Edexcel (B) Biology A-level

Topic 4: Exchange and Transport

Notes

Single-celled organisms do not have specialised transport systems. Substances can enter the cell by passive transport as the diffusion distances are short. However, multicellular organisms require specialised transport systems and gas exchange surfaces. This is because:

- Diffusion distance is greater
- Metabolic rate is higher
- Surface area : volume ratio is smaller

Therefore, large organisms have specialised gas exchange surfaces and a mass transport system. In mammals, these include the alveoli and the cardiovascular system.

Characteristics of a mass transport system:

- Vessels
- Directional movement
- Transport medium
- Maintenance of speed

Features of an efficient exchange surface:
- Large surface area
- Thin
- Steep concentration gradient

Cell Membranes and Transport of Substances

All cells and organelles are surrounded by a partially permeable membrane composed of a sea of phospholipids with protein molecules between phospholipid molecules. Membrane proteins consist of transport proteins, receptor proteins, enzymes, structural and recognition proteins. The main function of the membrane is controlling the movement of substances in and out of the cell/organelle. It also contains receptors for other molecules such as hormones, and enables adjacent cells to stick together. The fluidity of the membrane (proteins and lipids are free to move) and the mosaic arrangement of the proteins give the structure of the membrane its name – the fluid mosaic model.

The movement of molecules through cell membranes depends on the properties of the molecule as well as the requirements of the cell. There are several types of movement:

- Diffusion – the passive movement of small, non-polar, lipid-soluble molecules, such as carbon dioxide and oxygen, from an area of high concentration to an area of low concentration. The molecules move directly through the phospholipid bilayer. The rate of gas exchange by diffusion becomes more rapid as surface area increases, diffusion distance decreases and the diffusion gradient becomes more steep.
- Facilitated Diffusion – requires a channel protein in the cell membrane to transport polar, charged and water-soluble molecules across the membrane.

- **Osmosis** – the movement of water molecules from an area of **low solute concentration to an area to high solute concentration** through a **partially permeable membrane**.
- **Active Transport** – the movement of molecules through **carrier proteins** from an area of **low concentration to** an area of **high concentration**. This process requires energy in the form of **ATP**. Hydrolysis of ATP provides an accessible store of energy for biological processes. Phosphorylation of ATP requires energy.
- **Endocytosis/Exocytosis** – the movement of large particles into and out of cells via the formation of vesicles. In endocytosis, particles are enclosed in **vesicles** made from cell surface membrane and transported into the cell. In exocytosis, vesicles containing large particles fuse with the cell surface membrane and are transported out of the cell.

The rate of **gas exchange** by diffusion becomes more rapid as:

- **Surface area** increases
- **Diffusion distance** decreases
- **Concentration gradient** becomes steeper

Osmosis = the movement of water molecules from an area of high water potential to low water potential across a partially permeable membrane (more dilute to less dilute).

In animals, water potential = osmotic potential.

Turgor pressure = inward pressure exerted by the plant cell wall on the protoplasm as the protoplasm expands and pushes out. In plants, turgor pressure is also a factor. Turgor pressure is generated because water moves in by osmosis, causing the protoplasm to swell and push against the cell wall, generating **hydrostatic pressure.** This generates a **reactive force** pushing inwards. A combination of these forces is turgor pressure and it **prevents water moving into a cell**.

When turgor pressure is balanced with osmotic potential the cell is at turgor.

Therefore, in plants: **water potential (ψ) = osmotic pressure (π) + turgor pressure (P).**

Gaseous Exchange Systems

In Mammals

Mammals conduct gas exchange via the lungs.

Boyle's Law = volume is inversely proportional to pressure.

Therefore, inhalation happens by the contraction of the intercostal muscles and diaphragm. This causes the **volume to increase** which causes the **pressure to decrease** and air moves into the lungs by diffusion **down the pressure gradient**.

Exhalation = intercostal muscles and diaphragm relax = volume decreases = pressure increases = air diffuses out down the pressure gradient.

Oxygen moves into the capillaries from the **alveoli** via diffusion. The alveoli provide a large surface area for diffusion and both the capillaries and the alveoli are made up of one layer of flattened epithelial cells to provide a short diffusion distance. Blood in the capillaries is deoxygenated as the oxygenated blood is continuously carried away so the concentration gradient is steep.

In Insects

Insects have a specialised gas exchange system despite being small because they have an exoskeleton which prevents them from simply taking in gas via diffusion through the skin.

Insects have openings called **spiracles** which can be opened and closed by **sphincters** (which close to prevent water loss). Oxygen diffuses in through the spiracles and down a tube called the **trachea**. Gas exchange doesn't happen here because the trachea is lined with **rings of chitin**, making it impermeable. The chitin rings prevent the trachea from collapsing.

