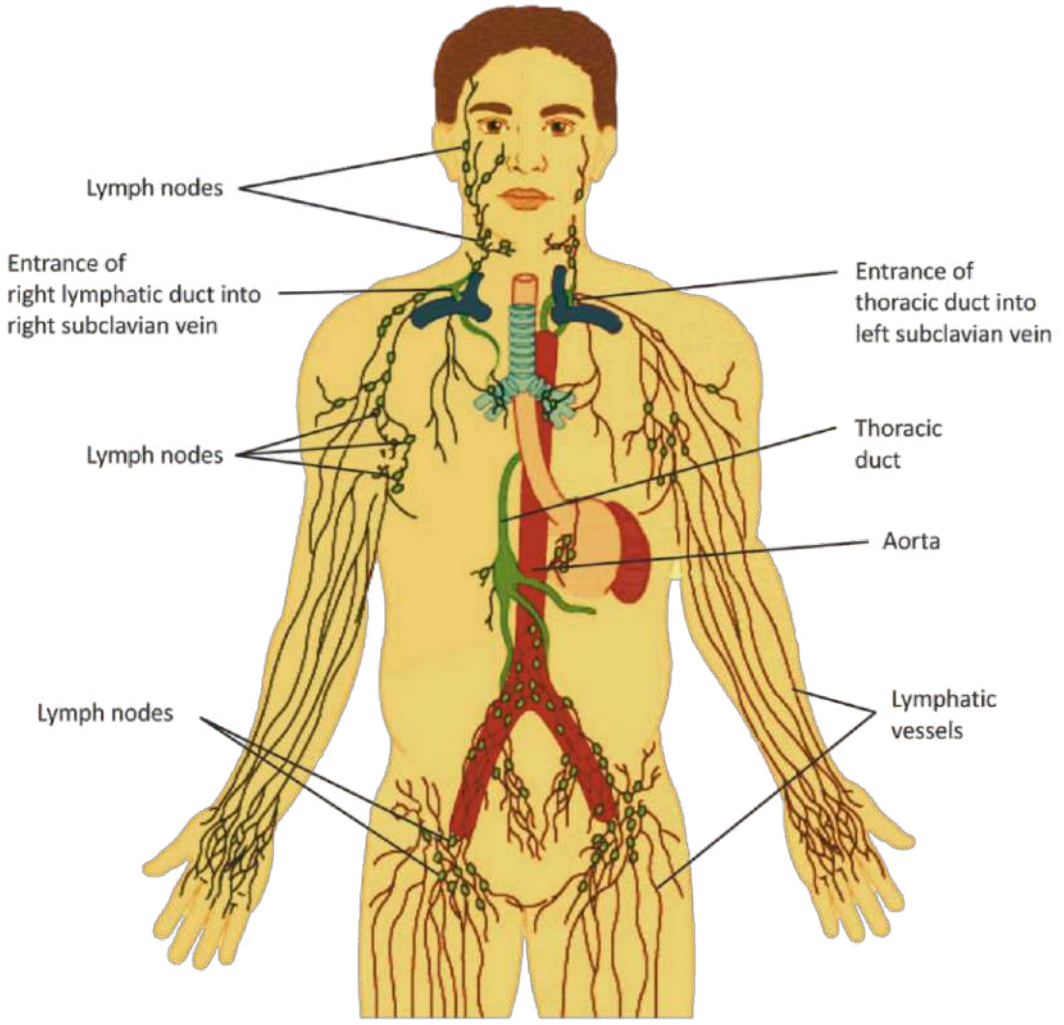


Figure 11.22: Human lymphatic system

Functions of the Lymphatic System

Lymphatic system returns the excess fluid and dissolved proteins and other substances to blood. In an average person, about three litres more fluid leaves blood capillaries daily. But it is absorbed by lymphatic capillaries and returned to bloodstream, before the blood enters heart. Lymphatic system also helps to defend body against foreign invaders. Lymph nodes filter lymph. They have lymphocytes and macrophages that destroy bacteria and viruses present in lymph. Spleen filters blood through its macrophages and lymphocytes that destroy foreign particles and aged RBCs. Spleen also functions to store RBCs.

Lymph Nodes and Lymphoid Masses

At certain spots, the lymph vessels have masses of connective tissue where lymphocytes are present. These are **lymph nodes**. Several afferent lymph vessels enter a lymph node and the lymph is drained by a single efferent lymph vessel. Lymph nodes are present in the neck region, axilla and groin areas of man. In addition to lymph nodes, several **lymphoid masses** are present in different areas e.g., in the mucosa and submucosa of alimentary canal. The larger lymphoid masses are spleen, thymus, tonsils and adenoids. These produce lymphocytes.

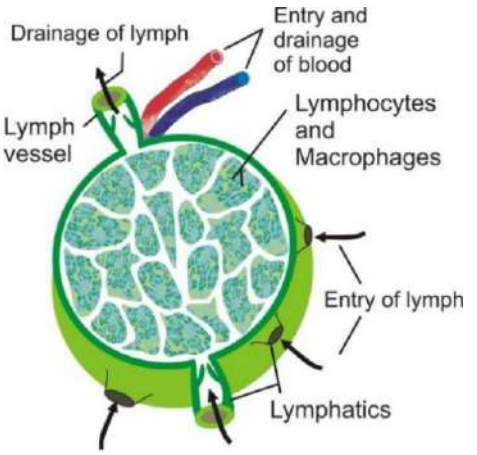


Figure 11.23: A lymph node

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. Compared to vein, an artery;
   (a) Has thinner walls (b) Is located more superficially
   (c) Carries blood away from an organ (d) Has no internal valves
2. Bicuspid valve guards the opening between;
   (a) Stomach and intestine (b) Pulmonary vein and left atrium
   (c) Right atrium and right ventricle (d) Left atrium and left ventricle
3. What is the state of bicuspid and tricuspid valves at the end of the first heart sound?
   (a) Bicuspid is closed, tricuspid is open (b) Bicuspid is open, tricuspid is closed
   (c) Both are open (d) Both are closed
4. By beating at normal speed, our heart pumps how much blood per minute?
   (a) 2 litres (b) 3 litres (c) 5 litres (d) 8 litres
5. Closure of tricuspid and bicuspid valves produces sound;
   (a) —Lubb‖ (b) —Dubb‖
   (c) First Lubb‖ then —Dubb‖ (d) None of these but —murmurs‖

6. SA-node initiates heartbeat in;
   (a) Right atrium only (b) Right atrium and partially left also
   (c) Right and left both (d) Left atrium and partially right also
7. Systolic pressure in young man is;
   (a) 60 mm of Hg (b) 80 mm of Hg (c) 100 mm of Hg (d) 120 mm of Hg
8. Blood pressure is highest in _____ and blood moves most slowly in;
   (a) Veins, capillaries (b) Arteries, capillaries
   (c) Capillaries, arteries (d) Veins, arteries
9. Instead of normal —lub-dubb|| sound, a —lub-hiss, lub-hiss|| sound indicates;
   (a) Blocked coronary artery (b) Damaged pacemaker
   (c) Defective semilunar valve (d) High blood pressure
10. In humans which one is the other system for the transport of materials, than blood circulatory system?
   (a) Lymphatic system (b) Digestive system
   (c) Nervous system (d) Respiratory system

SHORT QUESTIONS

1. What is the main difference between the walls of an artery and a vein?
2. Enlist the four valves present in heart and also state their locations.
3. State the phases of heartbeat.
4. List the principles and uses of Electrocardiogram.
5. Define angiography and angioplasty.
6. What is meant by Purkinje fibres?
7. What do you mean by vasoconstriction and vasodilation?
8. What is the rate of blood flow in different types of blood vessels?
9. State the role of baroreceptors and volume receptors in regulating the blood pressure.
10. Differentiate between thrombus and embolus.

LONG QUESTIONS

1. Describe the structure of the walls of heart and rationalize the thickness of the walls of each chamber.
2. Describe the flow of blood through heart as regulated by the valves.
3. Explain how a heartbeat is initiated and controlled.
4. Describe the detailed structure of arteries, veins and capillaries.
5. Describe the role of precapillary sphincters in regulating the flow of blood through capillaries.
6. Write the components of pulmonary circulation.
7. What are the main components of coronary, hepatic-portal and renal circulation?
8. Define blood pressure and explain systolic and diastolic pressure.

9. Define the term thrombus and differentiate between thrombus and embolus.
10. Identify the factors causing atherosclerosis and arteriosclerosis.
11. Write notes on Angina pectoris, heart attack, and heart failure.
12. Outline the main principles of coronary bypass and angioplasty.
13. Define hypertension and describe the factors that regulate blood pressure and can lead to hypertension and hypotension.
14. List the changes in life styles that can protect man from hypertension and cardiac problems.
15. Describe the structure and role of lymph capillaries, lymph vessels and lymph ducts.

INQUISITIVE QUESTIONS

1. Why is the pressure in the pulmonary circulation lower than in the systemic circulation?
2. Why is it so important for the human heart to develop early and begin functioning within the developing embryo?
3. Justify how vasoconstriction or vasodilation is reflective of emotions.
4. Justify in what way the blood circulatory system is dependent on the lymphatic system.
5. Interpret why the swelling of the lymph nodes is a cause of concern.
6. Trace the path of lymph from a lymph capillary until it is returned to the blood.

Chapter 12

HUMAN SKELETAL & MUSCULAR SYSTEMS

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Describe the structure of bone and compare it with that of cartilage.
- Explain the functions of osteoblasts, osteoclasts and osteocytes.
- Describe three types of joints i.e. fibrous joints, cartilaginous joints and synovial joints and give example of each.
- Describe the disorders of human skeleton (disc-slip, spondylosis, sciatica, arthritis, osteoporosis)
- and their causes.
- Describe the injuries in joints (dislocation and sprain) and their first aid treatment.
- Compare smooth muscles, cardiac muscles and skeletal muscles.
- Describe the ultrastructure of the skeletal muscle.
- Explain the sliding filaments model of muscle contraction.
- Describe the action of antagonistic muscles in the movement of knee joint.
- Explain muscle fatigue, cramps and tetany.
- Differentiate between tetanus and muscle tetany.

Support and movement are fundamental aspects of human biology, enabling us to perform a wide range of activities from basic locomotion to complex taks. This chapter delves into the structure of bones and cartilage, which provide the necessary support framework for the body. We will explore the various tyspes of joints, and examine the unique features of the three types of muscles—skeletal, smooth, and cardiac—that drive motions. The sliding filament model will be discussed to understand muscle contraction at a molecular level. Additionally, we will look at common disorders affecting the skeletal and muscular systems, highlighting their impact on human health and mobility.

12.1- BONES AND CARTILAGE

Bones, cartilage, and other connective tissues make an internal framework called skeleton that provides structural support, protects vital organs, and produces movement and locomotion.

Structure of Bone

Bones are made of connective tissue reinforced with calcium and specialized bone cells. The bone's surface is covered by a tough membrane called **periosteum**. The thick layer under periosteum is made of hard material and is called **compact bone**. It makes up

The broad ends of a bone are called **epiphysis** while the middle part along the length of bone is called **diaphysis** or shaft.

the majority of the bone tissue (Fig. 12.1). The basic structural units of compact bone are called **Haversian systems** A Haversian system is made of;

i. **Lamellae:** These are concentric layers of mineralized extracellular matrix that contains **collagen fibres** and small, needle-shaped crystals of calcium phosphate. The crystals are brittle but rigid, giving bone great strength. Collagen, on the other hand, is flexible but weak. As a result, bone is both strong and flexible.

ii. **Lacunae and Osteocytes:** The lamellae are separated by small spaces called lacunae. **Osteocytes**, which are mature bone cells, are located in the lacunae. Osteocytes are connected to each other and to the Haversian canal by small channels called **canaliculi**

iii. **Haversian canal:** The concentric layers of lamellae surround a central canal called the Haversian canal. It contains blood vessels, nerves, and lymphatic vessels.

