Gaseous Exchange and Respiration in Animals

Grade 10 Biology study notes, Section 3.3. Every sentence is written to make sense on its own. Adaptation tables show the structure, its modification and its function. Every figure is taken from the class textbook.

Introduction

- Gaseous exchange is the process by which respiratory gases pass across respiratory surfaces.
- The respiratory gases are carbon(IV) oxide and oxygen.
- Animals need energy to maintain vital body processes.
- The energy comes from respiration.
- Respiration uses oxygen and gives out carbon(IV) oxide as a by-product.
- Gaseous exchange supplies the oxygen needed for respiration and removes the carbon(IV) oxide that respiration produces.
- Respiration is a chemical process, while gaseous exchange is a physical process.

A. Characteristics of respiratory surfaces

- A respiratory surface is the site of the respiratory system where gaseous exchange takes place.
- Respiratory surfaces differ from animal to animal depending on body size, metabolic activity, habitat and the medium of gaseous exchange.
- The main function of a respiratory surface is to take oxygen into the body tissues and to remove carbon(IV) oxide from the body tissues.

Animal group	Respiratory surface
Mammals and birds	Alveoli in mammals; parabronchi in birds (lungs)
Bony fish (tilapia)	Gill filaments
Frogs (amphibians)	Skin, lining of the buccal cavity and alveoli of the lungs
Insects	Tracheoles

- Every effective respiratory surface is highly vascularised, so blood carries gases to and from the surface quickly.
- Every effective respiratory surface has a large surface area, so more gas can diffuse across at the same time.
- Every effective respiratory surface has a moist lining, so respiratory gases dissolve before they diffuse.
- Every effective respiratory surface has a thin epithelial lining, so gases cover only a short diffusion distance.

B. Structure and adaptations of respiratory surfaces

Insects: the tracheal system

- Insects are small, but insects are multicellular and therefore need a developed respiratory system.
- The breathing system of insects is called the tracheal system.
- The tracheal system has three parts: spiracles, tracheae and tracheoles.

- The tracheal system branches into all the body tissues.

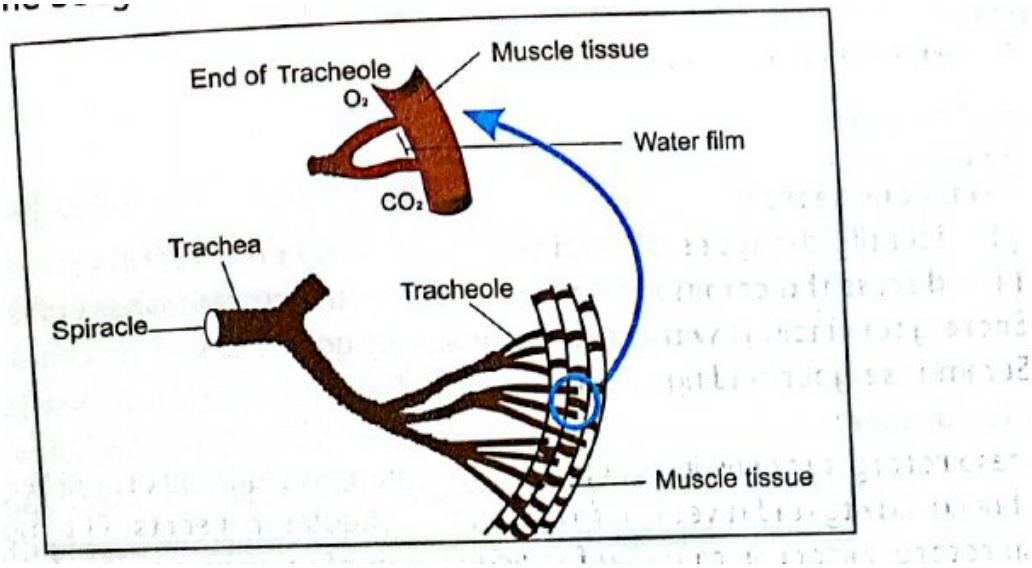


Figure 1: Tracheal system of an insect

Structure	Modification	Function
Spiracle	An opening on the abdomen or thorax, with a muscular valve and a fringe of hairs.	The muscular valve opens and closes the spiracle to control air flow and cut water loss. The hairs trap dust from inhaled air and reduce water loss. The spiracle lets air move into and out of the trachea.
Trachea	A large air tube reinforced with spiral bands of chitin.	The chitin bands keep the trachea open for continuous passage of gases. The chitin is impermeable, so no gas exchange happens across tracheae.
Tracheole	A very fine air tube in contact with every tissue, without chitin bands, numerous, with a moist lining.	Lack of chitin makes the wall permeable to gases. Large numbers give a large surface area. The moist lining dissolves the gases. Direct contact with cells delivers oxygen straight to tissues.

- Air is drawn in and out of the tracheal system by muscular movement of the abdominal wall.
- In wasps and bees, the abdominal segments move in and out lengthwise.
- In locusts and cockroaches, the abdominal segments move sideways (laterally).
- During breathing in, the thoracic spiracles open to let air into the trachea.
- During breathing out, the abdominal spiracles open to let air out of the trachea.
- Spiracles are on either side of the thorax and abdomen.

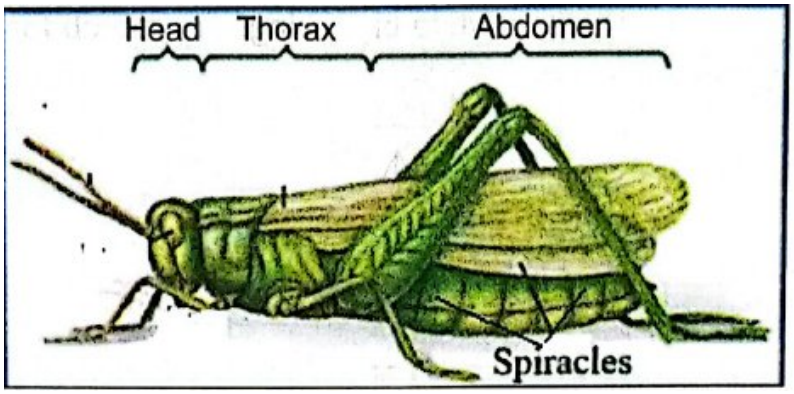


Figure 4: Head, thorax and abdomen of a locust, with spiracles

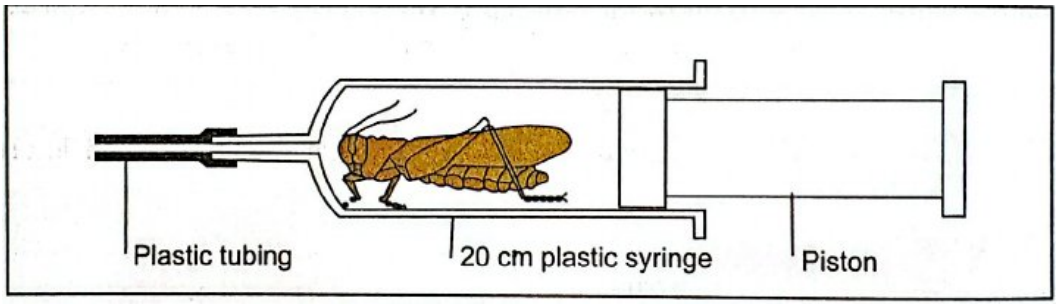


Figure 5: Locust inside a syringe (to observe abdominal movements)

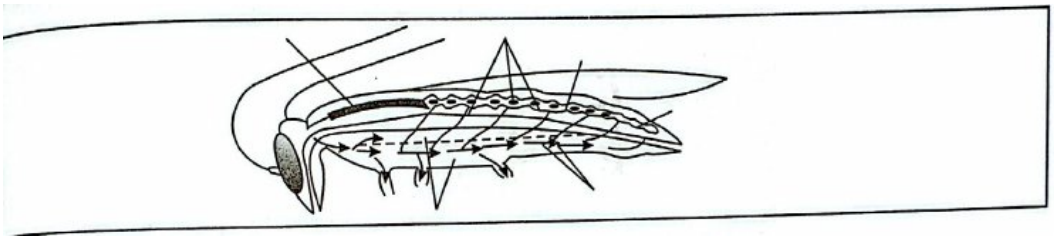


Figure 6: Position of spiracles in a locust

Aquatic insects

- Aquatic insects carry out gaseous exchange in water, so their tracheal system is modified.
- Dragonfly larvae and mayfly larvae have tracheal gills.
- Tracheal gills are outgrowths of the tracheal system found on the ventral side of the thorax.
- A thin cuticle that is permeable to oxygen and carbon(IV) oxide covers the tracheal gills.
- The gills allow gaseous exchange between the insect body and the surrounding water.
- Fanning movements of the gills keep the gills in contact with a constant supply of fresh water.

