Edexcel International Advanced Level (IAL) Biology AS Level Revision Notes

Topic 1: Molecules, Transport and Health

Lesson 1B: Mammalian Transport Systems

COMPREHENSIVE REVISION & REFERENCE GUIDE

1. Principles of Circulation and Surface Area to Volume Ratio

All living organisms must continuously exchange substances with their external environment. In single-celled organisms (e.g., *Amoeba*) and very small or microscopic multicellular organisms (such as many marine larvae), simple **diffusion** is entirely sufficient to satisfy all metabolic requirements. This efficiency is due to several structural characteristics:

- The physical distances from the outer perimeter to the innermost metabolic zones are exceedingly short.
- The total surface area in contact with the environment is very large relative to the internal volume.
- They possess a very large **surface area to volume ratio (SA:Vol)**, providing an ample exchange surface area for rapid material transport.
- Their overall metabolic demands are low; they do not internally regulate their core temperature and use comparatively small quantities of oxygen and substrate.

The Constraints of Increasing Size

As organisms scale upward in size, their internal volume increases as a cubic function, while their surface area expands only as a square function. Consequently, the **SA:Vol ratio decreases drastically** as size increases. The physical diffusion distances lengthen significantly, meaning materials would take too long to travel from the outer surface to deep internal tissues, failing to sustain metabolic life. To overcome this fundamental limitation of diffusion, large multicellular organisms have evolved specialized internal **mass transport systems**.

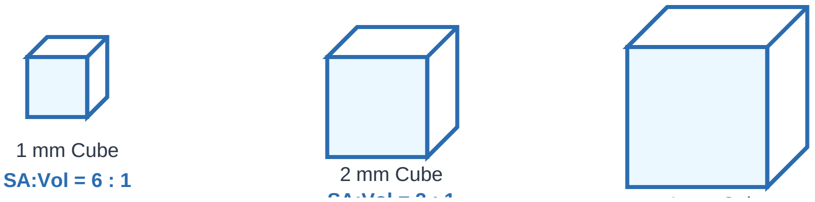

Figure 1: Geometric model proving the inverse relationship between organism size and SA:Vol ratio.

Exam Hint: The Purpose of Mass Transport

When writing about mass transport systems, always make it explicitly clear that they are required to **overcome the limits of diffusion** in organisms that have a small surface area to volume ratio.

Core Features of a Mass Transport System

A mass transport system moves materials collectively in a bulk liquid flow (mass flow) powered by a pressure gradient. These systems uniformly display several key evolutionary features:

1. **Exchange Surfaces:** Highly specialized areas to absorb resources and eliminate wastes (e.g., lungs, gills, tract linings).
2. **A System of Vessels:** A network of branched conduit tubes (arteries, veins, capillaries) to distribute the medium along specific routes.
3. **Directional Mechanics:** Structural mechanisms (e.g., specialized cardiac valves) that ensure substances travel one way.
4. **Propulsion Mechanism:** A mechanical pump (the heart) to generate pressure differences and maintain the bulk flow fast enough to meet metabolic demands.
5. **Transport Medium:** A suitable liquid medium (blood or hemolymph) in which materials are suspended or dissolved.
6. **Adaptability:** Control mechanisms to adjust the flow rate to match changing metabolic activity.

2. Open vs. Closed & Single vs. Double Circulatory Systems

Animals display several structural approaches to internal transport, classified by vessel integrity and path complexity:

- **Open Circulatory Systems:** Found in insects, where blood (hemolymph) is pumped into large, open body cavities (lacunae) and directly bathes internal organs.
- **Closed Circulatory Systems:** Present in all vertebrates, including mammals. The blood remains strictly enclosed within blood vessels. This configuration provides significant evolutionary advantages: blood pressure can be elevated to drive rapid flow, and blood distribution can be directed precisely to active metabolic tissues.

Single vs. Double Circulatory Systems

Vertebrates utilize either single or double circulatory arrangements, which directly determine their metabolic limits:

• **Single Circulation (e.g., Fish):** Blood passes through the heart exactly once during a full circuit around the body. The heart pumps deoxygenated blood to the gills, where it is oxygenated. This blood then travels directly through the systemic circulation to deliver oxygen to tissues before returning to the heart. Because blood pressure drops significantly within the tiny capillaries of the gills, it flows slowly through the rest of the body. This is sufficient for low-metabolic aquatic ectotherms, but limits active endothermic life.

- **Double Circulation (e.g., Mammals and Birds):** Blood flows through the heart twice during a complete circuit around the body, separating the system into two distinct loops:
  - **Pulmonary Circuit:** Carries deoxygenated blood from the right side of the heart to the lungs to undergo gas exchange, returning oxygenated blood to the left side of the heart at low pressure to avoid damaging delicate lung tissues.
  - **Systemic Circuit:** Receives this oxygenated blood and pumps it out from the powerful left ventricle at high pressure, rapidly distributing it to the rest of the body.