In addition to these structures, there are small channels that run perpendicular to the Haversian canals and connect them with each other and with the periosteum. They also contain blood vessels, nerves, and lymphatic vessels. Collagen fibres anchor the periosteum to the underlying bone tissue, providing additional strength and stability to the bone.

Beneath the compact bone there is **spongy bone** (Fig. 12.1). It has a latticework structure consisting of bony spikes that make it light and strong.

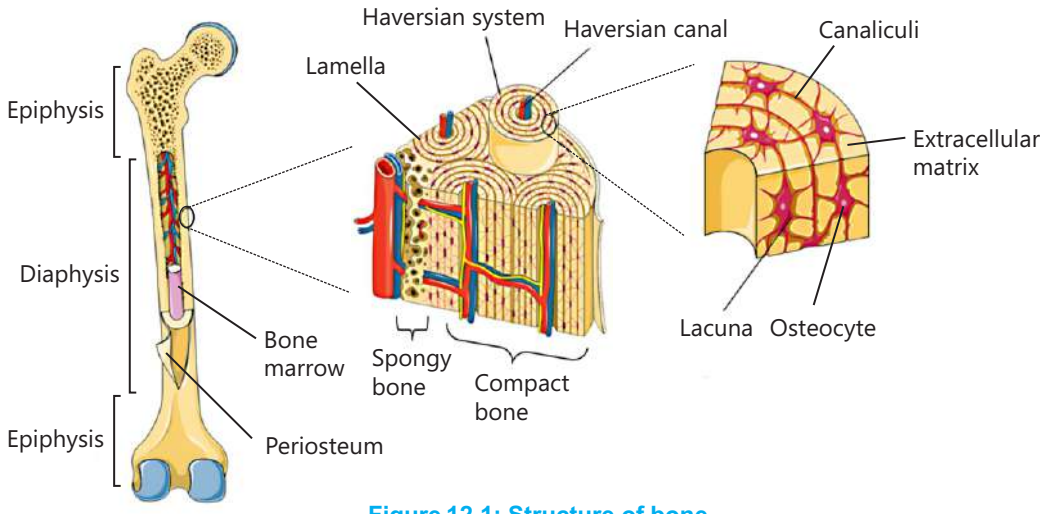


Figure 12.1: Structure of bone

Bone Marrow

Many bones also contain a soft tissue called bone marrow, which can be either red or yellow. Red bone marrow is found in spongy bone, the ends of long bones, ribs, vertebrae, the sternum, and the pelvis. It produces red blood cells, platelets, and

white blood cells. Yellow bone marrow fills the shafts of long bones. It consists mostly of fat cells and serves as an energy reserve. It can also be converted to red bone marrow and produce blood cells when severe blood loss occurs.

Despite their number and size, bones make up less than 20% of the body's mass.

Bones are not dry, rigid structures, as they appear. They are moist, living tissues.

Types of Bone Cells

There are three types of cells i.e., osteoblasts, osteocytes, and osteoclasts involved in the development, growth and remodelling of bones.

Osteoblasts are bone forming cells that synthesize and secrete unmineralized ground substance. Once the osteoblasts are surrounded by matrix, they become the osteocytes.

Osteocytes are mature bone cells which maintain healthy bone tissue by secreting enzymes and bone mineral content. They also regulate the calcium release from bone tissue to blood. **Osteoclasts** develop from macrophages and are involved in bone resorption, i.e., they break down bone and release calcium and phosphate in blood. The work of osteoclasts is important to the growth and repair of bone.

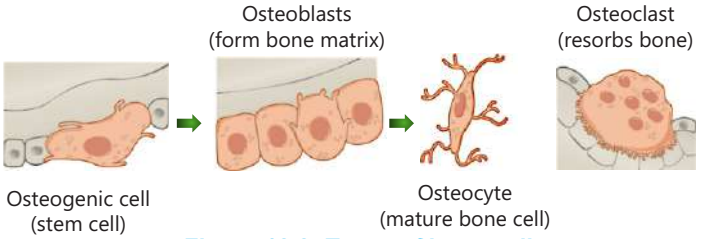


Figure 12.2: Types of bone cells

Bone Development

The process of bone formation is also called **osteogenesis** It begins during embryonic development and continues throughout life, playing a vital role in growth, maintenance, and repair of bones. There are two primary pathways of osteogenesis.

Even after bones have fully formed, osteogenesis continues in the form of bone remodelling. This ongoing process involves the breakdown of old bone by osteoclasts and the formation of new bone by osteoblasts.

1. The formation of long bones e.g., femur and humerus, involves the transition of cartilage into bone. In this process, the center of cartilage begins to harden (calcify), and the chondrocytes (cartilage cells) in this area die, leaving behind cavities. Blood vessels penetrate these cavities and introduce osteoblasts and osteoclasts. Osteoblasts (bone-forming cells) start building bone tissue, replacing the cartilage with new bone. The step by which cartilage is replaced by bone by the deposition of minerals is called **ossification** (Fig. 12.3). Osteoclasts (bone-resorbing cells) break down

the calcified cartilage, making room for more bone tissue to form. As the bone matures, some osteoblasts become trapped within the bone tissue and transform into osteocytes (mature bone cells), which help maintain the bone structure. This process continues until all cartilage is changed to a bone except some cartilage that remains only at the articular (joint) surfaces of the bones.

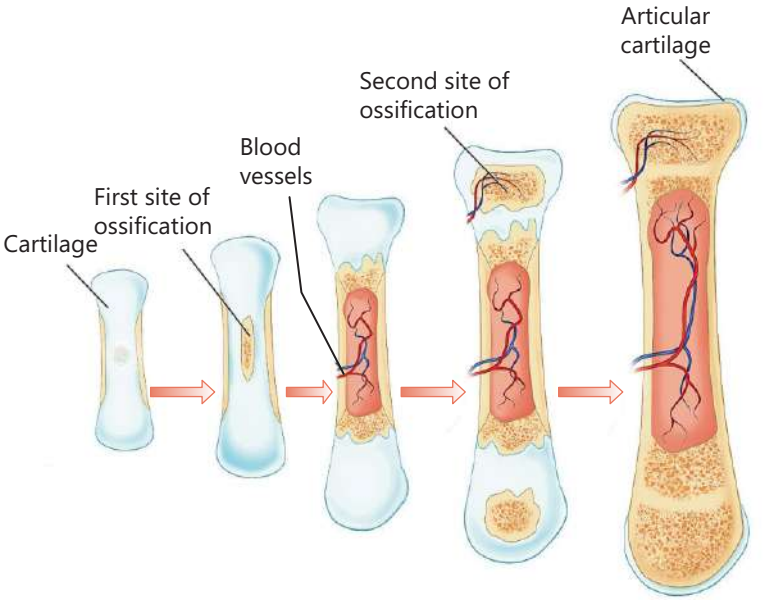


Figure 12.3: Development of bone from cartilage

2. A few bones, e.g., some bones of the skull, develop directly into hard bone without forming cartilage first. In these cases, the osteocytes are initially scattered randomly throughout the embryonic connective tissue but soon fuse into layers and become flat plates of bone.

Structure of Cartilage

As described in the previous paragraph, most of the cartilage of foetus is replaced by bone. However, some cartilage remains throughout life and provides flexibility. For example, at the areas between bones, at the end of nose, in the outer ear, and along the inside of the trachea.

A layer of connective tissue called **perichondrium** surrounds the cartilage. It contains blood vessels, lymphatic vessels, and nerves that supply the cartilage tissue. Inside perichondrium is the **cartilage matrix** which is composed of collagen, elastin, proteoglycans, and other fibres. It gives the tissue its strength, flexibility, and resistance to compression. Unlike other connective tissues, there are no blood vessels inside cartilage matrix. The cells of cartilage are supplied by diffusion. Because of this, it heals very slowly.

The cartilage cells, called **chondrocytes**, are present within small spaces called **lacunae**, which are embedded in cartilage matrix. Chondrocytes are responsible for synthesizing and maintaining the matrix of cartilage (Fig. 12.4).

Cartilage Types

Cartilage can be classified into three types. **Hyaline** cartilage is the most common type and is found in the nose, trachea, and the articulating surfaces of bones in joints. **Fibrocartilage** is found in areas of the body that experience high stress and tension, such as the intervertebral discs and the pubic symphysis. **Elastic cartilage** is found in the external ear and epiglottis.

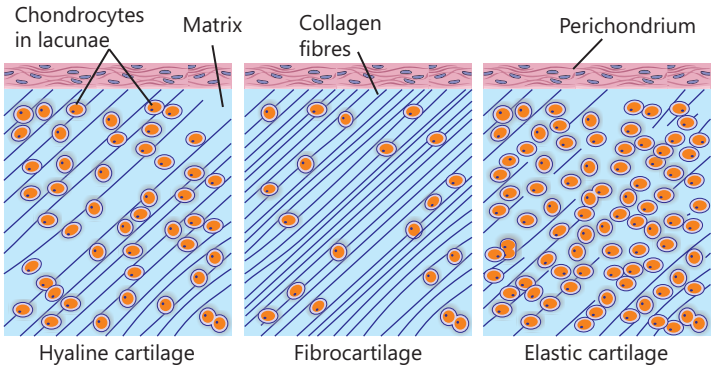


Figure 12.4: Cartilage types

Comparison between Bone and Cartilage

Feature	Bone	Cartilage
External covering	Periosteum	Perichondrium
Cell types	Osteoblast, osteocytes and osteoclasts	Chondrocytes
Extracellular matrix	Contains calcium crystals and collagen fibres	Contains collagen and other fibres
Blood vessels	Present	Absent
Growth & repair	Have the ability to grow and repair themselves throughout life	Has limited ability to repair itself, as it has no direct blood supply

Arrangement of Bones in Skeleton

Human skeletal system consists of 206 bones. Skeleton has two main divisions i.e., axial skeleton and appendicular skeleton (Fig. 12.5).

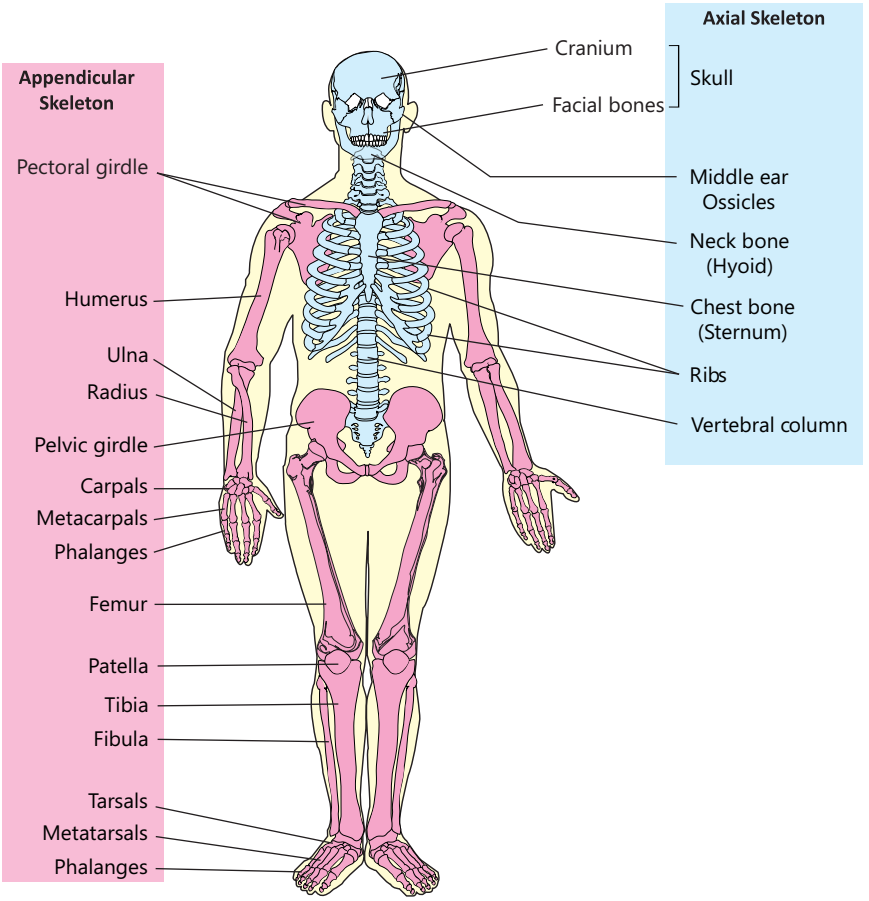


Figure 12.5: Human skeleton

Axial Skeleton

The axial skeleton forms the axis of the body. Its bones support and protect the organs of the head, neck, and chest. It consists of skull, ribs, spine, and sternum.

a- Skull: It consists of the following 22 bones.