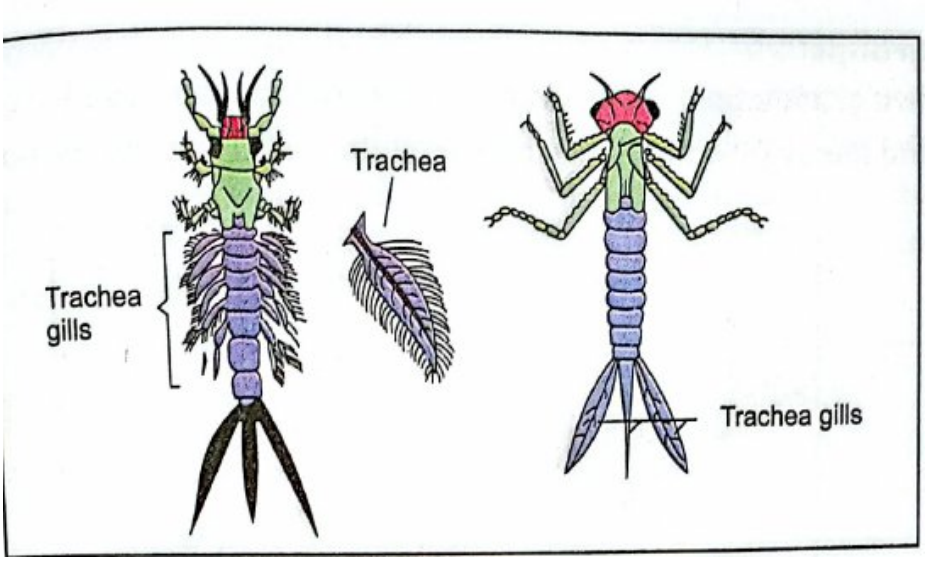


Figure 2: Tracheal gills in dragonfly

- Mosquito larvae and pupae have a respiratory siphon.
- In mosquito larvae, the respiratory siphon is an extension of the posterior spiracles.
- The siphon opens when the larva is beneath the water surface to take in air.
- The siphon closes when the larva submerges.
- Mosquito larvae come to the water surface periodically to breathe and to position themselves.
- In the pupal stage, a pair of siphons behind the head pierces the water surface for gaseous exchange.

- Oil was traditionally used to control mosquito larvae in standing water to prevent the spread of malaria.
- Oil lowers the surface tension of the water, so larvae cannot attach to the surface to get atmospheric oxygen.

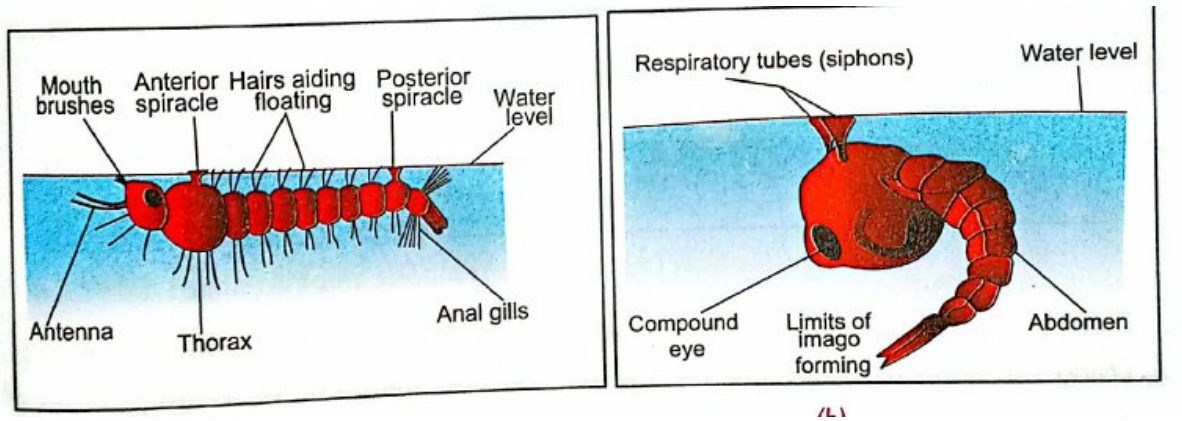


Figure 3: Respiratory siphon in mosquito larva (a) and pupa (b)

Insect	Structure	Modification and function
Dragonfly and mayfly larva	Tracheal gills	Thin permeable cuticle allows oxygen and carbon(IV) oxide to pass; fanning brings fresh water.
Mosquito larva and pupa	Respiratory siphon	Pierces the water surface to take in atmospheric air; closes when submerged.

Bony fish: gills

- Fish gills are located in gill chambers, one on each side of the head.
- The breathing system of a bony fish has the mouth (buccal cavity), gills, opercular cavity and operculum.
- A bony fish has four pairs of gills.
- Each gill has gill rakers, gill filaments and a gill bar (gill arch).

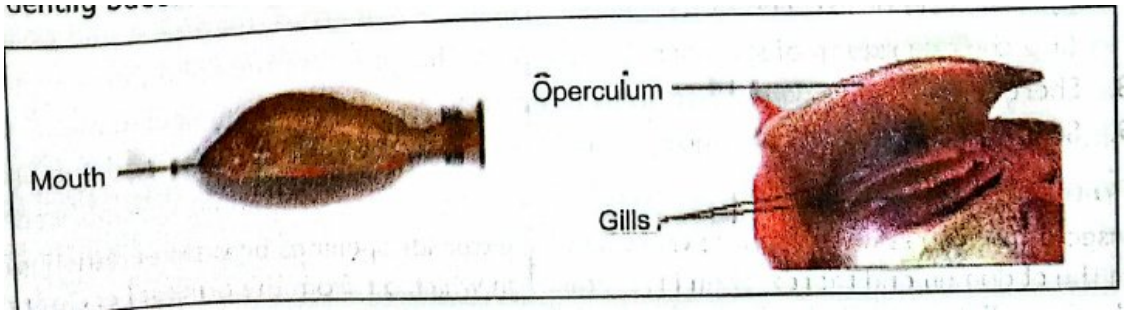


Figure 7: Operculum, gills and mouth of a fish



Figure 8: A gill in water in a Petri dish

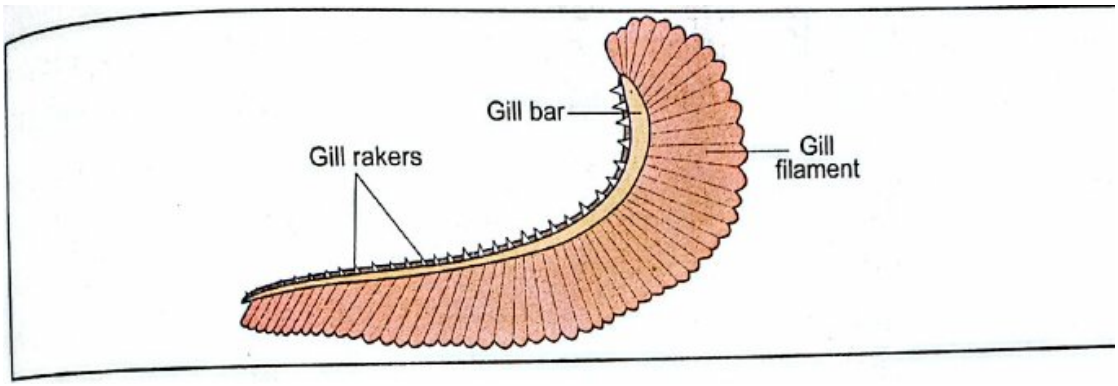


Figure 9: Gill structure

Structure	Modification	Function
Gill bar (arch)	A long, curved, bony structure.	Gives a surface for attachment of gill rakers and gill filaments.
Gill rakers	Numerous, pointed, teeth-like structures on the concave side of the gill bar.	Trap or filter solid particles in the water, which protects the delicate filaments from mechanical damage.
Gill filaments	Long and numerous, highly vascularised, covered by a thin epithelium, with permeable walls.	Long and numerous filaments give a large surface area. Many blood capillaries carry gases quickly. The thin epithelium shortens the diffusion distance for faster diffusion. The permeable wall lets gases pass through.
Operculum	A bony flap on each side of the head covering the gills.	Protects the gills from mechanical damage. Opens and closes to let water flow from the mouth cavity over the gills.

- The countercurrent flow system is the flow of water over the gills and of blood in the gill filament capillaries in opposite directions.
- As water flows over the gills, oxygen diffuses from the water into the blood in the gill filament capillaries.
- Carbon(IV) oxide diffuses from the blood in the gill filament capillaries into the water.
- Countercurrent flow keeps a concentration gradient across the gill filament, so diffusion continues along the whole length of the filament.
- A bony fish removed from water dies quickly because the gill filaments stick together and dry out, so the surface area and moisture are lost and the fish cannot absorb oxygen.