Oxygen then diffuses into small tubes called **tracheoles** which are permeable, and so gas exchange occurs here. Sometimes water builds up at the bottom of the tracheoles, which slows down diffusion. The water is removed in **active insects** because lactic acid builds up in the cells which decreases their water potential so water moves into the cells by osmosis, allowing gas exchange to occur.

Some active insects have to ventilate their respiratory systems via **mechanical ventilation** (by pumping the abdomen) and/or **air reserves**.

In Fish

Gas exchange in water is more difficult for fish because water is much denser and more viscous than air and only contains 5% oxygen.

Fish use Boyle's law to continually pump water over the gills. This allows gas exchange to occur. The gills are made of filaments covered by folds called **lamellae**. Continuous movement of water over the gills keeps them spread out to increase the surface area of the gills and prevent them from **sticking together.**

The floor of the mouth opens, and the **operculum** (gill flap) closes. The floor of the mouth is then raised to increase the pressure but a valve stops water from leaving. The increased pressure forces the operculum open which forces water over the gills.

To maintain the **maximum concentration gradient** between the water and the rich blood supply within the network of capillaries in the lamellae, a **countercurrent exchange system** operates. This is where water flowing over the gills and blood in the gill filaments flow in opposite directions, maintaining a steep concentration gradient over the entire gill filament.

In Plants

There are multiple layers of a plant leaf:

- Waxy cuticle (prevents water loss)
- Upper epidermis (is transparent to allow maximum light through to cells with chloroplasts)
- Palisade mesophyll layer (cells are stacked vertically to fit in as many cells as possible. These cells contain the most chloroplasts)
- Spongy mesophyll layer (air spaces provide an increased surface area for gas exchange)
- Lower epidermis, guard cells, stomata (guard cells open and close stomata to prevent excessive water loss. Walls of guard cells are thicker on the side adjacent to the stomata to enable opening and closing)

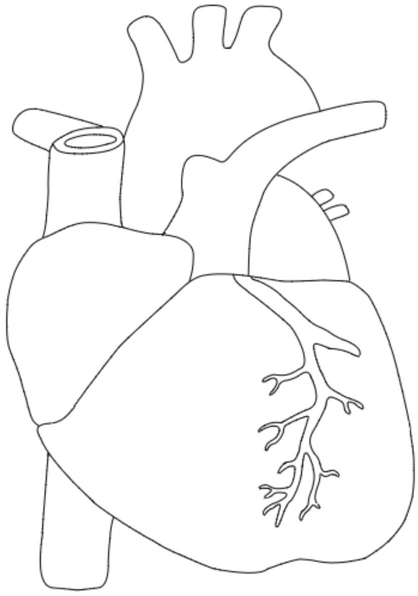
Plant cells undergo **photosynthesis and respiration.**

During the day, when conditions are favourable for photosynthesis, the **stomata opens** (this allows water loss so has to be balanced). This allows carbon dioxide to diffuse in and oxygen (as a waste product of photosynthesis) to diffuse out.

The stomata opens by ions (mainly K+) **moving into the guard cells by active transport**, which causes water to **move in by osmosis** because water potential is decreased, which makes the guard cell **turgid**. This causes the guard cell to **swell** and the stomata opens.

Lenticels are areas of loosely arranged cells which act as a pore to allow gas exchange in lignified (woody) plants.

Circulation and the Heart



Structure of the heart:

- Four chambers - right and left **atria**, right and left **ventricles**
- Four main blood vessels - **pulmonary vein** (from lungs to left atrium), **aorta** (from left ventricle to body), **vena cava** (from body to right atrium), **pulmonary artery** (from right ventricle to lungs)
- **Atrioventricular valves** - mitral or tricuspid/bicuspid - prevent backflow of blood from ventricles to atria
- **Semilunar valves** - pulmonary/aortic - separate arteries from ventricles
- **Tendinous chords**/valve tendons - prevent atrioventricular valves turning inside out due to pressure when the heart contracts
- **Septum** - muscle and connective tissue - prevents oxygenated/deoxygenated blood mixing
- **Coronary arteries** - wrapped around the heart to supply blood to cardiac muscle of the heart
- **Cardiac muscle** - thicker on the LHS because higher pressure is needed to pump blood further to all tissues in the body

Circulatory systems can either be **open or closed**, where the blood is confined to blood vessels only. They can be **single**, where the blood is only pumped once around the whole system, or **double**, where the blood is pumped twice.