- Eight **cranial bones** form cranium (brain box). The 2 paired bones are parietal bones and temporal bone. The 4 unpaired bones are frontal bone, occipital bone, ethmoid bone, and sphenoid bone.
- Fourteen **facial bones** are attached to the cranium. The 6 paired bones are lacrimal, zygomatic, nasal bones, inferior nasal concha, maxilla and palatine. The 2 unpaired bones are mandible (jaw bone) and vomer.

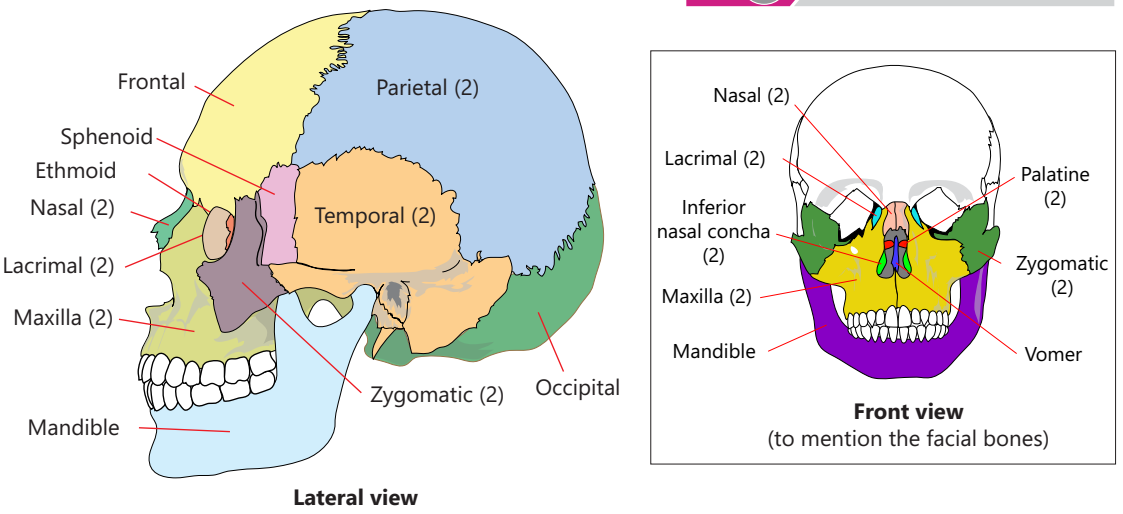


Figure 12.6: Human skull

b- Middle ear: There are 6 bones (3 pairs) in middle ears. These are called ossicles and include malleus, incus and stapes.

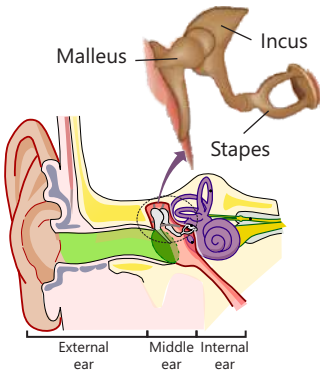


Figure 12.7: Middle ear ossicles

c- Neck bone: Hyoid bone is a small single bone which lies at the base of skull below the tongue. It does not articulate with any other bone of head.

d- Vertebral column: It consists of 33 bones called vertebrae. The vertebrae make five groups:

(i) Seven cervical vertebrae: These are the vertebrae of the neck. The first one is called atlas and the second one is called axis.

(ii) Twelve thoracic vertebrae: These are rib-carrying vertebrae and are found in chest region.

(iii) Five lumbar vertebrae; These are present in abdominal region.

(iv) Five sacral vertebrae; These are five fused vertebrae forming the sacrum. The sacrum articulates with the iliac bones of the hip to form the back of the pelvis.

(v) Four coccygeal vertebrae or coccyx; these vertebrae are fused in the adults. Sacral and coccygeal vertebrae are together called pelvic vertebrae.

e- Rib Cage & Chest bone: The rib cage consists of 24 bones (12 pairs) called ribs and a sternum. The sternum (chest bone) is a long flat bone located in the central part of the chest. The ribs articulate posteriorly with the thoracic vertebrae. On anterior side, 7 pairs of ribs attach directly with the sternum by means of separate costal cartilages. These are called true ribs. The 8^{th}, 9^{th} and 10^{th} pairs attach to the sternum by means of a common costal cartilage and are called false ribs. The last 2 pairs of ribs (11^{th} and 12^{th}) are known as floating ribs, because they do not attach to the sternum.

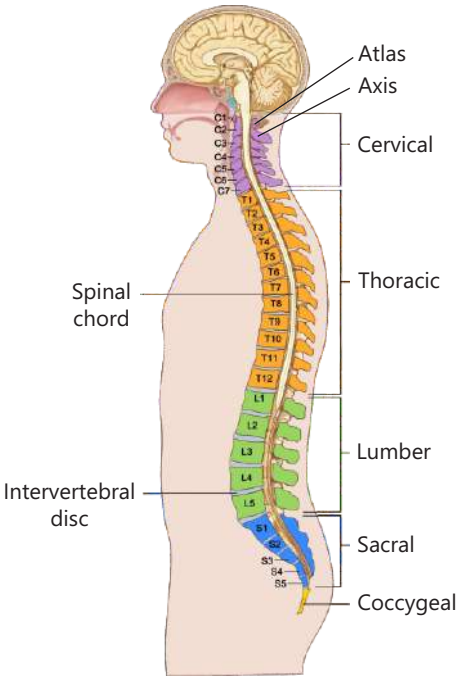


Figure 12.8: Vertebral column

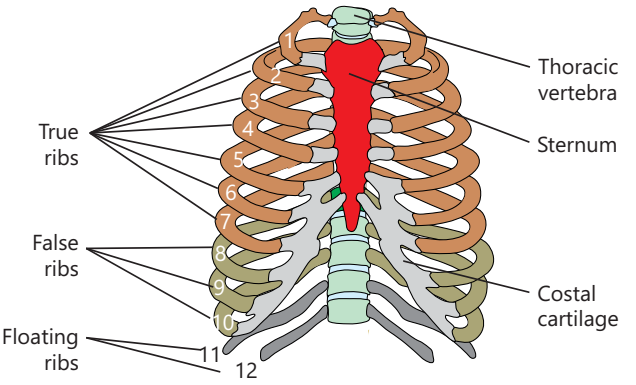


Figure 12.9: Rib cage

Appendicular skeleton

Appendicular skeleton includes the bones present in appendages (arms and legs). These are pectoral girdle, pelvic girdle, forelimbs and hindlimbs.

a- Pectoral girdle: It consists of 2 pairs i.e., a pair of clavicles (collar bones) and a pair of scapulae (shoulder bones). One end of each clavicle articulates with the sternum. The other end articulates with the scapula.

b- Forelimbs: Each forelimb (arm, wrist, hand, fingers) consists of the following 30 bones.

i. One humerus: It is a long bone, the end of which has a spherical head, which fits into the glenoid cavity.

ii. One ulna and one radius: These are long bones. Ulna is on the inner side of arm while radius is on outer side (thumb side). Ulna is slightly bigger than radius.
iii. Eight carpels: There short bones present in two rows and form the wrist. The upper row articulates with the radius and forms the wrist joint.
iv. Five metacarpals: These bones make up the palm of the hand.
v. Fourteen phalanges: Each finger has 3 phalanges while the thumb has 2 phalanges.

c- Pelvic girdle: It is made up of two hip bones. Each hip bone contains 3 bones i.e., ileum, ischium and pubis. In each hip bone, there is a bony socket, called acetabulum that is composed of the fusion of three bones. The two hip bones are joined at the front by the pubic symphysis (a cartilaginous joint that connects the pubic bones at the midline of the body).

d- Hindlimbs: Each hindlimb (leg, ankle, foot, toes) consists of 30 bones.

i. One femur: It is a long thigh bone. Its head fits into the acetabulum of pelvic girdle.
ii. One patella or kneecap: It is embedded in a long tendon which runs over the knee joint.
iii. One tibia and one fibula: Tibia or shin bone is the large bone in the leg. Fibula or outer bone is a thin bone that joins the tibia just below the knee joint and just above the ankle.
iv. Seven tarsals: These are short bones which are tightly attached to form the ankle.
v. Five metatarsals: These bones articulate with the tarsal and phalanges to form the sole of the foot.
vi. Fourteen phalanges: Each toe has 3 phalanges while the big toe comprises 2 phalanges.

Joints

A joint is a place where two bones or bone and cartilage come together. Three major kinds of joints are found in human body i.e., fibrous (immoveable) joints, cartilaginous (slightly moveable) joints and synovial (freely moveable) joints (Figure 12.10-a).

1- Fibrous Joints

In fibrous joints, the bones are directly connected to each other by fibrous connective tissue consisting mainly of collagen. These joints permit no movement of bones. Examples of fibrous joints include:

Sutures that occur only between the immovable bones of the skull.
Joints between the tibia and fibula bones in the lower leg.
Joints between teeth and their sockets in the jawbone.

2- Cartilaginous Joints

In these joints, the bones are connected by a layer of cartilage. Cartilaginous joints allow little movement of the bones. There are two main types of cartilaginous joints:

In some cartilaginous joints, the bones are connected by hyaline cartilage. For example, the joint between the first rib and sternum.

In some cartilaginous joints, the bones are connected by fibrocartilage. For example, pubic symphysis in the pelvic girdle and intervertebral discs.

3- Synovial joints

Synovial joints are the most common type of joint in the human body, and they allow a wide range of movement. A smooth, tough, and elastic hyaline cartilage, called **articular cartilage**, covers the ends of the bones in the joint. It provides a smooth and frictionless surface for movement. A **fibrous capsule** surrounds the synovial joint and helps to hold the bones together. The fibrous capsule is composed of an outer layer of ligaments and an inner lining of synovial membrane, which secretes **synovial fluid**, which lubricates the joint. Strong bands of connective tissue that connect the bones in the joint are call **ligaments**.

There are six main types of synovial joints based on the range of motion.

1- Ball-and-socket joints allow motion in all directions e.g., shoulder and hip joints.

2- Hinge joints allow movement in only one plane, like a door hinge e.g., elbow and knee joints.

3- Pivot joints allow rotational movement around a single axis e.g., joint between the first and second vertebrae of the neck.

4- Ellipsoidal joints allow movement in two planes, but not rotation e.g., joint of wrist with radius.

5- Saddle joints allow movement in two planes because one bone has a concave surface and the other has a convex surface e.g., thumb joint.

6- Gliding joints allow gliding movements between bones e.g., joints between the vertebrae and the joints between the bones in wrist and ankle.