Amphibians: buccal cavity, lungs and skin

- Amphibians live in both water and on land, which is called double habitation.
- Double habitation requires special adaptations for effective gaseous exchange.
- Frogs and toads have three respiratory surfaces: the lining of the buccal cavity, the lungs and the skin.
- Air is forced in and out of the lungs by pumping action of the floor of the mouth.
- Toads do not use the skin for gaseous exchange except when hibernating.

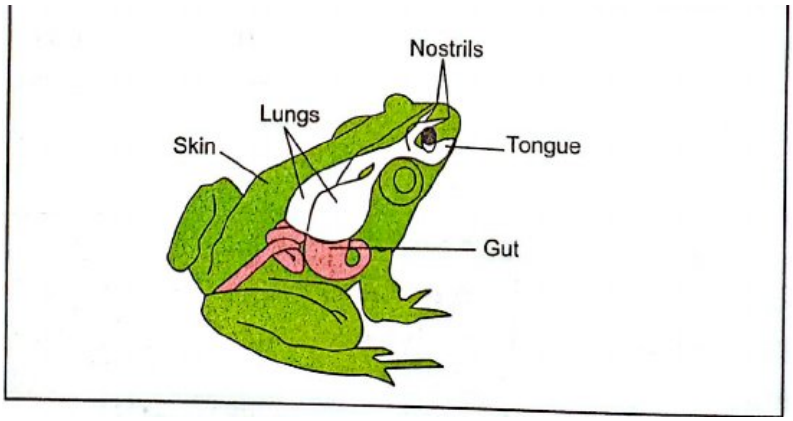


Figure 10: Gaseous exchange structures in frogs

Respiratory surface	Modification	Function
Epithelial lining of the buccal cavity	Moist, thin, rich in blood capillaries, large surface area.	Moisture dissolves gases. Thinness reduces diffusion distance. Capillaries carry gases. The large area gives maximum exchange.
Lungs (alveoli)	Moist epithelium, highly vascularised, thin epithelium, numerous alveoli.	Moisture dissolves gases. Capillaries transport gases efficiently. Thinness shortens diffusion distance. Many alveoli give a large surface area.
Skin (frogs)	Thin, moist, with a large network of blood capillaries.	Thin skin reduces diffusion distance. Moisture dissolves gases. Capillaries transport gases efficiently.

Birds: lungs, parabronchi and air sacs

- Birds fly at high altitudes where the oxygen concentration is low.
- Bird flight muscles need a lot of oxygen, so birds need a very efficient gaseous exchange system.
- Birds have lungs, as mammals do.
- The lungs connect to primary bronchi that extend from the trachea, which opens from the nares (nostrils).
- The primary bronchi divide into bronchioles inside the lungs.
- Bird bronchioles do not end in sac-like alveoli but develop into tube-like structures called parabronchi.
- Air flows through the parabronchi continuously in one direction.
- Birds have nine interconnecting air sacs that occur in pairs.
- Air sacs connect to the lungs so that most inhaled air bypasses the lungs and goes straight into the air sacs, which act as a reservoir of fresh air.
- Birds inhale and exhale twice for every breath.

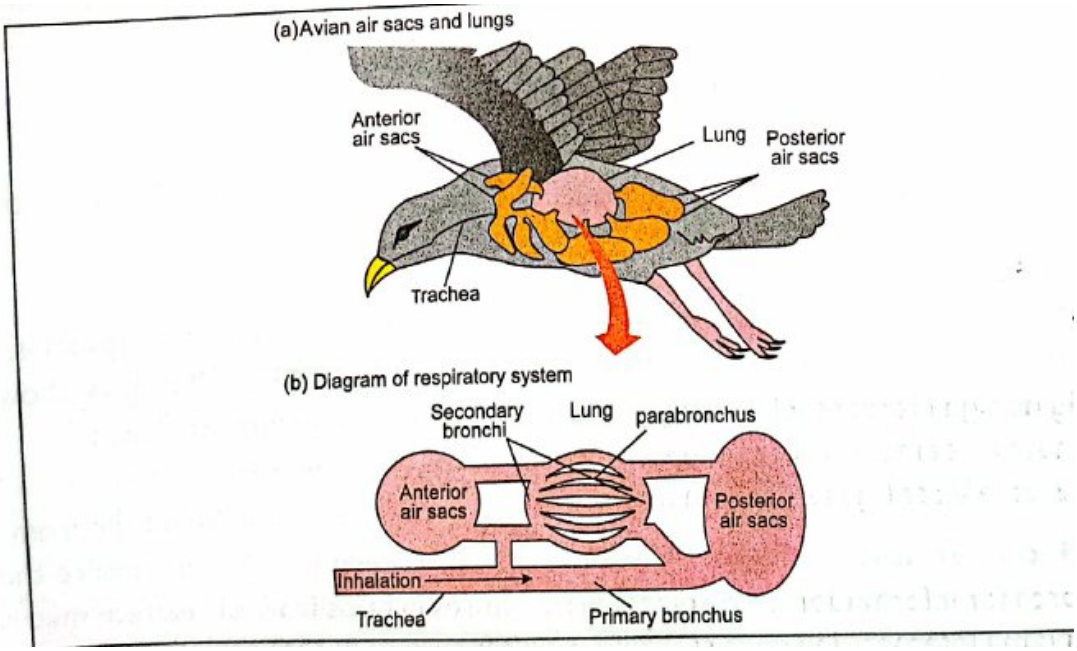


Figure 11: Respiratory system of a bird (a) and respiratory structure of a bird (b)

Structure	Modification	Function
Parabronchi (respiratory surface)	Highly vascularised, numerous, thin epithelial lining, moist epithelium.	Capillaries transport gases efficiently. Large numbers give a large surface area. Thinness shortens diffusion distance. Moisture dissolves gases.
Air sacs	Nine connected sacs in pairs.	Act as a reservoir of fresh air and keep air moving in one direction through the parabronchi.

Mammals: the human respiratory system

- The human respiratory system has nostrils, larynx, trachea, bronchi, lungs, diaphragm and a chest cavity made of ribs and intercostal muscles.

