

B3.1 Gas exchange

Form and function—Organisms

Standard level and higher level: 3 hours

Additional higher level: 1 hour

Guiding questions

- How are multicellular organisms adapted to carry out gas exchange?
- What are the similarities and differences in gas exchange between a flowering plant and a mammal?

SL and HL

B3.1.1—Gas exchange as a vital function in all organisms

Students should appreciate that the challenges become greater as organisms increase in size because surface area-to-volume ratio decreases with increasing size, and the distance from the centre of an organism to its exterior increases.

- **Gas exchange** is the process by which gases **passively diffuse** across a surface
- Organisms need gas exchange to acquire metabolic reactants (O_2) and expel waste products (CO_2)
- Small (unicellular) organisms carry out gas exchange directly across their body surface
- Large organisms require **specialized gas exchange surfaces**
 - **Surface area-to-volume ratio** decreases with increasing organism size
 - **Distance from the center of an organism** to its exterior increases with increasing organism size, so a transport system is needed to deliver gases exchanged at the surface to inner body cells

B3.1.2—Properties of gas-exchange surfaces

Include permeability, thin tissue layer, moisture and large surface area.

Gas-exchange surfaces are adapted for increasing diffusion rate and efficiency:

- **Permeability:** oxygen and carbon dioxide are **small non-polar molecules** that can diffuse through gas exchange surfaces (like stomata or plasma membranes)
- **Thin tissue layer:** reduces the diffusion distance to improve rate of gas exchange
- **Moisture:** allows gases to dissolve, which helps them move between air & cells more efficiently
- **Large surface area:** increases the number of gas molecules that can diffuse at the same time

B3.1.3—Maintenance of concentration gradients at exchange surfaces in animals

Include dense networks of blood vessels, continuous blood flow, and ventilation with air for lungs and with water for gills.

- **Concentration (or pressure) gradients** are necessary for passive diffusion of gases, so organisms must be adapted to maintain them
- For example, in alveolar lungs of a mammal:
 - **Dense networks of blood vessels** surround gas exchange surfaces to reduce diffusion distance
 - **Continuous blood flow** prevents the equilibration of gases near exchange surfaces
 - **Ventilation with air** in lungs introduces fresh air with high O₂ and low CO₂ to maintain gradients
- For example, in fish:
 - Water flows through the mouth, then gills, then exits; this **unidirectionality** enhances gas exchange
 - Blood in capillaries flows in the **opposite direction** to water in the gills to maintain gradients

B3.1.4—Adaptations of mammalian lungs for gas exchange

Limit to the alveolar lungs of a mammal. Adaptations should include the presence of surfactant, a branched network of bronchioles, extensive capillary beds and a high surface area.

- **Airway branching:** air enters the **trachea** in the lungs, which splits into a **branched network of bronchioles** that distribute air to alveoli & reduce air velocity to allow for efficient gas exchange
- **Alveoli** (functional unit of mammalian lungs) are small air sacs where gas exchange occurs; their small size allows gas concentrations (like O₂) to quickly establish a gradient with blood capillaries
- **Extensive capillary beds** surround the alveoli to increase surface area for gas exchange
- **Pulmonary surfactant** produced by **type II pneumocytes** is composed of phospholipids & proteins
 - A thin layer of water (moisture) lines the alveoli due to leakage from the interstitium; it increases surface tension within the alveoli & risks their collapse despite providing essential moisture
 - The **surfactant reduces surface tension** in alveoli by forming a **phospholipid monolayer** at the **air-water interface**, which regulates the effects of moisture & prevents alveolar collapse
- The alveolar walls are composed of mostly **type I pneumocytes** which are very thin to reduce diffusion distance

B3.1.5—Ventilation of the lungs

Students should understand the role of the diaphragm, intercostal muscles, abdominal muscles and ribs.

- **Ventilation (breathing)** is the movement of air due to pressure differences between the atmosphere and the gases in the lungs
- **Inspiration (inhalation)** is the movement of air from the atmosphere into the lungs due to an **increase in the volume of the thoracic cavity**, which **decreases pressure in the lungs** to drive air entry
 - **Diaphragm** contracts & flattens
 - **External intercostal muscles** contract to move the **ribcage outwards & upwards**
 - **Internal intercostal muscles** relax
 - **Abdominal wall muscles** relax
- **Expiration (exhalation)** is the movement of air from the lungs into the atmosphere due to a **decrease in the volume of the thoracic cavity**, which **increases pressure in the lungs** to allow air to leave
 - **Diaphragm** relaxes & adopts dome-shaped curvature
 - **External intercostal muscles** relax
 - **Internal intercostal muscles** contract to move the **ribcage inwards & downwards**
 - **Abdominal wall muscles** contract to further **reduce the volume of the thoracic cavity**

B3.1.6—Measurement of lung volumes

Application of skills: Students should make measurements to determine tidal volume, vital capacity, and inspiratory and expiratory reserves.