Joint Transplantation

It is a surgical procedure in which a damaged joint is replaced with a healthy natural joint (from donor) or an artificial joint. The most common types of joint transplantation are:

Total joint replacement: In this procedure, the entire damaged joint is replaced with an artificial joint made of metal, plastic, or ceramic.

Partial joint replacement: In this procedure, only the damaged part of the joint is replaced with an artificial component. This is often used in the knee joint.

Allograft transplantation: In this procedure, a healthy joint from a donor is transplanted to replace the damaged joint. This technique is often used in the ankle and knee joints.

Chondrocyte implantation: In this procedure, chondrocytes from patient's own joint are implanted into the damaged joint. This technique is often used in the knee joint.

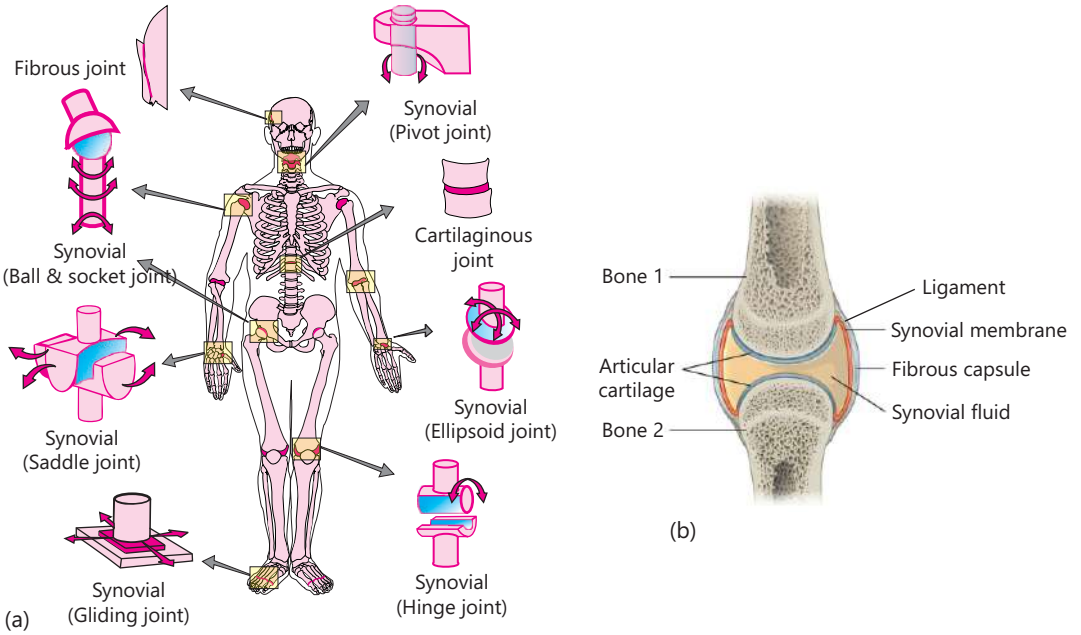


Figure 12.10: (a)- Types of joints; (b)- Structure of a synovial joint

Human Skeleton & Musculature helps in Bipedal Posture

The bipedal posture of humans is linked to skeleton and musculature in several ways.

1. The human vertebral column has a distinctive S-shaped curve, which helps to distribute weight evenly and maintain balance while standing and walking.
2. Human pelvis is shorter and broader, which helps to stabilize the torso and support the body's weight on two legs.
3. The human femur is also angled inward towards the knee joint, which helps to keep the body's centre of mass over the feet. It allows stability while standing and walking.
4. The muscles are located in the buttocks, are much larger in humans. They play a crucial role in stabilizing the torso and propelling the body forward while walking.
5. The calf muscles are also well-developed in humans, providing power for walking and running.
6. Human foot has a longitudinal arch that helps to absorb shock and distribute weight evenly across the foot.
7. The toes are shorter and less prehensile, allowing the foot to function more effectively as a lever during walking and running.

Problems due to Improper Posture

Improper posture can negatively affect bones and joints, causing:

Vertebral Misalignment: This can lead to back and neck pain, and herniated discs by putting pressure on vertebrae and nerves.

Joint Strain: Poor posture can strain neck, shoulders, hips, and knees, leading to pain, inflammation, and potentially arthritis.

Muscle Imbalances: Overused and underused muscles from poor posture can pull bones and joints out of alignment.

12.2- Disorders of Skeletal System

Skeletal system is susceptible to a wide range of disorders that can impact its structure and function. These disorders can affect any part of the skeletal system, including bones, joints, and connective tissues.

Disorders of the Skeleton

1- Disc Slip

The intervertebral discs between vertebrae act as shock absorbers and help in movement. A herniated or slipped disc occurs when the outer layer of the intervertebral disc tears or ruptures, causing the inner gel-like substance to leak out and press against nearby nerves or spinal cord. It may be due to a trauma, degenerative changes due to aging, or repetitive strain on vertebral column. Symptoms of slipped disc include pain, numbness, and tingling in the affected area, weakness or loss of muscle function, and in severe cases, bowel or bladder dysfunction.

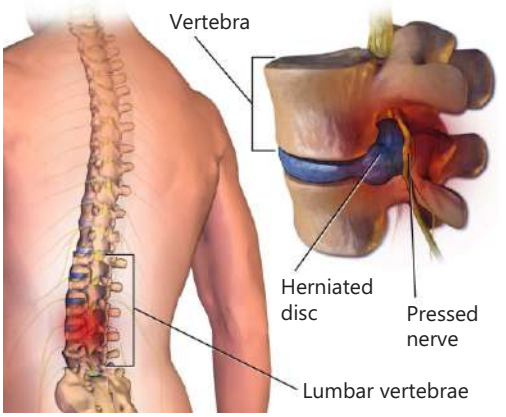


Figure 12.11: Disc slip (herniation)

2- Spondylosis

Spondylosis means degeneration of vertebrae, intervertebral discs, ligaments or cartilage of vertebral column. It may result in narrowing and fusion of intervertebral disc and development of bone outgrowths. It puts pressure on the nerves or spinal cord. Spondylosis is most common in the lower back (lumbar vertebrae) and neck (cervical vertebrae). The most common cause is the natural degeneration of intervertebral discs. It occurs with aging, genetic factors, trauma, and prolonged periods of poor posture and obesity. Symptoms include back or neck pain, stiffness, and reduced range of motion.

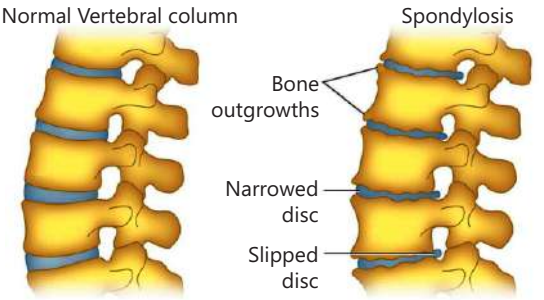


Figure 12.12: Spondylosis

3- Sciatica

Sciatica means compression or irritation of the sciatic nerve. The sciatic nerve starts from lower back and goes down through the buttocks into each leg. Sciatica is often caused by a herniated disc or bulging disc, which can put pressure on the sciatic nerve. Other causes of sciatica include trauma, infection, inflammation, and spondylosis.

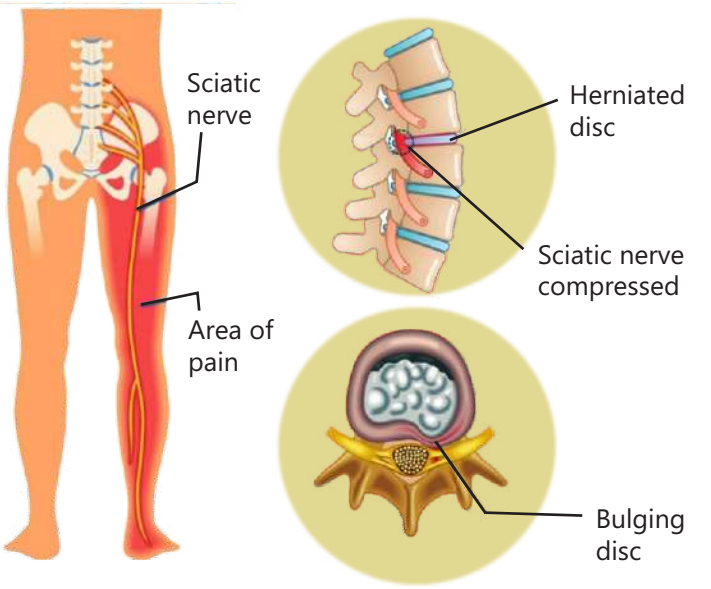


Figure 12.13: Sciatica and its causes

Symptoms include pain or discomfort in the lower back, buttocks, legs, or feet, tingling or numbness in the legs or feet, weakness or difficulty moving the legs or feet.

4- Arthritis

Arthritis include different inflammator conditions that affect th joints. Symptoms of all type include joint pain an stiffness. Other symptom may include redness, warmth, swelling in affected joints. The following are important types of arthritis.

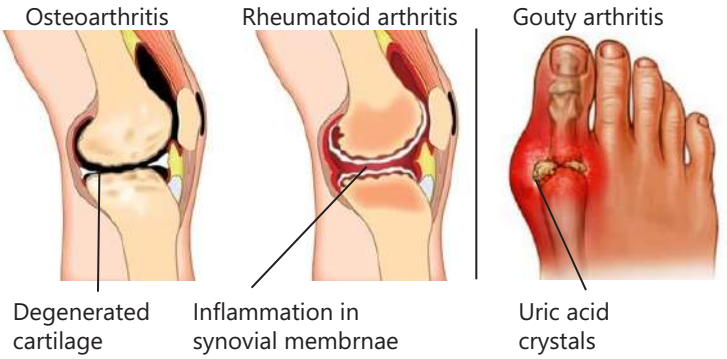


Figure 12.14: Types of arthritis

Osteoarthritis is the most common type. It occurs when the articular cartilage at the ends of bones in joints gradually softens and disintegrates. It affects knee, hip and intervertebral joints.

Rheumatoid arthritis is the result of an autoimmune disorder in which synovial membrane becomes inflamed. Most commonly, the wrist and hands are involved.

Gouty arthritis (or gout) occurs when there is a build-up of uric acid in the blood, which can form crystals in the joints and cause inflammation. The most

common joint affected is the joint of the big toe. Other joints (knees, wrists and fingers) may also be affected.

5- Osteoporosis

Osteoporosis is a condition characterized by weakened bones that are more prone to fractures and breaks. It occurs when bone density decreases, making the bones fragile and porous. Its causes include:

As people age, bone mass naturally decreases. But it can be more pronounced in some individuals.

In women, a drop in oestrogen levels after menopause accelerates bone loss.

Lack of calcium and vitamin D in the diet can impair bone health. Calcium is crucial for bone strength, while vitamin D helps the body absorb calcium.

Lack of weight-bearing exercise can lead to weakened bones.

Certain treatments such as long-term use of corticosteroids, can contribute to bone loss.

Smoking and alcohol consumption can also increase the risk of osteoporosis.