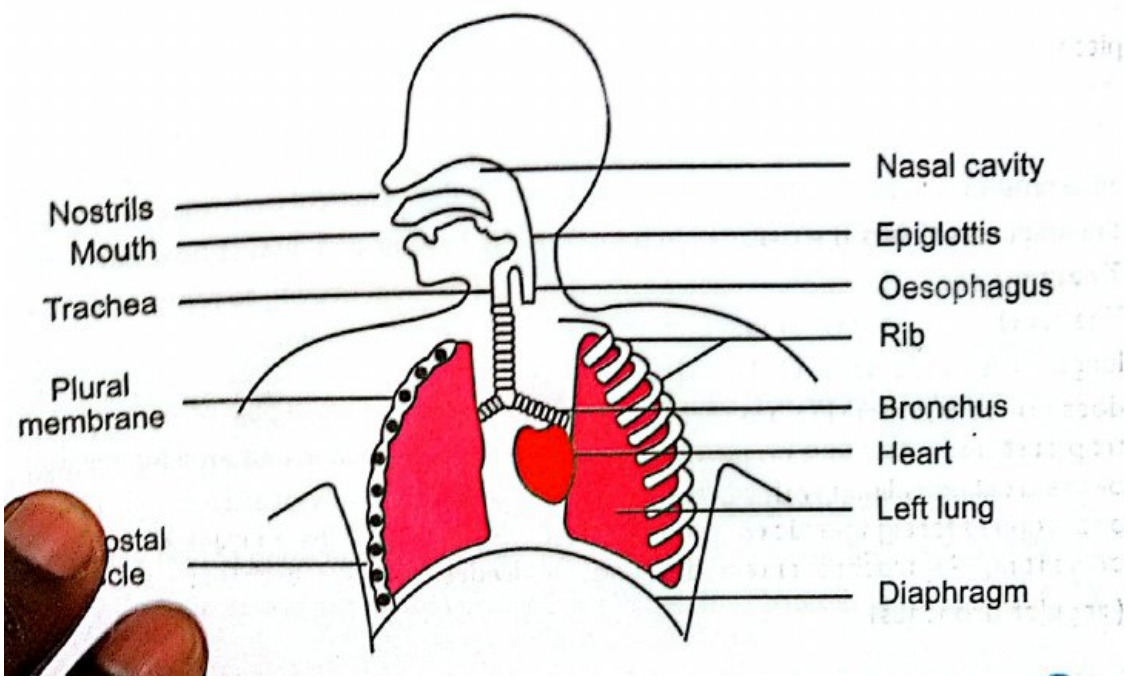


Figure 12 (a): Structure of the human respiratory system

Structure	Modification	Function
Nostrils	Two openings lined with hairs, warm and moist; the nasal cavity lining has olfactory cells.	Let air in and out. Hairs filter dust. Warmth and moisture condition the inhaled air. Olfactory cells detect smell.
Larynx	Located on top of the trachea, with muscle fibres and vocal cords.	The vocal cords control the pitch of the voice.
Glottis and epiglottis	The glottis is an opening on top of the larynx with a cartilage flap called the epiglottis.	The epiglottis stays open for breathing and closes the trachea during swallowing so food cannot enter the lungs.
Trachea	Hollow, with C-shaped rings of cartilage, goblet cells and a ciliated epithelium.	The hollow tube carries air. The C-shaped rings keep the trachea open and prevent collapse. Goblet cells secrete mucus that traps dust. Cilia beat in waves and move mucus and trapped particles towards the pharynx for swallowing or spitting.
Bronchi and bronchioles	The trachea divides into two bronchi, and each bronchus divides into bronchioles.	Carry air to the alveoli.
Lungs and pleural membranes	Lungs enclosed in a double pleural membrane with pleural fluid in the pleural cavity.	Pleural fluid lubricates the membranes so they glide over each other as the lungs inflate and deflate.
Alveoli	Groups of tiny air sacs covered by a network of blood capillaries, with thin and moist epithelium.	Capillaries transport gases. Thin epithelium shortens diffusion distance. Moisture dissolves gases. Many alveoli make the lungs spongy and give a large surface area.
Intercostal muscles	External and internal muscles between the ribs.	External muscles raise the rib cage upwards and outwards. Internal muscles lower it downwards and inwards. These movements change the volume and pressure of the thoracic cavity.
Diaphragm	A muscular sheet attached to the sternum that separates the thorax from the abdomen.	Contracts (flattens) to increase thoracic volume during breathing in. Relaxes (domes) to reduce thoracic volume during breathing out.

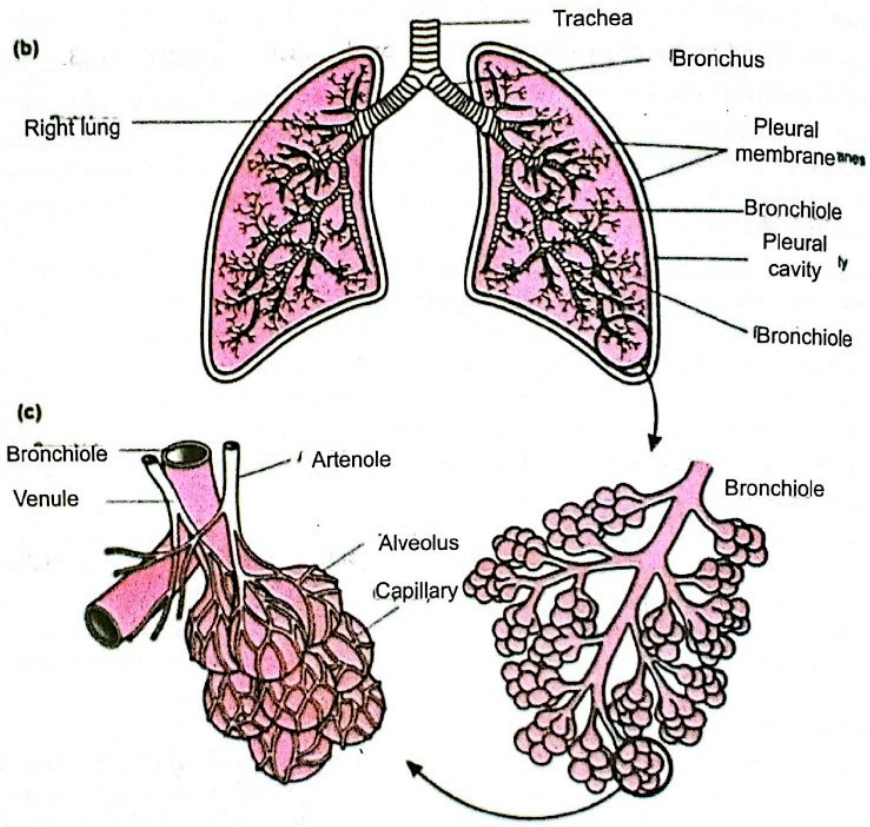


Figure 12 (b) and (c): Lungs and alveolus

Dissecting a rat or rabbit to examine respiratory structures (Activity 9)

- Pin the animal ventral side up on the dissecting board.
- Cut ventrally from the mouth towards the stomach to open the thorax.
- Pull the xiphoid cartilage to stretch the diaphragm, then identify the heart and lungs.
- Cut the trachea high up, pull it down together with the lungs, and connect a straw to the trachea to blow air in.
- Count the lobes of the lungs, and draw labelled diagrams of the structures.



Figure 13: Rat placed ventrally on a dissecting board

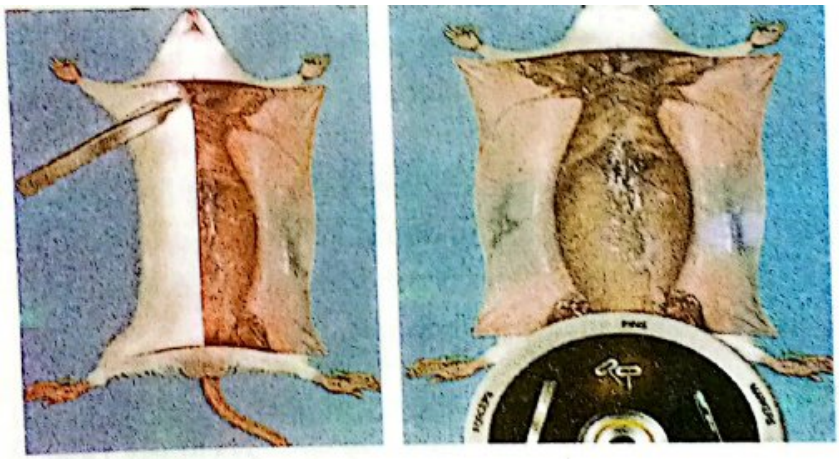


Figure 14 (a) and (b): Skin pinned to the sides



Figure 15: Diaphragm open

C. Mechanism of gaseous exchange in humans

- Effective gaseous exchange needs the lungs to be ventilated continuously.
- Breathing movements ventilate the lungs.
- Breathing is a physical process with changes in the volume and air pressure of the thoracic cavity.
- Movement of the ribs and the diaphragm causes these changes.
- Breathing in is also called inhalation or inspiration.
- Breathing out is also called exhalation or expiration.

Inspiration (breathing in)

- The external intercostal muscles contract and the internal intercostal muscles relax.
- This action pulls the rib cage upwards and outwards.
- At the same time, the diaphragm muscles contract and the diaphragm flattens from its dome shape.
- The upward and outward rib movement and the flattened diaphragm increase the volume of the thoracic cavity.
- The increase in volume lowers the pressure inside the thoracic cavity.
- Atmospheric pressure is now higher than the pressure inside the thoracic cavity.
- Air therefore rushes in through the nostrils and trachea and inflates the lungs.

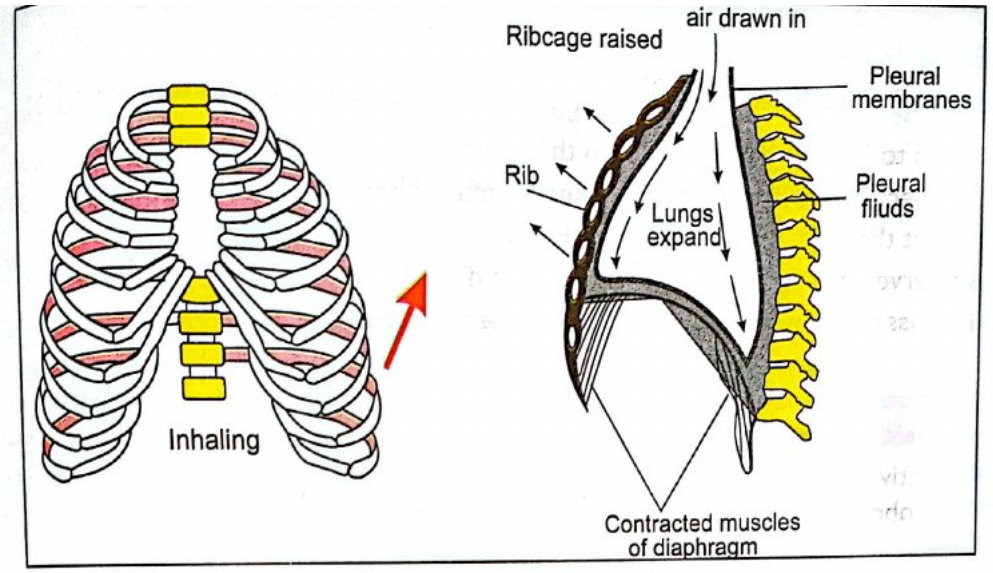


Figure 16: Movement of ribs (a) and inflation of lungs (b) during inspiration

Expiration (breathing out)

- The internal intercostal muscles contract and the external intercostal muscles relax.
- This action moves the rib cage downwards and inwards.
- At the same time, the diaphragm muscles relax and the diaphragm returns to its dome shape.
- These movements decrease the volume of the thoracic cavity.
- The decrease in volume raises the pressure inside the thoracic cavity.
- The higher pressure forces air out of the lungs through the trachea and nostrils, and the lungs deflate.