- **Lung volume** is the amount of air in the lungs at a given time during breathing
- **Spirometers** are commonly used to determine lung volumes by measuring the amount & velocity of inhaled & exhaled air
 - **Tidal volume (TV):** the amount of air exhaled or inhaled during one breath
 - **Inspiratory Reserve Volume (IRV):** the amount of air that can be forcibly inhaled after the TV, for example during a deep inhalation
 - **Expiratory Reserve Volume (ERV):** the amount of air that can be forcibly exhaled after the TV, for example during a cough
 - **Residual Volume (RV):** the amount of air in the lungs after maximal exhalation (cannot be measured by spirometry)
- **Vital Capacity (VC)** is the total amount of air exhaled after maximum inhalation; $IRV + TV + ERV$

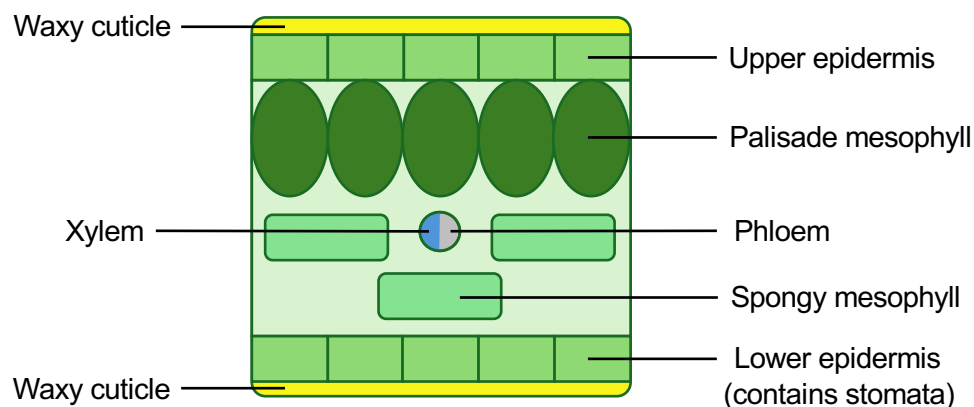
B3.1.7—Adaptations for gas exchange in leaves

Leaf structure adaptations should include the waxy cuticle, epidermis, air spaces, spongy mesophyll, stomatal guard cells and veins.

- **Waxy cuticle** covers the leaf surface & is composed of lipids to reduce water loss by evaporation
- **Upper epidermis cells** produce and secrete the waxy cuticle
- **Palisade mesophyll cells** are densely packed together under the upper epidermis for maximal exposure to sunlight & contain many chloroplasts for photosynthesis
- **Spongy mesophyll cells** are loosely packed under the palisade mesophyll & contain many air spaces to provide a high surface area for gas exchange
- **Veins (vascular bundles)** contain xylem and phloem tubes that help transport nutrients to leaf cells
- **Lower epidermis cells** produce/secrete waxy cuticle & contain stomata
- **Stomata** are microscopic openings in the lower epidermis that are **opened** when **guard cells swell** & **closed** when guard cells shrink

B3.1.8—Distribution of tissues in a leaf

Students should be able to **draw and label a plan diagram** to show the distribution of tissues in a transverse section of a dicotyledonous leaf.



B3.1.9—Transpiration as a consequence of gas exchange in a leaf

Students should be aware of the factors affecting the rate of transpiration.

- **Transpiration** is the loss of water by evaporation through stomata
- Spongy mesophyll cells contain a thin layer of water (moisture) which is lost by the plant through evaporation when stomata are open (but it is replenished by water from xylem vessels)
- Transpiration rate is affected by:
 - **Sunlight** stimulates stomatal opening, which **increases transpiration**
 - **Higher temperatures increase transpiration** by providing the energy needed for evaporation
 - **Wind increases transpiration** by increasing evaporation at the leaf surface, which creates a stronger water concentration gradient between the inside & outside of leaves
 - **Higher humidity** in the environment **decreases transpiration** as it reduces the water concentration gradient between the inside & outside of leaves

B3.1.10—Stomatal density

Application of skills: Students should use micrographs or perform leaf casts to determine stomatal density.

$$\text{Stomatal density} = \frac{\text{Number of stomata}}{\text{Area of field view (mm}^2\text{)}}$$

- **Stomatal density** is the number of stomata per unit area of a leaf surface
- It can be calculated by mounting a thin layer of epidermis onto a light microscope & counting the number of stomata in a **field of view** (the area of the leaf surface visible through the microscope at a specific magnification)
- Instead of cutting a leaf, nail polish can be painted over the leaf surface & dried, which creates an imprint (**leaf cast**) of the leaf surface (including stomata) on the nail polish that can be examined under a microscope when the nail polish is removed from the leaf by tape

NOS: Reliability of quantitative data is increased by repeating measurements. In this case, repeated counts of the number of stomata visible in the field of view at high power illustrate the variability of biological material and the need for replicate trials.