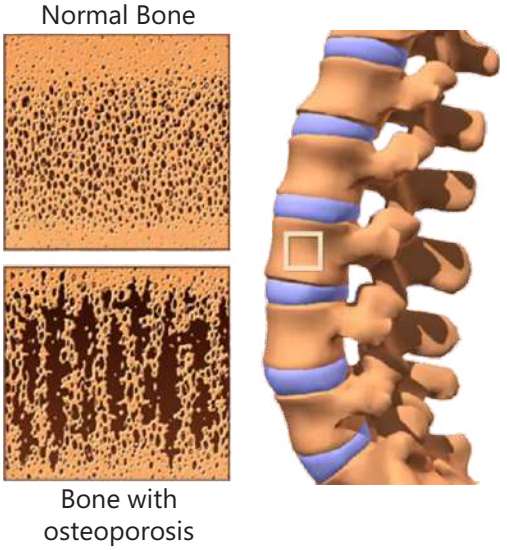


Figure 12.15: Normal bone and osteoporosis

Injuries to Joints

Joints can be subject to a variety of injuries, which can result in pain, swelling, and reduced motion. Here are some common injuries to joints:

1- Dislocations

A dislocation is when the bones in a joint are forced out of their normal positions. This can happen as a result of a sudden impact or trauma. A severe dislocation can cause tearing of the muscles, ligaments and tendons. Symptoms include swelling, intense pain, and immobility of the affected joint. Rheumatoid arthritis can also cause joint dislocation. A dislocated joint can only be successfully corrected by a physiotherapist. Surgery may be needed to repair or tighten the stretched ligaments.

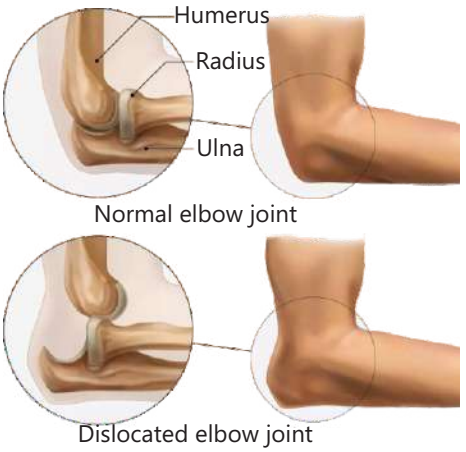


Figure 12.16: Dislocation in elbow joint

2- Sprain

A sprain is an injury to the ligaments that connect bones in a joint. Commonly injured ligaments are in the ankle, knee and wrist. This can happen when the joint is forced beyond its normal range of motion, causing the ligaments to stretch or tear. Sprains are usually treated with physical therapy. Dressings is done to immobilize the sprain and provide support.

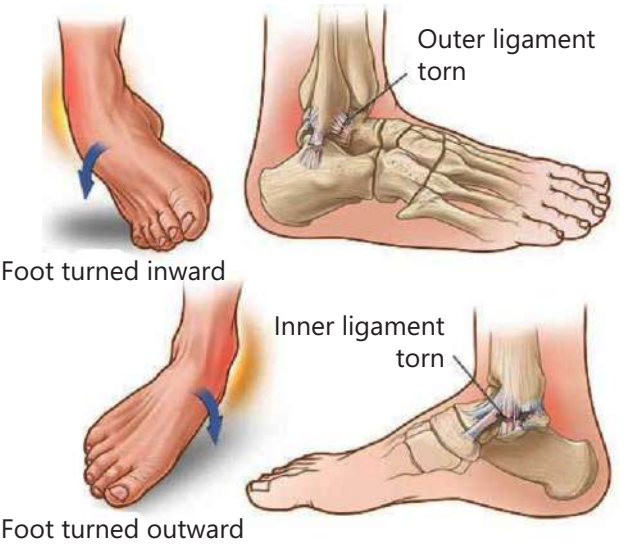


Figure 12.17: Ankle sprain

First aid Treatment for Dislocation and Sprain

First aid treatment for dislocation and sprain includes the following steps (Fig. 12.18):

1. **Immobilize the affected area:** Keep the affected area immobile and do not attempt to re-align the dislocated joint. Use a sling or splint to support the limb.

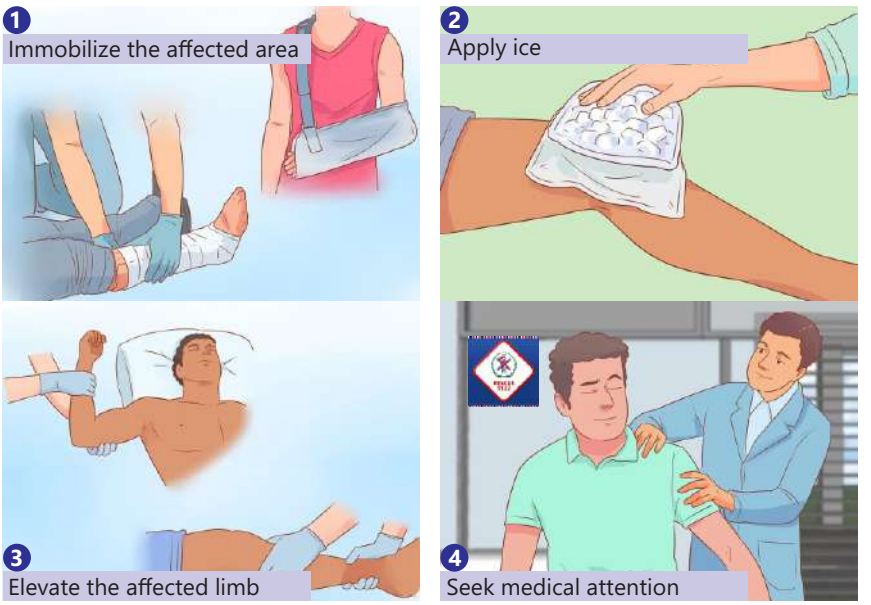


Figure 12.18: First aid treatment for dislocation or sprain

2. **Apply ice:** Apply an ice pack or cold compress to the affected area to reduce swelling and pain.

3. **Elevate the affected limb:** In the case of dislocation, if possible, elevate the affected limb above to help reduce swelling.
4. **Seek medical attention:** Dislocations and sprain require medical attention, so call for emergency medical services 1122 or take the person to the hospital for further evaluation and treatment.

12.3- MUSCLES

Muscle is defined as the tissue that can contract in a coordinated way to produce movements of body parts or whole body. The individual cells of muscle are called **muscle fibres** or **myofibres**.

Muscles' ability to contract and relax not only enables the body to move, but also provides the force that pushes substances, such as blood and food, through the body.

Types of Muscles

Human body has three types of muscle tissues: skeletal, smooth, and cardiac (Fig. 12.19).

Although our focus in this chapter is on humans, it is important to realize that essentially all animals employ muscles. For example, when a mosquito flies, its wings are moved rapidly through the air by quickly contracting flight muscles. When an earthworm burrows through the soil, its movement is driven by strong muscles pushing its body past the surrounding soil.

1- Skeletal Muscles

Skeletal muscles are responsible for moving parts of the body, such as the limbs, trunk, and face. The muscle fibres of skeletal muscles are elongated cells with striations. Because their contractions are usually consciously controlled, skeletal muscles are called as voluntary muscles.

2- Smooth Muscles

Smooth muscles are present in the walls of the stomach, intestines, blood vessels, and other internal organs. Smooth muscle fibres are spindle-shaped, have a single nucleus and lack striations. Smooth muscle fibres are surrounded by connective tissue. Because most of their movements cannot be consciously controlled, smooth muscle is referred to as involuntary muscle.

3- Cardiac Muscles

These are found only in the walls of the heart. Their fibres branch extensively. The muscle fibres of cardia muscles are striated like skeletal muscle, but each cell usually contains one nucleus located near the centre.

Comparison of three types of muscle tissues

Property	Skeletal Muscle	Smooth Muscles	Cardiac Muscles
Appearance	Regular striped	Un-striped	Irregular striped
Cell shape	Spindle or cylindrical	Spindle	Branched
Number of nuclei	Many per cell	One per cell	One per cell
Voluntary control	Have voluntary control	Usually, no voluntary control	No voluntary control

Function	To move skeleton	To move substances through hollow organs	To pump blood

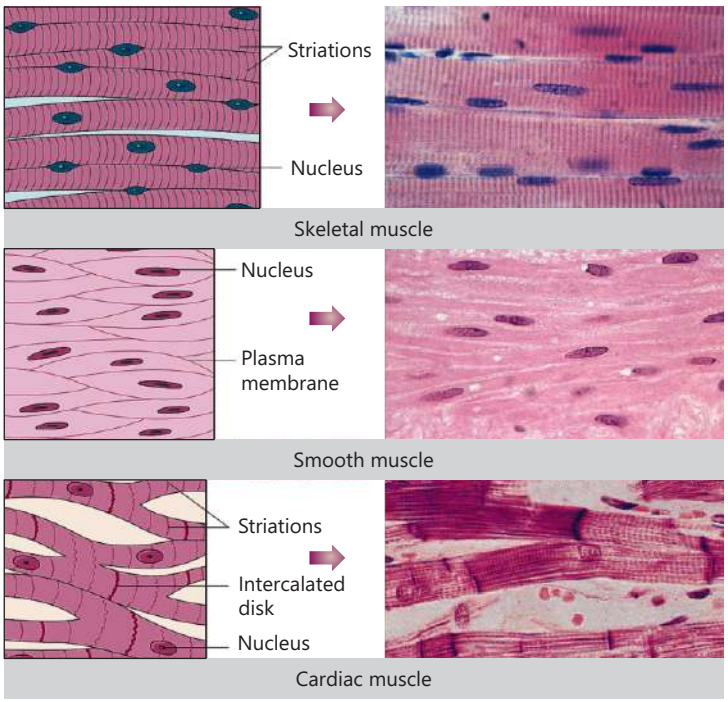


Figure 12.19: Types of muscles

Structure of Skeletal Muscles

The cells of skeletal muscles i.e., muscle fibres (myofibres) are in the form of bundles which are enclosed by collagen fibres and connective tissue. At the ends of a skeletal muscle, the collagen and connective tissue forms **tendons** which attach the muscle to bones.

Ultrastructure of Skeletal Muscles

Each skeletal muscle cell i.e., muscle fibre is a cylindrical multinucleated cell, enclosed by a plasma membrane called **sarcolemma** (Fig. 12.20). Its cytoplasm is called **sarcoplasm** and it contains **sarcoplasmic reticulum (SR)**. The sarcolemma penetrates deep into the cell to form hollow elongated tubes, the **transverse tubules (T-tubules)**. The T-tubules reach the ends of SR.

Each muscle fibre contains a bundle of 4 to 20 elongated threadlike structures called **myofibrils**. Myofibrils are made up of two types of filaments: thick filaments composed of **myosin** and thin filaments composed of **actin**. The thick filaments create dark bands called **A-bands**, while the thin filaments create light bands called **I-bands**. These alternating dark and light bands give skeletal muscle its striped (striated) appearance.

We can summarize the structural organization of a skeletal muscle as;

A skeletal muscle is made of groups of cells called muscle fibres.

Each muscle fibre contains bundles of myofibrils in its cytoplasm.

Each myofibril is made of 2 types of myofilaments (myosin and actin).

The thin actin filaments are attached to protein discs called **Z-lines**. The section between two Z-lines is a **sarcomere**, the smallest unit of muscle contraction. Within a sarcomere, the thin filaments extend from the Z-line toward the center, where they overlap with thick filaments. This overlap creates the **A-band**, with a lighter central region called the **H-band**, where no overlap occurs (Fig. 12.20).