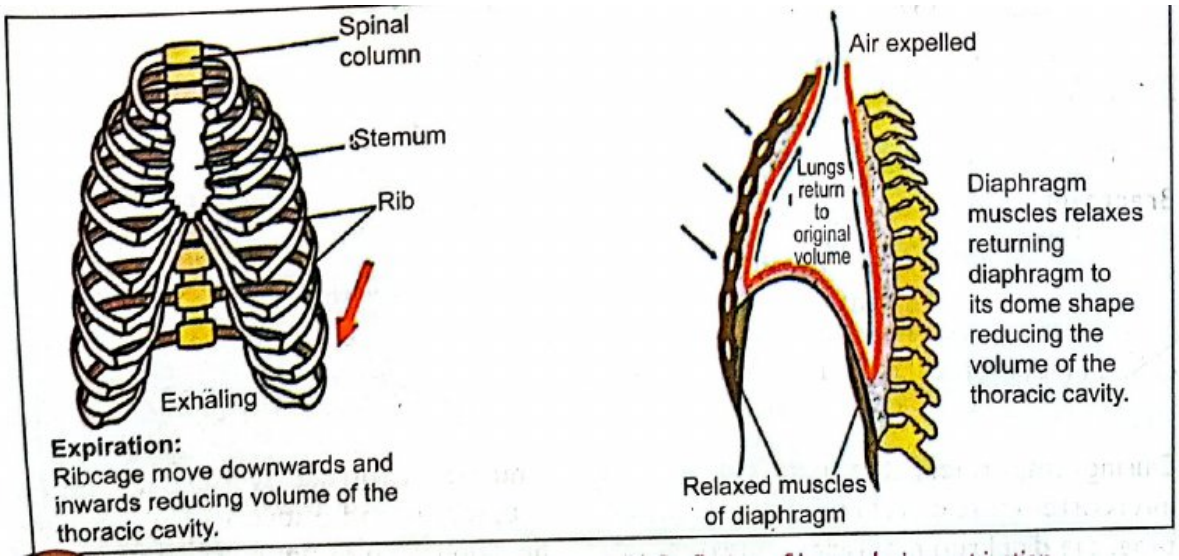


Figure 17: Movement of rib cage (a) and deflation of lungs (b) during expiration

Event	Inspiration	Expiration
External intercostal muscles	Contract	Relax
Internal intercostal muscles	Relax	Contract
Rib cage	Moves upwards and outwards	Moves downwards and inwards
Diaphragm	Contracts and flattens	Relaxes and domes
Thoracic volume	Increases	Decreases
Thoracic pressure	Decreases (below atmospheric)	Increases (above atmospheric)
Air movement	Into the lungs	Out of the lungs

Gaseous exchange in the alveoli

- Alveoli are groups of air sacs surrounded by thin-walled blood capillaries.
- A film of moisture covers the inner wall of each alveolus and dissolves oxygen from the inhaled air.
- Oxygen concentration is lower in the blood in the surrounding capillaries than in the film of moisture, which creates a concentration gradient.
- Oxygen diffuses along this gradient through the thin epithelium of the alveolus and the capillary wall into the bloodstream.
- In the blood, oxygen combines with haemoglobin and is transported to the body tissues.
- Carbon(IV) oxide concentration is higher in the blood reaching the alveolar capillaries than in the film of moisture, which creates the opposite gradient.
- Carbon(IV) oxide diffuses from the blood through the capillary wall and alveolar epithelium into the film of moisture.
- From the film of moisture, carbon(IV) oxide vaporises into the alveolar cavity and leaves the body when breathing out.

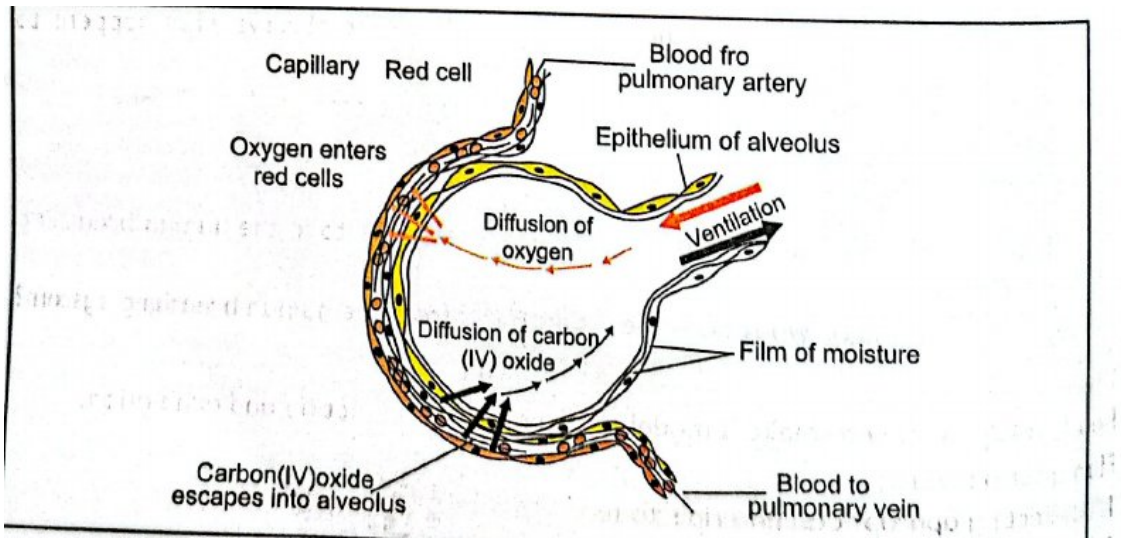


Figure 18: Exchange of gases in the alveolus

Gas	Percentage in inhaled air	Percentage in exhaled air
Oxygen	20	16.9
Carbon(IV) oxide	0.03	4.0
Nitrogen and other gases	79.97	79.97

- Exhaled air has less oxygen than inhaled air because the body uses oxygen for respiration.
- Exhaled air has more carbon(IV) oxide than inhaled air because respiration produces carbon(IV) oxide.
- The percentage of nitrogen and other gases stays the same because the body does not use these gases.

Model to demonstrate breathing (Activity 12)

- The model uses two balloons tied to a Y-shaped connector, a glass tube, a rubber stopper, a bell jar and a rubber sheet.
- The glass tube represents the trachea and the Y-shaped connector represents the bronchi.
- The balloons represent the lungs and the bell jar represents the chest cavity.
- The rubber sheet represents the diaphragm.

- Pulling the rubber sheet down increases the volume in the bell jar, so air rushes into the balloons and the balloons inflate.
- Releasing the rubber sheet decreases the volume in the bell jar, so air is forced out of the balloons and the balloons deflate.
- The model differs from the human system because the model has no ribs, no pleural membranes and no alveoli, and the diaphragm is a flat sheet.

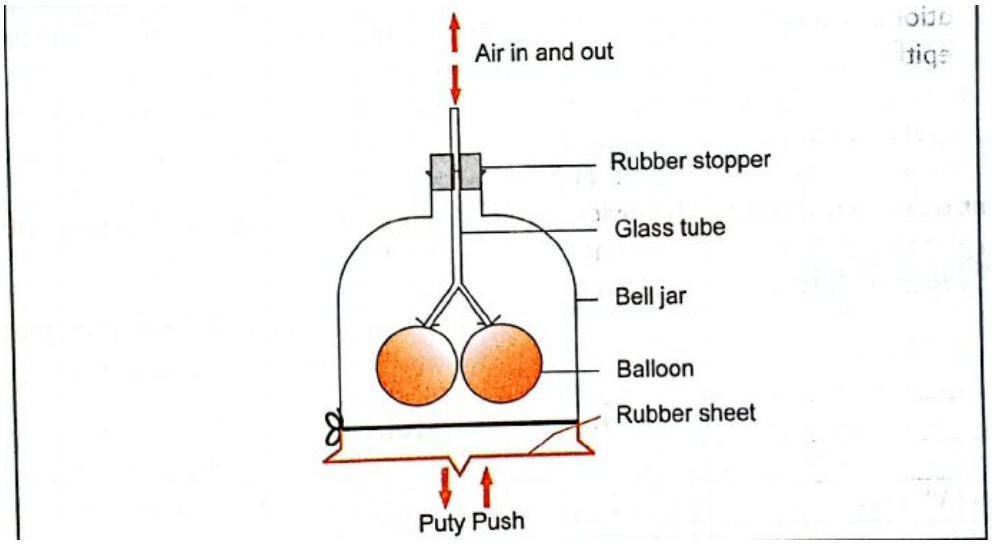


Figure 19: Model to demonstrate breathing in human beings

D. Aerobic and anaerobic respiration

- Respiration is the breakdown of food substances in cells in a series of enzyme-controlled reactions to release energy.
- Respiration takes place in the mitochondria and the cytoplasm of cells.
- Animals get the energy from ingested food substances.