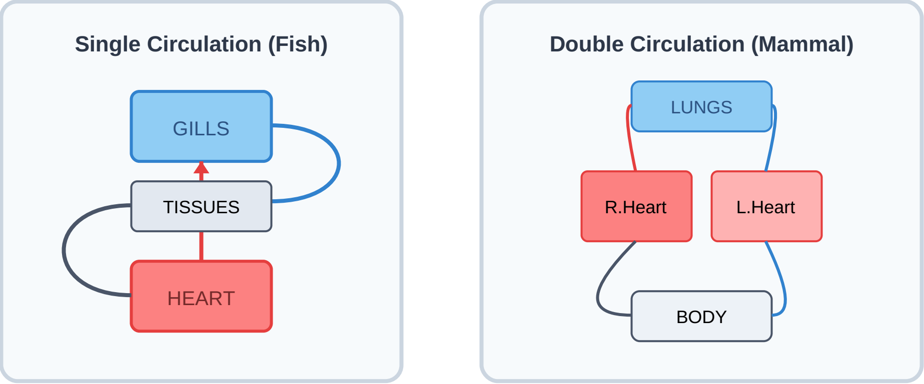

Figure 2: Architectural schematics comparison between single tracking vs double separate-circuit dynamics.

3. The Roles and Specialized Components of Mammalian Blood

Blood is the primary transport medium of the mammalian cardiovascular system. It is a complex suspension composed of cellular elements suspended in a liquid matrix called plasma:

Plasma (Fluid Transport Matrix)

Comprising over 50% of total blood volume, plasma is an aqueous fluid that transports all blood cells alongside vital dissolved materials, including:

- **Nutrients:** Digested materials like glucose and amino acids absorbed from the small intestine, carried to tissues for processing, storage, or immediate respiration.
- **Excretory Wastes:** Carbon dioxide (CO_2) and urea, carried away from cells to the lungs and kidneys for excretion.
- **Hormones:** Systemic chemical messengers delivered from endocrine glands to specific target organs.
- **Thermal Distribution:** Transfers heat from metabolically active internal core organs (e.g., liver, working skeletal muscles) to the skin surface to regulate core body temperature.

- **Buffer Capacity:** Plasma proteins and dissolved ions act as structural chemical buffers to maintain a stable, narrow blood pH range.

Erythrocytes (Red Blood Cells)

Erythrocytes are highly specialized transport cells, averaging roughly 4–6 million cells per mm^3 of blood. Their unique adaptations include:

- A distinct **biconcave disc shape**, which maximizes the cell's surface area to volume ratio to support rapid gas diffusion.
- **Absence of a nucleus and key organelles** upon maturation, freeing massive internal volume to hold hemoglobin molecules. Each erythrocyte packs roughly 250–300 million hemoglobin molecules, allowing a single cell to carry approximately 1,000 million oxygen molecules.
- A limited lifespan of roughly 120 days before being broken down in the spleen and liver.

Leucocytes (White Blood Cells) and Platelets

• **Leucocytes:** Considerably larger than erythrocytes, white blood cells retain their nuclei and act as the core defense network against pathogens. They can dynamically alter their physical shape, allowing them to squeeze through thin capillary walls to enter infected or damaged tissues during inflammatory responses.

• **Platelets:** Small, membrane-bound cellular fragments derived from large bone marrow cells called **megakaryocytes**. Platelets circulate in concentrations of 150,000–400,000 per mm^3 and are essential for triggering the blood clotting cascade.

4. Oxygen Transport Dynamics and Dissociation Adaptations

Hemoglobin is a large, complex globular protein with a quaternary structure consisting of four folded polypeptide subunits. Each subunit wraps around a non-protein iron-containing **heme prosthetic group**. This iron core binds oxygen in a loose, reversible reaction to form **oxyhaemoglobin**:

$$Hb + 4O_2 \rightleftharpoons Hb{\bullet}4O_2$$

Cooperative Binding and the Sigmoid Dissociation Curve

The relationship between hemoglobin oxygen saturation and the surrounding partial pressure of oxygen (pO_2) produces a non-linear, **sigmoid (S-shaped) oxygen dissociation curve**. This shape is a direct result of a structural mechanism called **cooperative binding**:

- When hemoglobin is completely deoxygenated, its subunits are locked in a tense configuration that is relatively resistant to binding oxygen.
- The binding of the very first oxygen molecule alters the shape of the entire protein, relaxing the remaining subunits and making it significantly easier for subsequent oxygen molecules to bind.
- The final oxygen molecule binds hundreds of times faster than the first. This process operates symmetrically in reverse during unloading: as oxygen leaves, the protein tightens, making it progressively easier to unload remaining oxygen molecules.

This cooperative mechanism allows hemoglobin to function efficiently. In the lungs, where pO_2 is high, hemoglobin binds oxygen rapidly to become fully saturated. In respiring body tissues, where pO_2 drops, hemoglobin rapidly unloads its oxygen to supply the cells.

The Bohr Effect

The affinity of hemoglobin for oxygen is dynamically regulated by the local concentration of carbon dioxide (pCO_2) and the resulting pH shifts. In highly active tissues, cellular respiration releases large volumes of carbon dioxide, which reduces local pH. This acidic environment alters the shape of the hemoglobin molecule, **reducing its affinity for oxygen**. This shifts the oxygen dissociation curve **downward and to the right**, causing hemoglobin to unload oxygen more readily to sustain working cells. Conversely, in the lungs where pCO_2 is low, hemoglobin's affinity for oxygen increases, maximizing oxygen uptake.