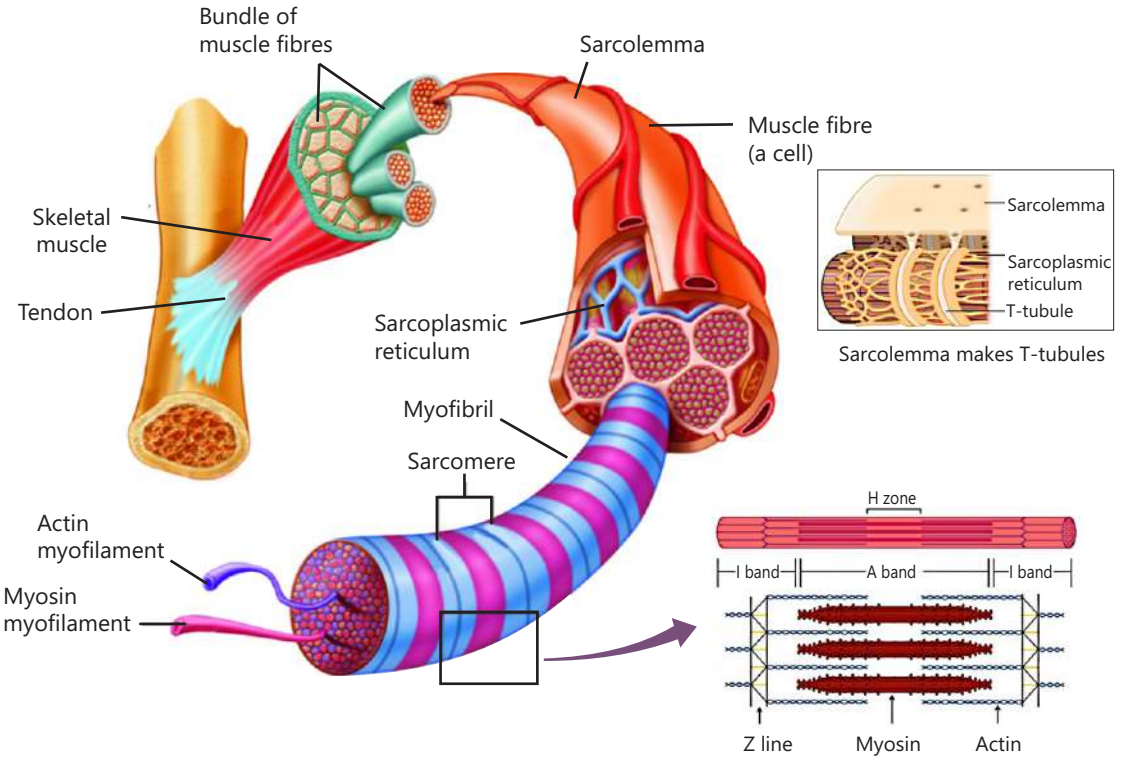


Figure 12.20: Ultrastructure of skeletal muscle

During muscle contraction, the thin filaments slide deeper into the A-band, causing the H-band and I-band to narrow. The A-bands are pulled closer together, shortening the muscle. The center of the H-band may have a dark line called the **M line** which helps stabilize the thick filaments.

Biochemistry of Myofilaments

Thick myofilaments, about 16 nm in diameter, are made up of many myosin proteins. Each myosin protein consists of two intertwined polypeptide chains, ending in a globular "head." These myosin heads extend from the thick filaments and connect to actin during muscle contraction (Fig. 12.21).

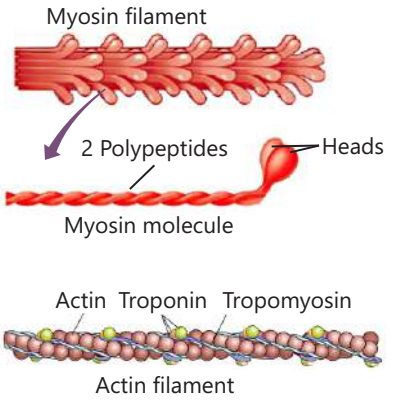


Figure 12.21: Structure of myofilaments

Thin myofilaments, 7-8 nm in diameter, are made of three proteins: (i) Core is made of two twisted strands of actin. (ii) Two strands of **tropomyosin** wrap about actin core and stiffen it. In a relaxed muscle fibre, they block myosin binding sites on actin. (iii) **Troponin** protein is present at regular intervals on thin myofilaments. It is made of three polypeptides. One polypeptide is inhibitory and binds to actin; second polypeptide binds to tropomyosin to keep it in place. The third polypeptide binds to calcium ions.

Mechanism of Muscle Contraction - Sliding Filament Model

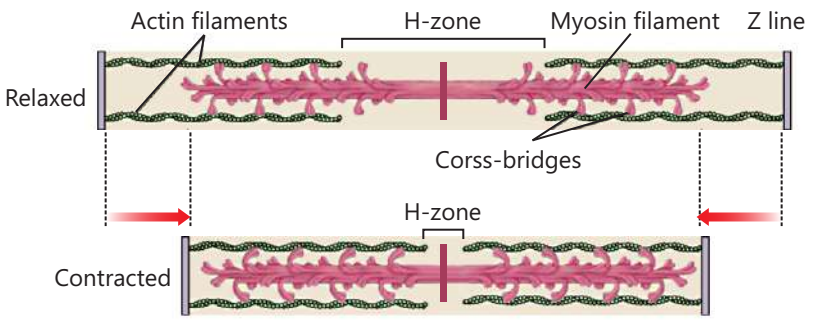


Figure 12.22: Sliding filament model of muscle contraction

The sliding filament model explains how a muscle contracts. According to this model, a muscle contracts when its thin myofilaments slide past the thick ones so that they overlap to a greater degree. It occurs in the following steps (Fig. 12.23);

1- Sarcomeres at relaxed state

In a relaxed muscle, sarcomeres are at their normal length. The myosin heads are not bound to actin because the binding sites on actin are blocked by tropomyosin of thin filaments. Troponin, another protein, is attached to tropomyosin. Myosin heads have hydrolysed ATP into ADP and Pi.

When a nerve impulse reaches sarcolemma, a neurotransmitter (acetylcholine) is released by motor neuron at the synapse. It

2- Arrival of Nerve Impulse

When a nerve impulse reaches the muscle fibre, it travels along the sarcolemma to the T-tubules and then to the sarcoplasmic reticulum (SR). The SR releases calcium ions into the cytosol. These calcium ions bind to troponin, causing it to shift tropomyosin away from the myosin-binding sites on actin.

stimulates the sarcolemma to produce its own electrochemical impulses which are carried into the muscle fibre to the T tubules.

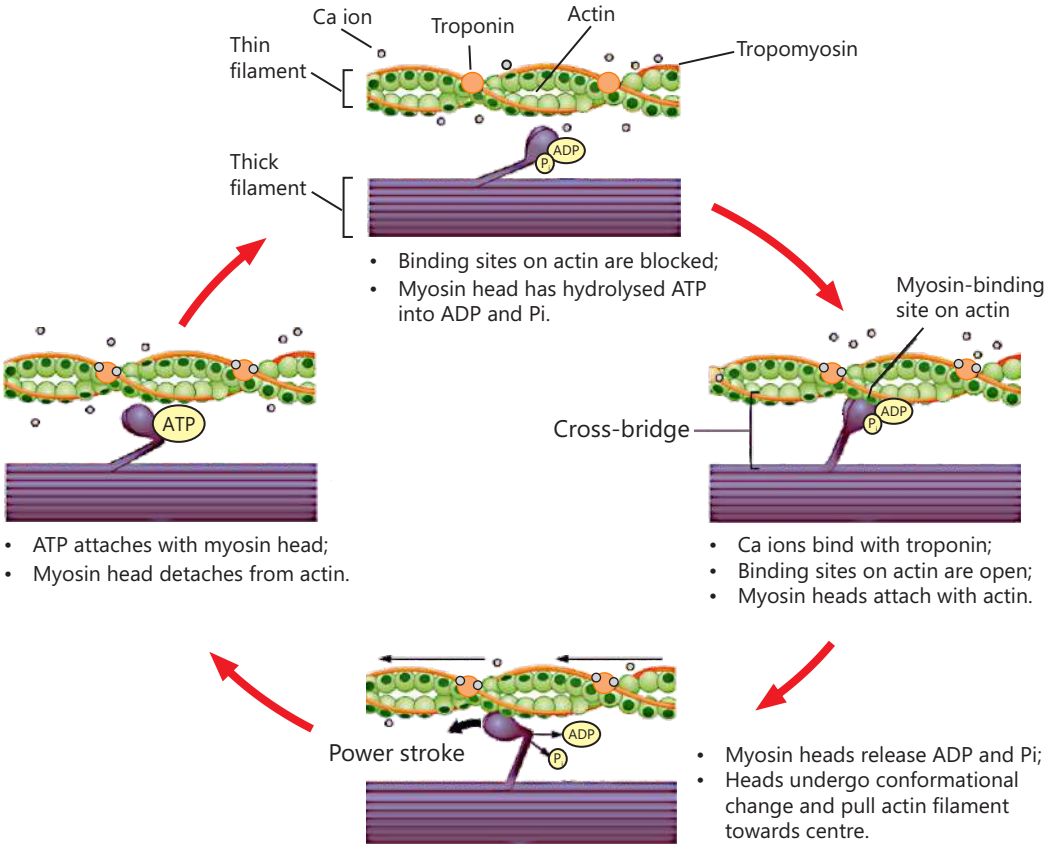


Fig. 12.23: Steps of a power-stroke (cross bridge cycle)

3- Cross-bridges and Power-stroke

When binding sites on actin are exposed, the myosin heads bind to them and form **cross-bridges**. Once the cross-bridges are formed, the myosin heads release the ADP and Pi, and undergo conformational change. They bend towards the centre of sarcomere, pulling actin filaments with them. This pulling action is called a **power stroke**. It shortens the sarcomere, bringing Z-lines closer together and H-zone disappears. It occurs simultaneously in all sarcomeres, causing the muscle to contract. The adjacent A-bands of sarcomeres come closer to each other but do not shorten.

4- Separation of Myosin Heads from Actin

After pulling, the myosin head receives a new molecule of ATP. This allows the head to detach from actin. Splitting of this ATP into ADP and Pi puts the head into its original conformation, allowing the cross-bridge cycle to begin again.

After death, the cells can no longer produce ATP and therefore the cross-bridges cannot be broken. It causes the muscle stiffness of death, or **rigor mortis**. A living cell, however, always has enough ATP to allow the myosin heads to detach from actin.

Arrangement of Skeletal Muscles at Moveable Joints

Skeletal muscles are attached to bones by tough connective tissues called **tendons**. Typically, a muscle has two attachment points on different bones. The end attached to the stationary bone during contraction is called the **origin**, while the end attached to the bone that moves is the **insertion**. The middle part of the muscle is known as the **belly** (Fig. 12.24).

For the movement of bones at a joint in two directions muscles work in pairs. They produce opposing actions when they contract. Such arrangement of muscles is called antagonistic arrangement. In such arrangement, when one muscle, called **flexor**, contracts it bends the bone at joint. When the opposing muscle, called **extensor**, contracts it straightens the bone at joints.

During such antagonistic action, when a muscle e.g., flexors contracts, the other muscle i.e., extensor is relaxed and vice versa.

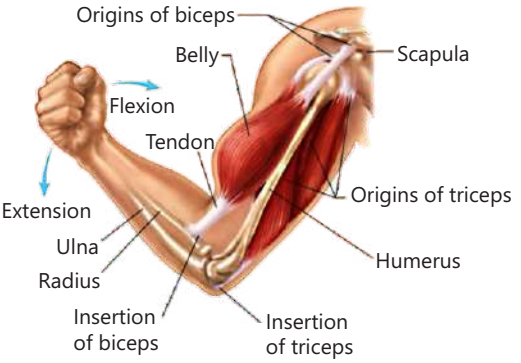


Figure 12.24: Arrangement of skeletal muscles at elbow joint

Movement at Knee Joint

The knee joint is located between the femur (thigh bone) and the tibia and fibula (lower leg bones). Flexion, or bending, of the lower leg is done by the **hamstrings**. It is a group of three muscles at the back of the thigh. The hamstrings originate at the pelvic girdle and the top of the femur, with insertions at the upper parts of the fibula and tibia.