Aerobic respiration

- Aerobic respiration is the chemical breakdown of food substances in the presence of oxygen to yield energy, carbon(IV) oxide and water.
- The energy released is very high and could burn the body cells.
- The cell therefore releases the energy in small quantities and in stages.

Glucose + Oxygen → Carbon(IV) oxide + Water + Energy (ATP)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy (ATP)}$$

- The textbook prints the glucose formula as C6H12O; the correct formula is C6H12O6.

ATP: the energy currency

- Some of the energy released in respiration is used to form adenosine triphosphate (ATP).
- ATP forms when energy joins adenosine diphosphate (ADP) to an inorganic phosphate.
- ATP stores energy in its bonds and makes the energy available to the cell when the cell needs it.
- ATP is the immediate source of energy for most biological activities.
- Energy is released when ATP breaks down to ADP and phosphate.

$$ADP + PO_4^{3-} + \text{energy} \rightarrow ATP$$

$$ATP \rightarrow ADP + PO_4^{3-} + \text{energy}$$

The two phases of aerobic respiration

Feature	Glycolysis	Krebs cycle
Order	First phase	Second phase
Site	Cytoplasm	Matrix of the mitochondria
Oxygen needed?	No	Yes
What happens	One glucose molecule breaks down into two molecules of pyruvate (pyruvic acid, a 3-carbon compound) and two molecules of ATP.	Pyruvic acid is oxidised by oxygen in a series of enzyme reactions into carbon(IV) oxide, water and energy.
Energy	2 ATP	Most of the ATP; the textbook gives 38 ATP per glucose for the whole process

- Pyruvic acid formed in glycolysis goes to the Krebs cycle if oxygen is available.
- If oxygen is not available, pyruvic acid breaks down only partially to lactic acid.

Glucose → Pyruvic acid + Energy (glycolysis)
Pyruvic acid + Oxygen → Carbon(IV) oxide + Water + Energy (Krebs cycle)

Conditions needed for respiration

- The cells must be supplied with food or glucose.
- Oxygen must be taken in to react with the glucose.
- Respiratory enzymes must be present to catalyse the reactions.
- A favourable temperature must be kept for efficient enzyme action.
- The end products (water, carbon(IV) oxide and ATP) must be removed constantly from the mitochondria.
- The skunk cabbage plant has a high respiratory rate that can produce temperatures as high as 37 °C, which makes a warm environment for pollinators.

Anaerobic respiration

- Anaerobic respiration is the breakdown of food substances without using oxygen.
- Anaerobic respiration takes place in the cytoplasm.
- Glucose is not broken down completely into carbon(IV) oxide and water in anaerobic respiration.
- An intermediate compound, lactic acid, is produced instead.
- Anaerobic respiration releases less energy than aerobic respiration because most of the energy stays locked in the lactic acid.
- Animal tissues can respire anaerobically for a limited time when oxygen is absent.
- Lactic acid becomes toxic if the lactic acid builds up in cells, so muscles must remove lactic acid quickly.
- Lactic acid can be broken down further to release its energy if oxygen becomes available.
- Anaerobic respiration lets cells keep obtaining energy even when oxygen is used up.

Glucose → Pyruvic acid + Energy
Pyruvic acid → Lactic acid + Energy

- Lactic acid fermentation is the breakdown of sugars to energy and lactic acid in animal tissues and in micro-organisms.
- Bacteria break down the sugar in milk to lactic acid and energy, which makes milk sour.
- Lactic acid also forms in muscles during strenuous exercise.

Feature	Aerobic respiration	Anaerobic respiration (animals)
Oxygen	Required	Not required

Feature	Aerobic respiration	Anaerobic respiration (animals)
Site	Cytoplasm and mitochondria	Cytoplasm
Breakdown of glucose	Complete	Incomplete
End products	Carbon(IV) oxide, water and energy	Lactic acid and a little energy
Energy yield	High (38 ATP per glucose in the textbook)	Low

Experiments on respiration

- Activity 15 investigates aerobic respiration in a grasshopper kept in a flask with sodium hydroxide pellets (soda lime) in a 37 °C water bath.
- The grasshopper takes in oxygen for respiration.
- The sodium hydroxide absorbs the carbon(IV) oxide the grasshopper produces.
- The total volume of gas in the flask falls, so the coloured water rises in the capillary tube.
- The rise of coloured water shows that organisms take in oxygen for the breakdown of food and release carbon(IV) oxide and water.

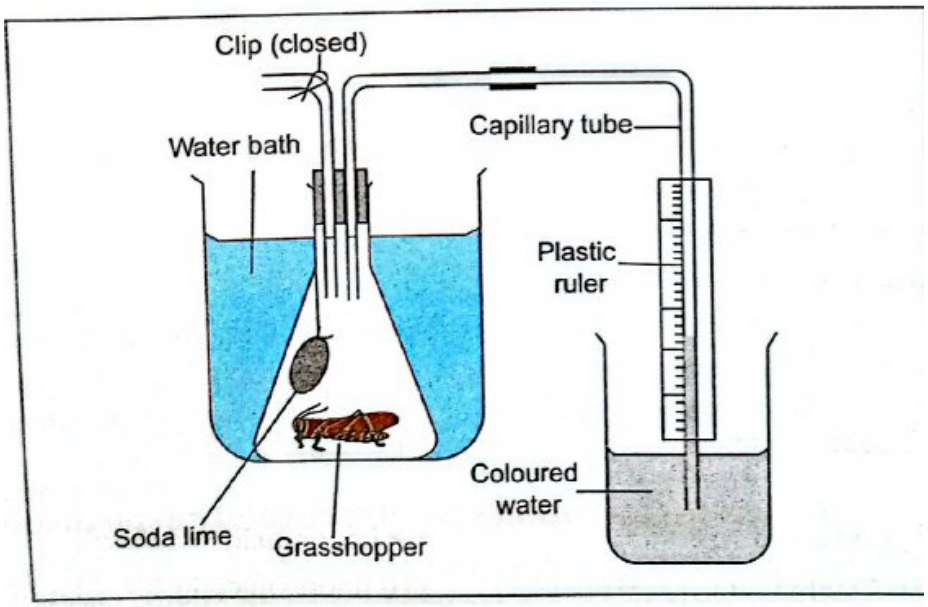


Figure 20: Experiment to investigate aerobic respiration

- Activity 16 investigates lactic acid fermentation by incubating 100 ml of boiled and cooled milk at 37 °C.
- The initial pH of the milk was about 7.1, which is slightly alkaline.
- The final pH was about 4.2, which is acidic.
- Lactobacillus bacteria broke down the lactose in the milk anaerobically to lactic acid and energy.
- The lactic acid lowered the pH of the milk.

Factors affecting the rate of respiration

Factor	Effect on rate of respiration	Reason
Oxygen concentration	Low oxygen gives a low rate; high oxygen gives a high rate.	Oxygen is needed to oxidise food substrates.
Substrate (glucose) concentration	More glucose raises the rate; less glucose lowers the rate.	Glucose is the main respiratory substrate.
Temperature	Rate rises up to the optimum, then falls.	Respiration is enzyme-controlled. Temperatures above the optimum denature enzymes. Low temperatures inactivate enzymes.
Age	Younger organisms have a higher rate.	Younger organisms have higher metabolic rates and a higher demand for energy.
Emotions	Anger, fear and anxiety raise the rate.	These emotions stimulate adrenaline, which increases glucose metabolism.
Surface area to volume ratio	A high ratio raises the rate.	A high ratio loses more heat, so more energy must be produced to replace it.

Exercise, lactic acid and oxygen debt

- During strenuous exercise such as sprinting, muscle cells use oxygen rapidly to provide energy for contraction.
- Oxygen demand then exceeds oxygen supply.
- The muscle cells respire anaerobically and produce lactic acid and energy.
- Lactic acid build-up causes muscle fatigue and cramps.
- Oxygen debt is the extra oxygen needed to remove the lactic acid that builds up when oxygen supply is less than demand.
- The body pays back the oxygen debt by breathing faster and deeper during recovery.
- The heart beats faster to carry oxygen to the muscles and lactic acid from the muscles to the liver.
- In the liver, some lactic acid is oxidised to carbon(IV) oxide, water and energy, and some is converted to glycogen.
- Breathing rate rises after exercise because the body needs more oxygen to remove the lactic acid.



Figure 21: An athlete panting after a race

Energy requirements and respiratory substrates

- The amount of energy released depends on the food substrate that is oxidised.

- One gram of carbohydrate yields about 17 kJ of energy.
- One gram of protein yields about 22 kJ of energy.
- One gram of fat yields about 38 kJ of energy, although the textbook gives 31 kJ in one place.