Multiple areas of a single leaf can be used to calculate stomatal density in order to account for variation, which increases the reliability of the collected quantitative data.

Additional higher level

B3.1.11—Adaptations of foetal and adult haemoglobin for the transport of oxygen

Include cooperative binding of oxygen to haem groups and allosteric binding of carbon dioxide.

- **Hemoglobin (Hb)** is a protein in **red blood cells (erythrocytes)** that carries up to 4 oxygen molecules
- Hb is composed of **4 polypeptide subunits**; each subunit has an **iron-containing heme group** that binds 1 oxygen molecule & an **allosteric site** that binds carbon dioxide
- **Cooperative binding** is the phenomena where the binding of O₂ to any Hb subunit increases the affinity of the other subunits to oxygen
- **Adult Hb** is composed of **2 α chains & 2 β chains** but **fetal Hb** is composed of **2 α chains & 2 γ chains** (which have a higher affinity for oxygen than β chains)
 - In the **placenta**, O₂ dissociates from adult Hb & binds to fetal Hb due to its higher affinity; this helps deliver oxygen to the fetus during pregnancy

B3.1.12—Bohr shift

Students should understand how an increase in carbon dioxide causes increased dissociation of oxygen and the benefits of this for actively respiring tissues.

- CO₂ is produced by actively respiring tissues & decreases Hb affinity to O₂ in 2 ways:
 - CO₂ binds each Hb subunit directly at its **N-terminal (allosteric site)**, which causes a conformational change in Hb that **decreases** its **affinity** for O₂
 - CO₂ is converted to **carbonic acid** in the blood, which **reduces blood pH & lowers Hb affinity** to O₂
- **Bohr shift** is the reduction in Hb affinity to O₂ in areas of high CO₂/low pH (i.e. high metabolic activity), which increases O₂ unloading to tissues with high metabolic activity (e.g. muscles)

B3.1.13—Oxygen dissociation curves as a means of representing the affinity of haemoglobin for oxygen at different oxygen concentrations

Explain the S-shaped form of the curve in terms of cooperative binding.

- The **oxygen dissociation curve** represents **Hb's oxygen saturation (y-axis)** against the **partial pressure of oxygen in the blood (x-axis)**
- The **sigmoid (S-shape)** form of the curve is due to cooperative binding; oxygen saturation is **not** directly proportional to oxygen partial pressure in the blood
- The oxygen dissociation curve of fetal Hb lies to the **left** of the adult Hb curve due to the higher affinity of fetal Hb to oxygen
- The oxygen dissociation curve **shifts to the right** to **increase oxygen release** (i.e. reduce affinity) at **high CO₂** and **low pH**
- The oxygen dissociation curve **shifts to the left** to **decrease oxygen release** (i.e. increase affinity) at **low CO₂** and **high pH**

Linking questions

- How do multicellular organisms solve the problem of access to materials for all their cells?
- What is the relationship between gas exchange and metabolic processes in cells?

Review questions

SL and HL

- Explain why larger organisms require specialized gas exchange surfaces. [2]
- Outline **two** methods for determining stomatal density. [2]
- Explain the importance of maintaining concentration gradients in gas exchange. [2]
- Explain how concentration gradients are maintained in mammalian lungs. [3]
- Outline the properties of gas exchange surfaces. [4]
- Explain how ventilation helps to maintain concentration gradients in humans and fish. [4]
- Outline the factors that affect transpiration. [4]
- Draw and label a plant diagram to show the distribution of tissues in a transverse section of a dicotyledonous leaf. [7]
- Explain how leaves are adapted for gas exchange. [7]
- Describe the mechanism of ventilation in mammalian lungs. [8]
- Compare and contrast gas exchange in a flowering plant and a mammal. [8]

Additional Higher Level

- Define the Bohr shift. [1]
- State **two** factors that can affect the affinity of hemoglobin to oxygen. [2]
- Describe the structure of hemoglobin. [3]
- Outline how foetal and adult haemoglobin are adapted for transport of oxygen. [3]
- Explain the S-shaped form of the curve in terms of cooperative binding. [3]
- Compare and contrast allosteric binding of non-competitive inhibitors to enzymes and carbon dioxide to hemoglobin. [3]
- Explain how the structure of hemoglobin regulates oxygen delivery to body tissues. [4]
- Explain the significance of cooperative binding in hemoglobin. [4]
- Explain how changes in metabolic activity of body tissues affects oxygen delivery. [5]
- Discuss the relationship between gas exchange and metabolic processes in cells. [8]

References

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