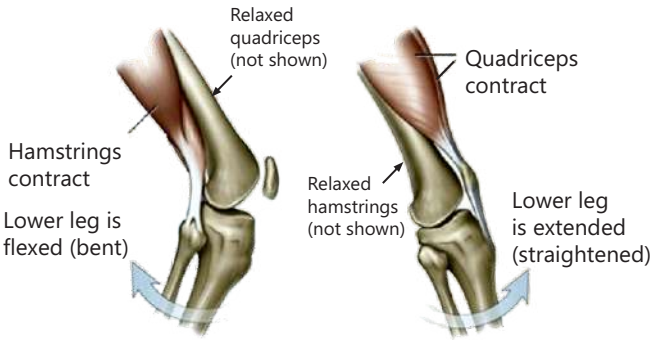


Figure 12.25: Movement at knee joint

Extension, or straightening, of the lower leg is done by the **quadriceps**. It is a group of four muscles at the front of the thigh. The quadriceps originate at the ilium

(part of the pelvic girdle) and femur, with insertions at the patella (kneecap) and tibia. When the hamstrings contract, the lower leg bends and the quadriceps relax. When the quadriceps contract, the lower leg straightens and the hamstrings relax.

Muscle Disorders

The following are some common muscle disorders.

1- Muscle Fatigue

Muscle fatigue means a decline in muscle performance that occurs after prolonged or intense physical activity or due to some disease. Its symptoms include pain, decreased muscle strength, and reduced endurance. The following factors contribute to muscle fatigue:

During exercise, the muscles use ATPs to contract. When the supply of ATPs is depleted, the muscle is no longer able to contract.

As muscles work, they produce metabolic wastes e.g., lactate, hydrogen ions, and reactive oxygen. These wastes contribute to muscle fatigue.

When muscle fibres are repeatedly activated, they are not able to effectively handle calcium ions, which can impair muscle function.

Prolonged or intense exercise can cause small amounts of damage to muscle fibres, leading to inflammation and reduced muscle function.

Muscle fatigue typically improves with rest. If it is severe, it requires medical attention.

2- Muscle Cramps

Muscle cramps are sudden, involuntary, and often painful contractions of a muscle or group of muscles. They usually last from a few seconds to several minutes and most commonly occur in the legs and feet. Common causes include dehydration, an imbalance of salts, overuse or injury of the muscle, certain medications (like diuretics), and medical conditions such as diabetes, liver disease, and nerve damage.

To relieve muscle cramps, gently stretch and massage the affected muscle. Applying heat or cold to the area and using pain-relieving medications can also help.

3- Tetany

Tetany is a condition characterized by involuntary muscle contractions or spasms due to increased muscle tone and hyperexcitability of the nerves. These contractions can occur in various parts of the body such as hands, feet, face, or larynx. The most common cause of tetany is hypocalcaemia (low level of calcium in blood) which may be due to vitamin D deficiency, renal failure, or thyroid disorders. Tetany may also be due to other salts imbalances, such as low level of magnesium in blood. Treatment for tetany depends on the underlying cause. If tetany is caused by salts imbalances, treatment may involve calcium or magnesium supplements or intravenous fluids to restore electrolyte balance.

Difference between Tetany and Tetanus

Tetany and tetanus are different conditions often confused due to their similar names:

1. Tetany involves increased muscle tone and overactive nerves, causing involuntary muscle contractions or spasms. Tetanus is a severe bacterial infection caused by *Clostridium tetani*, which produces a toxin affecting the nervous system, leading to muscle stiffness and spasms.
2. Tetany can affect various body parts like the hands, feet, face, or larynx. Tetanus mainly affects the jaw and neck muscles.
3. Tetany can result from issues like electrolyte imbalances or nerve problems. Tetanus is caused by a specific bacterial infection.
4. Tetanus is more serious and potentially life-threatening compared to tetany.

Muscles pull but do not push.

Muscles can only pull, not push. This is because muscle fibres are designed to contract and shorten, pulling on tendons and thus moving bones. When a muscle contracts, it pulls on the bone via the tendon, and when it relaxes, the bone moves back to its original position.

Muscles cannot push because they only generate force by pulling. If a muscle were to push, it would need to be attached to bones at both ends and make both ends move closer together, which is not possible in the body. Muscles are usually attached to bone at only one end.

Skeleton is a system of rods and levers

The skeleton works like a system of rods and levers. Bones act as the rods, giving structure and support to the body and protecting internal organs.

In this system, joints serve as fulcrums (pivot points) for the levers, allowing movement. Muscles generate the effort or force, while the weight or resistance being moved is the load.

For example, when lifting a weight, the bicep muscle in the upper arm acts as a lever. The elbow joint is the fulcrum, the bicep provides the effort, and the weight is the load.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. Which structures are part of the appendicular skeleton?
   (a) Ethmoid bone (b) Floating ribs (c) Lumber vertebrae (d) Humerus bone
2. The term muscle fibre or myofibre refers to;
   (a) A cellular organelle (b) A cell
   (c) A tissue (d) An organ
3. Which of these extends the entire length of a muscle fibre?
   (a) Sarcomere (b) Myofibril (c) Myosin filament (d) Actin filament
4. Actin filaments are made of proteins;
   (a) Myosin and troponin (b) Actin and troponin
   (c) Actin and myosin (d) Actin, tropomyosin and troponin
5. In a muscle, the Z-line are the proteins for the attachment of the ends of;
   (a) Actin filaments (b) Myosin filaments

(c) Both actin and myosin filaments (d) Sarcomeres

6. Sarcomere is a part between;
   (a) Two H-lines (b) Two A-bands (c) Two Z-lines (d) Two I-bands
7. Which part of muscle fibre releases calcium ions which trigger contraction?
   (a) Sarcolemma (b) Sarcoplasm
   (c) T-tubules (d) Sarcoplasmic reticulum
8. Which statement is correct to describe sliding filament model of muscle contraction?
   (a) Myosin filaments pull on the sarcomere so that actin filaments are shortened.
   (b) Myosin filaments pull on actin filaments so that sarcomere is shortened.
   (c) Actin filaments pull on myosin filaments so that sarcomere is shortened.
   (d) Actin filaments pull on sarcomere so that myosin filaments are shortened.
9. When a muscle fibre shortens, which of the following also shortens?
   (a) Actin filament (b) Myosin filament (c) Sarcomere (d) Z-line
10. Which statement correctly describes an event of muscle contraction?
    (a) Myosin heads bind to troponin.
    (b) ATP binds to the actin binding site.
    (c) ATP is used to detach the myosin head from actin.
    (d) Troponin blocks the binding sites.
11. Tendons connect bone and;
    (a) Bone (b) Ligaments (c) Muscle (d) Cartilage
12. What is true about antagonistic pair of muscles?
    (a) It provides a backup if one of the muscles is injured
    (b) One muscle pushes while other pulls
    (c) It allows muscles to produce opposing movements
    (d) It doubles the strength of contraction

SHORT QUESTIONS

1. Name three types of cells associated with bone and write their functions.
2. Name the bones of cranium.
3. Enlist the bones in the five groups of vertebrae.
4. What bones make the rib cage.
5. Name the bones of pectoral girdle and pelvic girdle.
6. Name the bones of forelimbs and hindlimbs.
7. What is fibrous joint? Give examples.
8. Name the steps involved in bone repair.
9. What skeletal structures are affected from the osteoarthritis?
10. List the major parts of skeletal muscle fibre.
11. What do you mean by I-band, A-band and H-zone?
12. Describe the antagonistic arrangement of skeletal muscles.

13. Ligaments are elastic while tendons are hard. Justify.
14. Draw a diagram of sarcomere and label its parts.
15. Differentiate between:
    - Compact and spongy bone
    - Axial skeleton and appendicular skeleton
    - True ribs, false ribs and floating ribs
    - Rheumatoid arthritis and osteoarthritis
    - Fibrous and cartilaginous joints
    - Cartilaginous and synovial joint
    - Osteoblasts and osteocytes
    - Tropomyosin and troponin
    - Ligament and tendon
    - Tetany and tetanus

LONG QUESTIONS

1. Explain the structure of bone.
2. Describe the structure of three types of cartilage.
3. Write the cause and symptoms of joint dislocation, spondylosis, and sciatica.
4. Describe the types of arthritis, with their causes, symptoms and treatments.
5. Describe the three types of muscles.
6. Explain the ultrastructure of skeletal muscle.
7. Write a detailed note on the sliding filament model of muscle contraction.
8. Explain the action of antagonistic muscles in the movement of knee joint.
9. Draw a diagram of sarcomere and label its parts.
10. Describe causes and symptoms of muscle fatigue, cramps and tetany.
11. Justify how the main functions of the skeleton are to act as a system of rods and levers.
12. Justify why do the muscles pull but do not push.

INQUISITIVE QUESTIONS

1. Why is calcium essential for both the structural integrity of bones and the process of muscle contraction?
2. Why is the human skeleton designed with both rigid bones and flexible joints instead of being made of a single solid structure?
3. Why do muscles always work in pairs (antagonistic muscles) rather than alone?
4. Why does prolonged inactivity or space travel lead to muscle atrophy and bone weakening??

Glossary

A

Active Site - The region on an enzyme where the substrate binds and the reaction occurs.

Acylglycerol - A type of lipid composed of glycerol and fatty acids.

Aerobic Respiration - Energy-releasing process that uses oxygen to break down glucose.

Algae - Simple autotrophic organisms, often aquatic, ranging from unicellular to multicellular forms.

Alveoli - Tiny air sacs in the lungs where gas exchange between air and blood occurs.

Amino Acids - Building blocks of proteins, each containing an amino group and a carboxyl group.

Amylase - An enzyme that breaks down starch into maltose and glucose.

Anaerobic Respiration - Energy-releasing process in the absence of oxygen.

Angina pectoris - Chest pain caused by reduced blood flow to the heart muscles.

Angiography - A medical imaging technique used to view blood vessels.

Angioplasty - A procedure to restore blood flow through a blocked artery.

Annual ring (in plants) - A ring in a tree trunk representing one year of growth.

Antagonistic muscles - Pairs of muscles that work in opposition to move a body part.

Antibody - A protein produced by B-lymphocytes that binds to specific antigens to neutralize them.

Antigen - A foreign substance that triggers an immune response.

Arthritis - Inflammation of the joints causing pain and stiffness.

Atherosclerosis - Build-up of fatty deposits in the walls of arteries, narrowing them.

Atria (of heart) - The upper chambers of the heart that receive blood returning to the heart.

AV node - Atrioventricular node; relays electrical signals from atria to ventricles.

B

Bacteria - Prokaryotic, unicellular microorganisms that may be beneficial or pathogenic.

Binary Fission - A method of asexual reproduction in prokaryotes where one cell divides into two.

Biodiversity - The variety of living organisms in a particular habitat or ecosystem.

Bioenergetics - The study of energy flow and transformation in living organisms.

Bioinformatics - The application of computational tools to analyze biological data.

Biological Classification - The systematic grouping of organisms into categories based on evolutionary relationships.

Biomolecule - Organic molecules such as carbohydrates, proteins, lipids, and nucleic acids found in living organisms.

Bronchi - Two large tubes that branch from the trachea and carry air into the lungs.

Bronchi - The two main branches of the trachea that lead into the lungs.

C

Calvin Cycle - A series of biochemical reactions in the chloroplast stroma that convert carbon dioxide into glucose.

Capillaries - Smallest blood vessels where exchange of gases and nutrients occurs.

Cartilaginous Joint - A joint where bones are connected by cartilage, allowing limited movement.

Cell - The basic structural and functional unit of life.

Cell Membrane - Semi-permeable membrane enclosing the cytoplasm, controlling movement of substances.

Cell Theory - The theory stating that all living things are composed of cells, and all cells come from pre-existing cells.

Cell Wall - A rigid outer structure in plant, fungal, and some prokaryotic cells.

Cellular Respiration - The process by which cells break down glucose to release energy.