Factors affecting daily energy requirement in humans

- Basal metabolic rate (BMR) is the basic minimum amount of energy that a person needs to keep body cells alive at rest.
- BMR drives functions such as brain and nerve activity, temperature control, breathing, heartbeat, making enzymes and hormones, and cell growth.
- BMR is 45% to 70% of the total daily energy expenditure.
- Age, sex and body size determine BMR.

Factor	Effect on energy requirement	Reason
Age	Young children need more energy per kilogram; energy need falls with age.	Children have many actively dividing cells and are physically more active. Adults become less active.
Sex	Males need more energy than females of the same age.	From puberty males develop more muscle and females store more fat. Muscle is more metabolically active than fat.
Body size	Small people need more energy-giving food per kilogram.	Small bodies have a large surface area to volume ratio and lose more heat. Big bodies retain more heat.
Occupation or daily activity	Manual workers need more energy than office workers.	Heavy physical work uses more energy.
Pregnancy and lactation	Higher energy need.	Pregnant women need energy for growth of maternal tissues such as breast and placenta. Lactating mothers need energy for milk production.

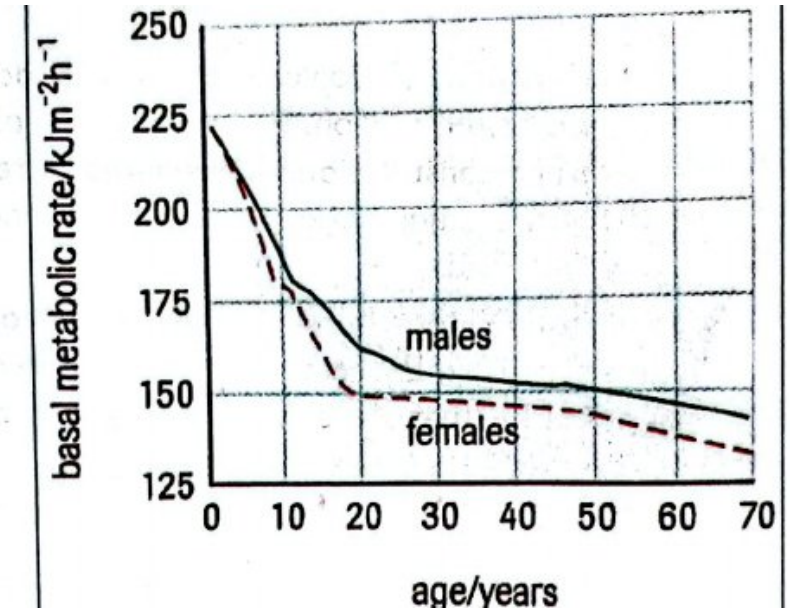


Figure 22: Graph showing how BMR declines with age

Age (years)	Male (kJ per day)	Female (kJ per day)
2	5,500	5,500
5	7,000	7,000
8	8,800	8,800
11	10,000	9,200

Age (years)	Male (kJ per day)	Female (kJ per day)
14	12,500	10,500
18	14,200	9,600
25	12,100	8,800

Respiratory substrates

- Respiratory substrates are energy-rich food substances that release energy when they are oxidised.
- The three main respiratory substrates are carbohydrates, lipids (fats and oils) and proteins.

Substrate	Use in respiration	Energy per gram	Dietary sources
Carbohydrates	Main source of energy. Glucose is oxidised directly. Starch, cellulose and glycogen are first hydrolysed to monosaccharides by enzymes.	About 17 kJ (2898 kJ per mole of glucose)	Maize, rice, fruits, sweet potatoes, sugarcane, sorghum, yams, cassava
Lipids (fats and oils)	Used mainly when carbohydrate reserves are used up. Hydrolysed first to fatty acids and glycerol.	About 38 kJ	Sesame, sunflower, groundnuts, coconut, cashew nuts, milk, ghee, meat, cheese, butter
Proteins	Not normally used. Used in extreme starvation when carbohydrates and fats are absent. First converted to carbohydrates.	About 22 kJ	Beans, peas, groundnuts, sesame, cashew nuts, meat, milk, eggs, cheese

- Fats are not the main respiratory substrate because fats are not very soluble and are not transported easily to the sites of respiration.
- Oxidising one gram of fat also needs more oxygen than oxidising one gram of glucose.

Respiratory quotient (RQ)

- Respiratory quotient is the ratio of the volume of carbon(IV) oxide produced to the volume of oxygen used in respiration.
- Respiratory quotient helps to determine the type of substrate being oxidised and the type of respiration taking place.

Respiratory quotient (RQ) = Volume of CO_2 produced ÷ Volume of O_2 used

Substrate	Example equation	RQ
Carbohydrate (glucose)	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$; RQ = 6 ÷ 6	1.0
Lipid (oleic acid)	$2C_{18}H_{34}O_2 + 51O_2 \rightarrow 36CO_2 + 34H_2O$; RQ = 36 ÷ 51	0.7
Protein (amino acid)	$C_7H_{15}NO_2 + 9O_2 \rightarrow 7CO_2 + 7H_2O + NH_3$; RQ = 7 ÷ 9	0.8 (textbook average 0.9)

- For carbohydrates, the carbon(IV) oxide produced equals the oxygen used, so the RQ is 1.0.
- For lipids and proteins, the carbon(IV) oxide produced is less than the oxygen used, so the RQ is below 1.0.
- An RQ above 1.0 indicates anaerobic respiration.
- An RQ above 1.0 may mean the animal is not getting enough oxygen and lactic acid may be building up in the muscles.

Worked answers to Table 3 of the textbook

Food	CO_2 produced	O_2 consumed	RQ	Comment
A	12	12	1.0	Carbohydrate, aerobic respiration
B	360	510	0.71	Lipid (fat), aerobic respiration
C	252	280	0.9	Protein, aerobic respiration
D	4	3	1.33	RQ above 1.0: anaerobic respiration

Importance of gaseous exchange and respiration

- Gaseous exchange and respiration are essential processes in animals.
- Respiration is a chemical process, while gaseous exchange is a physical process.
- Gaseous exchange lets animals get oxygen for respiration.
- Gaseous exchange also lets animals remove the carbon(IV) oxide made during respiration.
- Respiration yields energy for muscular contraction, secretion of enzymes, cell division, repair of worn-out tissues and functioning of major organs such as the brain, heart and kidneys.

Assessment questions (with answers)

1. What is a respiratory surface?

Answer: The site of the respiratory system where gaseous exchange occurs.

2. State four characteristics of an effective respiratory surface and give the reason for each.

Answer: Highly vascularised (blood carries gases away quickly); large surface area (more diffusion); moist lining (gases dissolve); thin epithelium (short diffusion distance).

3. Name the respiratory surface of (i) a mammal, (ii) a bony fish, (iii) an insect, (iv) a bird and (v) a frog.

Answer: (i) Alveoli. (ii) Gill filaments. (iii) Tracheoles. (iv) Parabronchi. (v) Skin, buccal cavity lining and alveoli of the lungs.

4. Give three ways, apart from being moist, in which the skin of a frog is adapted for gaseous exchange.

Answer: It is thin, which shortens the diffusion distance. It has a rich network of blood capillaries, which transports gases efficiently. It has a large surface area, which allows more diffusion.

5. Describe the structure of the insect tracheal system and the function of spiracles, tracheae and tracheoles.

Answer: Spiracles are valved openings that admit air and reduce water loss; tracheae are large chitin-reinforced tubes that carry air; tracheoles are fine, moist, chitin-free tubes that supply oxygen to cells by diffusion.

6. Explain why the trachea of an insect is not ideal for gaseous exchange.

Answer: Its wall is reinforced with impermeable chitin bands, so gases cannot diffuse through the wall.

7. Explain how spiracles are adapted to prevent water loss and dust entry.

Answer: They have muscular valves that close, and hairs that trap dust and reduce evaporation.

8. Describe how air enters and leaves the tracheal system of a locust.

Answer: Muscular movement of the abdominal wall pumps air; thoracic spiracles open for breathing in and abdominal spiracles open for breathing out.

9. How are the tracheal gills of dragonfly larvae and the respiratory siphon of mosquito larvae adapted for gaseous exchange?

Answer: Tracheal gills have a thin permeable cuticle and are fanned to bring fresh water. The siphon pierces the water surface to take in atmospheric air and closes when the larva submerges.

10. Explain why oil was used to control mosquito larvae.

Answer: Oil lowers the surface tension of the water, so the larvae cannot attach to the surface to get oxygen and they die.

11. Name the parts of a fish gill and give the function of each.

Answer: Gill bar supports rakers and filaments. Gill rakers filter solid particles. Gill filaments are the site of gaseous exchange. The operculum protects the gills and pumps water over them.