Advantages of a double circulatory system:

- **Concentration gradient** is maintained, as oxygenated and deoxygenated blood do not mix
- Blood pressure to the **body tissues is higher**
- Blood pressure to the **lungs is lower**, which avoids damaging the capillaries in the lungs and increases time for gas exchange
- Organisms can develop **larger bodies**

Due to the heart's ability to initiate its own contraction, it is referred to as **myogenic:**

1. Depolarisation originates in the **Sinoatrial Node**.
2. Depolarisation spreads through the atria, causing atrial systole. Cannot spread directly to the ventricles due to the region of nonconductive tissue - annulus fibrosus.
3. Stimulates another region of conducting tissue - **Atrioventricular Node**.

4. Slight delay for atrial diastole. AVN passes depolarisation into the conducting fibres - **Bundle of His**.
5. Bundle of His splits into two branches - **Purkinje Fibres**. Causes ventricular systole.

There are 3 stages of the cardiac cycle:

1) **Atrial systole** – during atrial systole the **atria contract.** This forces the atrioventricular **valves open** and blood flows into the ventricles.

2) **Ventricular systole – contraction of the ventricles** causes the **atrioventricular valves** to **close** and **semilunar valves to open,** thus allowing **blood to leave the left** ventricle through the **aorta** and right ventricle through the **pulmonary artery**.

3) **Cardiac diastole** – atria and ventricles relax and **pressure inside the heart chambers decreases.** This causes the **semilunar valves** in the aorta and pulmonary arteries to close, preventing backflow of blood.

The functions of blood include **transport, defence against pathogens** and **formation of lymph and tissue fluid**. Blood is made up of plasma and blood cells (erythrocytes, leukocytes and platelets).

- Plasma
- Transports digested food products (e.g. glucose, amino acids), nutrient molecules, hormones, excretory products (e.g. carbon dioxide, urea).
- Transfers heat around the body.

- Erythrocytes (red blood cells)
- Transport oxygen and some carbon dioxide.
- Adapted via their biconcave shape and lack of nucleus. Contain haemoglobin.

- Leukocytes (white blood cells)
- Granulocytes:
    A. Neutrophils (phagocytosis)
    B. Basophils (histamine - inflammation/allergic response)
    C. Eosinophils (response to parasites, allergic reactions, inflammation, immunity)
- Agranulocytes:
    D. Monocytes
    E. Lymphocytes

- Platelets
- Fragments of megakaryocytes
- Involved in blood clotting

Blood Clotting

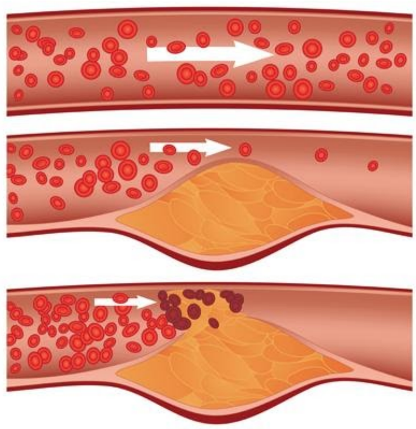
Thrombosis, also known as blood clotting, prevents blood loss when a blood vessel is damaged, prevents the entry of disease-causing microorganisms, and provides a framework for repair.

A cascade of reactions which lead to clot formation:

- When a blood vessel is damaged, platelets attach to exposed collagen fibres.
- A protein called thromboplastin is released from platelets and this protein triggers the conversion of inactive prothrombin (protein) into active thrombin (enzyme). In order for the conversion to occur calcium ions and vitamin K must be present.
- Thrombin catalyses the conversion of soluble fibrinogen into insoluble fibrin.
- Fibrin forms a network of fibres in which platelets, red blood cells and debris are trapped to form a blood clot.

Atherosclerosis

Atherosclerosis is the hardening of arteries caused by the build-up of fibrous plaque called an atheroma. Atheroma formation is the cause of many cardiovascular diseases and occurs as following:



- The endothelium which lines the arteries is damaged, for instance by high cholesterol levels, smoking or high blood pressure.
- This increases the risk of blood clotting in the artery and leads to an inflammatory response, causing white blood cells to move to the site of damage.
- Over time, white blood cells, cholesterol, calcium salts and fibres build up and harden, leading to plaque (atheroma) formation.
- The build-up of fibrous plaque leads to narrowing of the artery and restricts blood flow thus increasing the blood pressure which in turn damages the endothelial lining and the process is repeated.

Atherosclerosis is multi-factorial and has modifiable and non-modifiable risk factors. Factors such as genetics, age, diet, gender, high blood pressure, high cholesterol levels, smoking and physical inactivity, obesity all increase the risk of atherosclerosis. Thus risk of CVD can be reduced by stopping smoking, regular exercise, reducing consumption of alcohol, dietary changes and maintaining healthy body weight. Atherosclerosis can cause **angina, stroke, myocardial infarction and aneurysm**.