Chemiosmosis - The movement of ions across a membrane to generate ATP, driven by the electron transport chain.

Chlorophyll - Green pigment found in chloroplasts responsible for capturing light energy in photosynthesis.

Chloroplast - A plant cell organelle where photosynthesis takes place.

Chromosome - A thread-like structure composed of DNA and proteins, found in the nucleus.

Glossary

Chronic Obstructive Pulmonary Disease - A group of lung diseases that cause airflow blockage and breathing problems.

Collenchyma - A type of plant tissue with thickened cell walls that provide support and flexibility.

Companion Cell - A type of cell in the phloem that supports the function of sieve tube elements.

Cytoplasm - Jelly-like substance within cells, excluding the nucleus, that contains organelles.

D

Dark Reactions (of Photosynthesis) - The light-independent reactions that use ATP and NADPH to convert carbon dioxide into glucose.

Decomposer - Organism that breaks down dead organic matter and recycles nutrients.

Denaturation - Loss of an enzyme's shape and function due to external stress such as heat or pH.

Diaphragm - Dome-shaped muscle involved in the process of breathing.

Diastase - A group of enzymes that break down starch into sugars.

Diffusion - Passive movement of molecules from an area of high concentration to low concentration.

Digestion - The breakdown of large food molecules into smaller, absorbable components.

Disaccharide - A carbohydrate formed by the combination of two monosaccharides.

Disc-slip - A condition where a spinal disc herniates and presses on nearby nerves.

DNA (Deoxyribonucleic Acid) - A type of nucleic acids; carries genetic information.

Domain - The highest taxonomic rank, above kingdom; includes Bacteria, Archaea, and Eukarya.

Double Circulation - A system of blood flow where blood passes through the heart twice in one complete cycle.

Duodenum - The first part of the small intestine where most chemical digestion occurs.

E

ECG - Electrocardiogram; a recording of the electrical activity of the heart.

Electron Microscope - A microscope that uses electrons to view very small objects in high detail.

Electron Transport Chain - A series of protein complexes in mitochondria that transfer electrons and produce ATP.

Embolus - A traveling blood clot or other substance that can block blood vessels.

Emphysema - A chronic lung disease involving damage to the alveoli.

Endocrine Gland - A gland that secretes hormones directly into the bloodstream.

Endocytosis - The process by which a cell engulfs substances from its surroundings.

Endoplasmic Reticulum - A cell organelle involved in protein and lipid synthesis.

Enzyme - A biological catalyst that speeds up chemical reactions in cells.

Enzyme inhibitor - A substance that reduces or blocks enzyme activity.

Epicardium - The outermost layer of the heart wall.

Exocrine Gland - A gland that releases its secretions through ducts to specific locations.

Exocytosis - The release of substances from a cell by the fusion of a vesicle with the membrane.

F

Fermentation - Anaerobic process that converts glucose to energy and by-products like alcohol or lactic acid.

Fibrous Joint - A joint where bones are joined by fibrous tissue and allow little to no movement.

Flagella - Long, whip-like structures used for locomotion in some cells.

Fungi - A kingdom of non-photosynthetic organisms with cell walls made of chitin.

G

Gastric gland - Glands in the lining of the stomach that secrete gastric juice.

Gastric juice - A mixture of hydrochloric acid, pepsinogen, and mucus secreted by gastric glands.

Gastrin - A hormone that stimulates secretion of gastric juice.

Gene - A segment of DNA that codes for a specific protein or trait.

Genetic Code - The sequence of bases in DNA or RNA that determines the sequence of amino acids.

Genome - The complete set of genes or genetic material in a cell or organism.

Glossary

Glycolysis - The first step of cellular respiration that breaks down glucose into pyruvate.

Golgi Apparatus - Organelle that modifies, packages, and transports proteins and lipids.

H

Haemoglobin - Oxygen-carrying protein found in red blood cells.

Halophytes - Plants adapted to grow in salty environments.

Heartbeat - One complete cycle of contraction and relaxation of the heart muscles.

Homeostasis - Maintenance of stable internal conditions in an organism.

Hormone - A chemical messenger produced by glands that regulate body functions.

Hydrolases - Enzymes that catalyze the hydrolysis of chemical bonds.

Hydrophytes - Plants adapted to live in water or very wet conditions.

Hypertension - Abnormally high blood pressure.

Hypertonic solution - A solution with higher solute concentration, causing water to leave a cell.

Hypotonic solution - A solution with lower solute concentration, causing water to enter a cell.

I

Ileum - The final part of the small intestine involved in the absorption of nutrients.

Immune System - The body's defence system against infectious organisms.

Immunity - The ability of an organism to resist disease.

Ingestion - The process of taking food into the body through the mouth.

Insulin - A hormone that regulates blood sugar levels.

Isomerases - Enzymes that catalyze the rearrangement of atoms within a molecule.

Isotonic solution - A solution with equal solute concentration as another solution, resulting in no net water movement.

J

Jejunum - The middle part of the small intestine where absorption of nutrients occurs.

Joint - The location where two or more bones meet. It allows movement and flexibility.

K

Kingdom - A high-level taxonomic category grouping related organisms; e.g., Animalia, Plantae.

Krebs Cycle - A series of chemical reactions in mitochondria that generate energy through the oxidation of acetyl-CoA.

L

Larynx - Voice box located in the throat involved in breathing and sound production.

Ligases - Enzymes that catalyze the joining of two molecules using energy from ATP.

Light Reactions (of Photosynthesis) - The light-dependent reactions in the thylakoid membranes that produce ATP and NADPH.

Lipase - An enzyme that breaks down fats into fatty acids and glycerol.

Lipid - A type of biomolecule including fats and oils used for long-term energy storage.

Lyases - Enzymes that catalyze the breaking of bonds without hydrolysis or oxidation.

Lymph - A clear fluid that circulates in the lymphatic system and helps in immunity.

M

Mesophytes - Plants that grow best in moderate conditions with adequate water.

Mitochondria - Powerhouse of the cell that generates energy (ATP) via aerobic respiration.

Monosaccharide - The simplest form of carbohydrate, consisting of a single sugar molecule.

Mucus - A thick, slippery substance secreted by membranes, protecting linings of the digestive and respiratory tracts.

Mutation - A change in the DNA sequence of a gene.

Myosin - A protein involved in muscle contraction.

N

Nucleic Acid - Biomolecule made of nucleotides, including DNA and RNA.

Nucleoside - A molecule consisting of a nitrogenous base attached to a sugar, without a phosphate group.

Nucleotide - The basic building block of nucleic acids (DNA and RNA), consisting of a sugar, phosphate group, and nitrogenous base.

Glossary

Nucleus - Control center of the cell containing DNA.

O

Osmosis - The diffusion of water across a selectively permeable membrane.

Osteoblasts- Cells that build new bone tissue.

Osteoclasts- Cells that break down bone tissue.

Osteocytes - Mature bone cells that maintain bone structure.

Osteoporosis- A condition where bones become weak and brittle.

Otitis media - Infection or inflammation of the middle ear.

Oxidoreductases - Enzymes that catalyze oxidation-reduction reactions.

P

Pathogen - A microorganism that causes disease.

Pentose - A five-carbon sugar found in nucleotides, such as ribose and deoxyribose.

Pepsin - An active enzyme in the stomach that digests proteins.

Pepsinogen - An inactive enzyme precursor secreted by stomach cells, converted to pepsin in acidic conditions.

Pericardium - A double-walled sac that encloses and protects the heart.

Peristalsis - Wave-like muscle contractions that move food through the digestive tract.

Phloem - Plant tissue that transports food from leaves to other parts.

Phospholipid - A lipid containing a phosphate group, important in cell membranes.

Photoperiodism - The response of organisms to the length of day or night.

Photosynthesis- Process by which green plants make food using sunlight, water, and carbon dioxide.

Plasmid - A small, circular DNA molecule found in bacteria, independent of chromosomal DNA.

Pleura - A double-layered membrane surrounding the lungs.

Polysaccharide - A complex carbohydrate formed by the linkage of many monosaccharides.

Prostaglandins - Lipid compounds that have hormone-like effects, such as regulating inflammation.

Protease - An enzyme that breaks down proteins into amino acids.

Protein - Biomolecule made of amino acids essential for growth and repair.

Pulse - The rhythmic throbbing of arteries as blood is pumped by the heart.

Purkinje fibers - Specialized fibers that carry electrical impulses in the heart's ventricles.

R

Red Blood Cells (RBCs)-Cells that carry oxygen from the lungs to the body tissues.

Rennin - An enzyme in the stomach of infants that helps digest milk proteins.

Respiration - The process of breaking down food to release energy.

Ribosome - Organelle where protein synthesis takes place.

RNA (Ribonucleic Acid)- A nucleic acid involved in protein synthesis and gene regulation.

S

SA node - Sinoatrial node; the heart's natural pacemaker.

Sciatica - Pain caused by irritation or compression of the sciatic nerve.

Sclerenchyma - A plant tissue composed of thick-walled cells that provide structural support.

Secretin - A hormone that stimulates the pancreas to release bicarbonate into the small intestine.

Segmentation (in small intestine) - Rhythmic contractions that mix food and increase contact with digestive enzymes.

Sequence homology - Similarity in nucleotide or amino acid sequences between organisms.

Sieve Tube Element - A phloem cell responsible for transporting sugars in plants.

Sinusitis- Inflammation of the sinus cavities.

Skeleton - The framework of bones that supports and protects the body.

Sliding filaments model - A theory explaining muscle contraction through the sliding of actin and myosin filaments.

Species - A group of organisms capable of interbreeding and producing fertile offspring.

Spondylosis - Degeneration of the spine, often associated with aging.

Sprain - Stretching or tearing of ligaments in a joint.

Glossary

Steroids - Lipid molecules with four fused rings, including hormones like testosterone and cholesterol.

Stomata - Pores on the leaf surface for gas exchange.

Structural homology - Similarity in body structures due to shared ancestry.

Synovial Joint - A freely movable joint enclosed by a fluid-filled capsule.

Systematics - The study of evolutionary relationships among organisms.

T

Tendon - A fibrous connective tissue that attaches muscle to bone.

Terpene - A class of hydrocarbons found in plant essential oils.

Thrombus - A blood clot formed in a blood vessel.

Thylakoid - Membrane-bound compartments inside chloroplasts where light-dependent reactions occur.

Trachea - Windpipe that connects the larynx to the bronchi.

Tracheid - A type of elongated xylem cell that conducts water and provides structural support.

Translocation of Food - The movement of food (mainly sugars) through the phloem from source to sink.

Transpiration - Loss of water vapor from plant leaves through stomata.

Tropic movement - Movement of a plant in response to a directional stimulus (e.g., light, gravity).

V

Vaccine - A substance used to stimulate the production of antibodies and provide immunity.

Vasoconstriction - Narrowing of blood vessels.

Vasodilation - Widening of blood vessels.

Vein - Blood vessel that carries blood toward the heart.

Ventricles (of heart) - The lower chambers of the heart that pump blood out to the body and lungs.

Vernalization - The induction of flowering in plants by exposure to low temperatures.

Villi - Finger-like projections in the small intestine that increase surface area for absorption.

Virus - A non-cellular infectious agent that replicates only inside host cells.

W

Waxes - Lipids composed of long-chain fatty acids and alcohols, used for protection in plants and animals.

White Blood Cells (WBCs) - Cells involved in defending the body against infection.

X

Xerophytes - Plants adapted to survive in dry environments.

X-ray Crystallography - A technique used to determine the three-dimensional structure of molecules by analyzing the pattern of X-ray diffraction.

Xylem - Vascular tissue in plants that conducts water and minerals from roots to shoots.

Z

Zygote - The single cell formed by the fusion of male and female gametes.