12. Explain how gill filaments are adapted for gaseous exchange.

Answer: They are numerous and long (large surface area), highly vascularised (efficient transport), thin-walled (short diffusion distance) and permeable.

13. What is countercurrent flow and why is it efficient?

Answer: Water and blood flow in opposite directions across the gill filaments, which keeps a concentration gradient along the whole filament so more oxygen diffuses into the blood.

14. Explain why a bony fish dies shortly after removal from water.

Answer: The gill filaments collapse, stick together and dry, so the surface area and moisture are lost and the fish cannot take in oxygen.

15. State the respiratory surfaces of a frog and explain why a toad does not use its skin.

Answer: Buccal cavity lining, lungs and skin. Toads have a drier, less permeable skin, so toads use skin only when hibernating.

16. Explain how the structure of a bird's respiratory system suits the high oxygen demand of flight.

Answer: Air sacs act as a fresh-air reservoir and air flows one way through numerous, vascularised, thin parabronchi, so exchange is very efficient.

17. Explain the function of (i) the epiglottis, (ii) C-shaped cartilage rings, (iii) goblet cells and (iv) cilia in the trachea.

Answer: (i) Closes the trachea when swallowing. (ii) Keep the trachea open. (iii) Secrete mucus that traps dust. (iv) Beat to move mucus and dust towards the pharynx.

18. Give three adaptations of the alveolus for gaseous exchange.

Answer: Covered by a network of capillaries, thin epithelium, and a moist lining; the large number of alveoli gives a large surface area.

19. Describe what happens in the thorax during inspiration.

Answer: External intercostals contract, ribs move up and out, diaphragm contracts and flattens, thoracic volume increases, pressure falls, and air rushes in.

20. Describe what happens in the thorax during expiration.

Answer: Internal intercostals contract, ribs move down and in, diaphragm relaxes and domes, volume decreases, pressure rises, and air is forced out.

21. Explain what would happen to breathing if the intercostal muscles were damaged by a disease.

Answer: Rib movement would be limited, so thoracic volume would change less and breathing would rely mostly on the diaphragm and become shallow.

22. Explain the difference in gas composition between inhaled and exhaled air.

Answer: Exhaled air has less oxygen (16.9% against 20%) because oxygen is used in respiration, and more carbon(IV) oxide (4.0% against 0.03%) because respiration produces it.

23. Explain how oxygen moves from the alveolus to the blood and carbon(IV) oxide moves the other way.

Answer: Oxygen dissolves in the moisture film, then diffuses down its concentration gradient into the capillaries. Carbon(IV) oxide diffuses down its gradient from the blood into the alveolus and is exhaled.

24. Write the word and chemical equation for aerobic respiration.

Answer: Glucose + oxygen → carbon(IV) oxide + water + energy; $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy.

25. State the site and products of glycolysis and of the Krebs cycle.

Answer: Glycolysis: cytoplasm, gives pyruvic acid and 2 ATP without oxygen. Krebs cycle: mitochondrial matrix, gives carbon(IV) oxide, water and energy and needs oxygen.

26. Explain why energy is released in small stages in aerobic respiration.

Answer: Releasing all the energy at once would produce heat that could burn the cells.

27. What is ATP and why is it important?

Answer: Adenosine triphosphate is an energy-rich molecule that stores energy from respiration and gives immediate energy for cell activities when broken down to ADP and phosphate.

28. Compare aerobic and anaerobic respiration in animals.

Answer: Aerobic needs oxygen, breaks glucose down completely to carbon(IV) oxide and water and gives much energy. Anaerobic needs no oxygen, gives lactic acid and little energy.

29. Taiz got muscle cramps after playing soccer for 30 minutes. Explain.

Answer: His muscles used oxygen faster than it was supplied, respired anaerobically and produced lactic acid, which caused fatigue and cramps.

30. Define oxygen debt and give two changes that help to recover it.

Answer: Oxygen debt is the extra oxygen needed to remove accumulated lactic acid. The body breathes faster and deeper, and the heart beats faster.

31. Explain the results of the grasshopper experiment with sodium hydroxide.

Answer: The grasshopper used oxygen, the sodium hydroxide absorbed its carbon(IV) oxide, so the gas volume fell and coloured water rose up the capillary tube.

32. Explain why the pH of milk fell from about 7.1 to 4.2 after incubation.

Answer: Lactobacillus bacteria broke down lactose anaerobically to lactic acid, which lowered the pH.

33. State four factors affecting the rate of respiration and explain the effect of temperature.

Answer: Oxygen concentration, glucose concentration, temperature, age, emotions. High temperatures denature respiratory enzymes and low temperatures inactivate them, so the rate falls on both sides of the optimum.

34. Explain why males generally have a higher energy requirement than females of the same age.

Answer: Males develop more muscle and females store more fat, and muscle is more metabolically active than fat.

35. Explain why small-bodied people need more energy-giving food per kilogram.

Answer: They have a large surface area to volume ratio, so they lose more heat and must produce more energy to replace it.

36. Name the three respiratory substrates and state which yields the most energy per gram.

Answer: Carbohydrates, lipids and proteins. Lipids (fats) yield the most energy per gram.

37. Give two reasons why fats are not the main respiratory substrate.

Answer: Fats are poorly soluble and not easily transported to respiration sites, and fats need more oxygen per gram to oxidise.

38. Define respiratory quotient and give its value for carbohydrates, proteins and lipids.

Answer: RQ is the volume of carbon(IV) oxide produced divided by the volume of oxygen used. Carbohydrates 1.0, proteins about 0.9, lipids about 0.7.

39. Calculate the RQ of glucose given $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$.

Answer: RQ = 6 ÷ 6 = 1.0.

40. Calculate the RQ for germinating seeds A (8.5 cm³ oxygen used, 10.2 cm³ carbon(IV) oxide produced) and B (9.1 cm³ used, 6.3 cm³ produced). Which came from flooded soil?

Answer: A: 10.2 ÷ 8.5 = 1.2. B: 6.3 ÷ 9.1 = 0.69. Seeds A came from flooded soil because an RQ above 1.0 shows anaerobic respiration caused by too little oxygen.

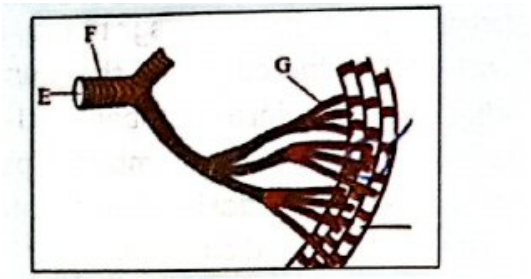
41. What does an RQ above 1.0 indicate?

Answer: Anaerobic respiration, possibly because oxygen is not sufficient and lactic acid is building up.

42. Explain why gaseous exchange and respiration are important to animals.

Answer: Gaseous exchange supplies oxygen and removes carbon(IV) oxide. Respiration releases energy for muscle contraction, enzyme secretion, cell division, tissue repair and organ function.

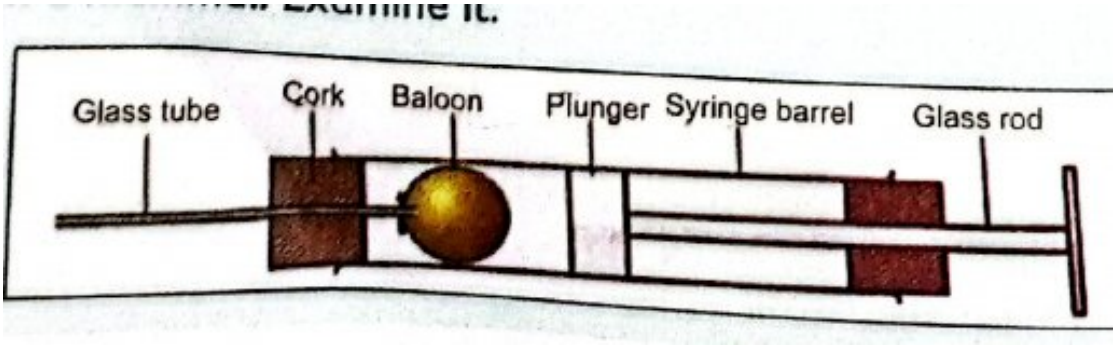
Diagram-based questions from the textbook



Question diagram: parts E, F and G of an insect tracheal system.

Identify parts E, F and G and explain why part F is not ideal for gaseous exchange.

Answer: E is the spiracle, F is the trachea and G is the tracheoles. F has impermeable chitin bands, so gases cannot diffuse through its wall.



Question diagram: apparatus to demonstrate breathing in a mammal.

Identify the mammalian structure represented by the balloon, the syringe barrel and the plunger, and say what happens to the balloon when the plunger is pulled away.

Answer: The balloon is a lung, the syringe barrel is the chest cavity (thorax) and the plunger is the diaphragm. Pulling the plunger away increases the volume and lowers the pressure, so air rushes in and the balloon inflates.