Transport of Gases in the Blood

Haemoglobin is a water soluble globular protein which consists of four polypeptide chains, 2 alpha and 2 beta, as well as a haem group. It **carries oxygen in the blood** as oxygen can bind to the haem (Fe^{2+}) group and oxygen is then released when required. Each Hb molecule can carry four oxygen molecules.

The affinity of oxygen for haemoglobin varies depending on the **partial pressure** of oxygen. The greater the concentration of dissolved oxygen in cells the greater the partial pressure.

Therefore, as partial pressure of oxygen increases, the **affinity of haemoglobin for oxygen** also increases. During respiration, oxygen is used and the partial pressure decreases, thus decreasing the affinity of haemoglobin for oxygen. As a result, oxygen dissociates from haemoglobin in respiring tissues where it is needed. After the unloading process, the haemoglobin returns to the lungs where it binds to oxygen again.

Dissociation curves illustrate the change in haemoglobin saturation as partial pressure changes. The saturation of haemoglobin is affected by its affinity for oxygen, therefore in the case where partial pressure is high, haemoglobin has high affinity for oxygen and is therefore highly saturated, and vice versa. Dissociation curves have a sigmoid shape because saturation affects affinity as oxygen binds **cooperatively** to haemoglobin.

Foetal haemoglobin has a higher affinity for oxygen compared to adult haemoglobin. This is important because maternal and foetal blood run in a countercurrent exchange system through the placenta – the difference in affinity is needed so that when oxygen dissociates from maternal haemoglobin it can bind to foetal haemoglobin.

Myoglobin is another respiratory pigment that is used for storage. It has a **higher affinity for oxygen** than haemoglobin and acts as a storage molecule for oxygen. It is only made up of **one subunit.**

The affinity of haemoglobin for oxygen is also affected by the partial pressure of carbon dioxide. In the presence of carbon dioxide, the affinity of haemoglobin for oxygen decreases, thus causing it to be released. This means that oxygen dissociates from haemoglobin and can be used in respiring tissues. This is known as the **Bohr effect.**

Transfer of Materials Between the Circulatory System and Cells

Tissue fluid forms as a result of the interplay between **hydrostatic pressure** and **oncotic pressure** in capillaries:

- Hydrostatic pressure: residual pressure from the heartbeat. This is higher at the arterial end of the capillary than the venous end.
- Oncotic pressure: as there is movement of fluid out of capillaries due to hydrostatic pressure, water potential of the capillaries becomes more negative (although oncotic pressure is relatively constant).

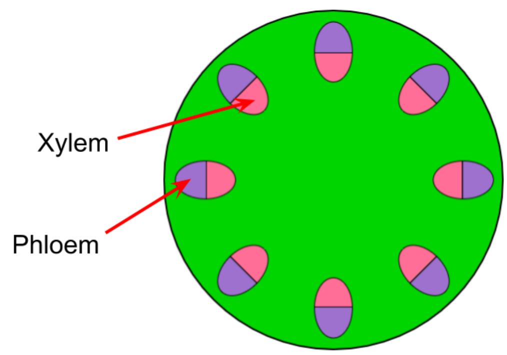
At the arterial end, hydrostatic pressure is greater than oncotic pressure and fluid moves out. At the venous end, oncotic pressure is greater than hydrostatic pressure but the overall movement is still net out of the capillaries. The fluid that moves out of the capillaries forms tissue fluid.

Excess tissue fluid has to drain into the **lymphatic system** (where it's then called lymph) to prevent tissues from swelling. The lymph passes through the lymphatic system and then drains back into the blood at the **subclavian vein.** Lymph contains lymphocytes that produce antibodies which are emptied into the blood along with the lymph. Lymph glands also remove bacteria and other pathogens. This is the reason the lymph nodes swell when there is an infection in the body.

Transport in Plants

Structure of the Xylem

- They transport **water and minerals as part of the transpiration stream**, and also serve to provide **structural support.**
- They are long cylinders made of **dead tissue with open ends**, therefore they can form a **continuous column**.
- Xylem vessels also contain **pits** which enable water to **move sideways** between the vessels.
- They are **thickened with a tough substance called lignin**, which is deposited in **spiral patterns** to enable the plant to remain flexible.