Fetal Hemoglobin Adaptation

A developing fetus relies entirely on oxygen transferred across the placenta from its mother's blood. If fetal hemoglobin shared the exact same oxygen affinity as maternal hemoglobin, little to no oxygen would transfer across the placental interface. To overcome this, the fetus expresses a unique structural variant called **fetal haemoglobin**, which possesses a **higher affinity for oxygen** than adult hemoglobin. Consequently, the fetal curve is shifted **leftward** relative to the adult curve, allowing fetal hemoglobin to bind oxygen even at low partial pressures where maternal hemoglobin is unloading it.

> ### Deep Dive: Elephant Seal Blood Adaptations
>
> Elephant seals can dive to depths of nearly 2 km and remain submerged for up to 2 hours without breathing. They survive using three key adaptations of the blood: they circulate up to twice the blood volume of land mammals of equivalent size, carry significantly higher concentrations of erythrocytes and hemoglobin, and maintain elevated levels of **myoglobin** in their muscle tissues. Myoglobin has an even higher affinity for oxygen than fetal hemoglobin, forming an exceptionally dense oxygen reservoir that turns their muscles nearly black.

5. Carbon Dioxide Transport and the Chloride Shift

Carbon dioxide released by respiring cells diffuses into the bloodstream down its concentration gradient, where it is transported to the lungs via three primary mechanisms:

1. Directly dissolved in solution within the plasma (roughly 5%).
2. Bound directly to the amine groups of hemoglobin to form **carbaminohaemoglobin** (roughly 10%–20%).
3. Converted into soluble **hydrogencarbonate ions (HCO_3^-)** inside red blood cells (the dominant pathway, roughly 75%–85%).

The Biochemical Cascade

As carbon dioxide enters erythrocytes, it reacts with water to form **carbonic acid (H_2CO_3)**, a reaction rapidly driven by the specialized enzyme **carbonic anhydrase**. Once formed, carbonic acid immediately dissociates into hydrogen ions (H^+) and hydrogencarbonate ions (HCO_3^-):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

To prevent dangerous shifts in blood pH, the free hydrogen ions (H^+) are immediately bound by hemoglobin, which acts as a buffer to form **haemoglobinic acid (HHb)**. As negatively charged hydrogencarbonate ions build up inside the cell, they diffuse out into the plasma down an electrical gradient. To maintain electrical neutrality, negative **chloride ions (Cl^-)** from the plasma are pumped into the erythrocyte. This structural exchange is known as the **chloride shift**.

6. The Blood Clotting Mechanism Cascade

Mammals maintain a finite, high-pressure blood supply. Any break in vessel integrity risks lethal blood loss and provides an entry point for pathogenic micro-organisms. To protect against this, the body initiates a highly regulated, multi-step enzymatic cascade known as the **blood clotting mechanism**:

- **Vascular Constriction:** When a blood vessel wall is severed, plasma, cells, and platelets flow out. The platelets make physical contact with exposed underlying tissue structures, such as collagen fibers, causing them to break open in large numbers. These platelets release **serotonin**, a localized vasoconstrictor that signals smooth muscle walls to contract, narrowing the vessel to reduce blood flow to the injured area.
- **The Coagulation Cascade:** Damaged tissue surfaces and ruptured platelets release a critical initiating enzyme called **thromboplastin**. In the presence of sufficient concentrations of **calcium ions (Ca^{2+})** and clotting factors synthesized via **Vitamin K**, thromboplastin catalyzes the conversion of the inactive, soluble plasma protein precursor **prothrombin** into the active proteolytic enzyme **thrombin**.
- **Fibrin Mesh Formation:** Active thrombin then acts as an enzyme to catalyze the conversion of another soluble plasma protein, **fibrinogen**, into the insoluble structural protein **fibrin**. Fibrin polymerizes into a tough, fibrous molecular mesh that spans the open wound. Moving erythrocytes and platelets become trapped within this mesh, forming a stable blood clot that dries into a protective scab, sealing the vessel so underlying tissues can heal.

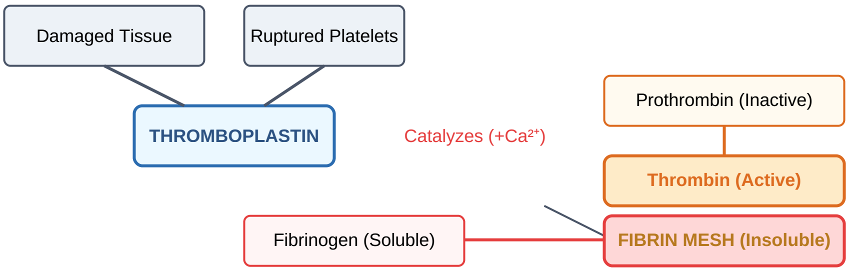

Figure 3: Biochemical enzymatic waterfall mapping out the mammalian coagulation cascade.