Structure of the Phloem

- They're tubes made of **living cells**

- Involved in **translocation** - the **movement of nutrients to storage organs** and growing parts of the plant.
- Consist of **sieve tube elements and companion cells.**
- Sieve tube elements form a tube to transport sugars such as sucrose, in the dissolved form of **sap.**
- Companion cells are involved in ATP production for active processes such as **loading sucrose into sieve tubes.**
- Cytoplasm of sieve tube elements and companion cells is linked through structures known as **plasmodesmata** which are **gaps between cell walls** which allow flow of substances between the cells.

Movement in the Xylem

1. Water moves into the plant via osmosis through **root hair cells.** These are fine, hair-like extensions of the membranes with a large surface area.

2. Water moves through the root by osmosis to replace water removed from the xylem. It can move through the symplast pathway or the apoplast pathway:

    a. **Symplast** = water moves through the cytoplasm via the plasmodesmata.

    b. **Apoplast** = water moves through cell walls and intercellular spaces which are permeable.

3. Once the water reaches a waterproof area of the root called the **Casparian strip**, it has to travel via the symplast pathway.

4. The water reaches the xylem. The movement of water in the xylem is known as the **transpiration stream.** The xylem contains a continuous column of water. The column is maintained via cohesion and adhesion:

    a. **Cohesion** = attraction between like molecules. Water forms hydrogen bonds with other molecules of water.

    b. **Adhesion** = attraction between unlike molecules. Water forms hydrogen bonds with other surfaces like pores in the mesophyll cells.

5. Evaporation causes hydrostatic pressure on the water in the xylem. This tension moves the whole column upwards due to cohesion. This model of movement in the xylem is called the cohesion-tension model.

6. When water reaches the leaf, it moves along via osmosis.

7. Water evaporates from the mesophyll cell walls.

8. Water diffuses from air spaces in the leaf out through the open stoma.

Movement in the Phloem

1) Transport of materials using a transport medium and pressure/force is known as the **mass flow or pressure flow hypothesis**. Movement in the phloem is called translocation. Substances moved in this way are called assimilates, the main one being sucrose. This is the glucose produced via photosynthesis that has been converted into sucrose because it has less of an osmotic effect.

2) Sucrose is moved from the **source** (an area that produces more sugar than required – e.g. the leaf) to the **sink** (an area that consumes more sugar for growth/storage than it produces – the root/shoot).

3) Sucrose can be loaded into the phloem via the symplast or the apoplast pathway.

4) **Symplast**:

    a) Sucrose moves by diffusion from leaf cell to companion cell of phloem into the phloem sieve tube.

    b) This decreases the water potential of the phloem so water moves into the phloem from the xylem by osmosis.

    c) This generates a hydrostatic pressure in the phloem so water moves down the sieve tube towards the sink down the pressure gradient.

5) **Apoplast**:

    a) Sucrose moves by diffusion from leaf cell to companion cell wall.

    b) Sucrose is moved via active transport across the companion cell wall into the cytoplasm.

    c) It moves through the plasmodesmata via diffusion into the sieve tube.

    d) Osmosis, hydrostatic pressure, movement towards the sink.

6) The phloem is **unloaded passively**:

    a) Sucrose moves into the companion cell and then into the root/shoot cell by diffusion.

    b) The sucrose is removed (e.g. stored or used for photosynthesis) which maintains the concentration gradient.

    c) As sucrose moves out of the phloem the water potential of the phloem increases and water moves out by osmosis e.g. back to the xylem.

Factors affecting Rate of Transpiration

- **Air Movement** = increases rate of transpiration because it removes still air from around the leaf. This increases the concentration gradient and therefore increases the rate of diffusion.
- **Humidity** = decreases the concentration gradient and therefore decreases rate of diffusion.
- **Temperature** = increases random motion, rate of evaporation, and therefore rate of transpiration. In addition, warmer air holds more water vapour. Plateaus when something else becomes limiting.
- **Light Intensity** = increases the number of stomata that are open for photosynthetic gas exchange. Plateaus when all stomata are open.

The Mass-Flow Hypothesis

Strengths:

1) There is evidence for it:
   a) You can use **radioactive isotopes** to mark glucose and use autoradiography to trace the resultant sucrose through the phloem.
   b) If **steam** is used to kill a ring of bark on a tree then it stops movement in the phloem (and not the xylem).
   c) **Aphids** feed off phloem tubes and exude sap at the other end of the body – this is evidence for high hydrostatic pressure in the phloem.

Weaknesses:

1) Doesn't explain why there can be **bidirectional movement** in the sieve tube.
2) Doesn't explain why there's movement at **different speeds** in the sieve tube.
3) Doesn't explain the presence of **sieve plates.**
4) Doesn't explain why sieve tube cells and companion cells **need to be alive** for movement in the phloem to occur.