The heart and circulation

Why large animals need a circulatory system, blood vessels, the cardiac cycle, and haemoglobin and the oxygen dissociation curve.

Why a circulatory system

As an organism gets larger, its **surface area to volume ratio** falls. Diffusion is fast over short distances but too slow to supply cells deep inside a large organism. Large animals also have a **high metabolic rate** and need to move oxygen, nutrients and waste quickly. A **mass transport** system (a heart and circulation) moves fluid by pressure, over long distances, and keeps steep concentration gradients at exchange surfaces.

Mammals have a **double circulation**: the right side of the heart pumps blood to the lungs, and the left side pumps it to the body at high pressure. Blood passes through the heart twice on each circuit.

Blood vessels

Vessel	Structure	Function
Artery	Thick **muscle** and **elastic** tissue in the wall, narrow lumen, no valves	Carries blood **away from the heart at high pressure**. Elastic fibres stretch and recoil to smooth the flow; muscle controls the diameter
Vein	Thin wall, **wide lumen**, **valves**	Carries blood **back to the heart at low pressure**. Valves stop backflow; skeletal muscles squeeze the veins
Capillary	**One cell thick** (endothelium), narrow, many branches, leaky	Exchange of substances between the blood and tissues. Short diffusion distance, a large surface area and slow flow

Tissue fluid forms when high pressure at the arterial end of a capillary forces fluid out through the walls. At the venous end, the low water potential of the blood plasma (due to proteins) draws water back in by osmosis. Excess fluid drains into the lymphatic system.

The mammalian heart

The heart has four chambers: **right and left atria** above, and **right and left ventricles** below. The left ventricle has a **thicker muscular wall** than the right, because it pumps blood to the whole body.

Major vessels:

- **Vena cava** brings deoxygenated blood from the body to the right atrium.

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- **Pulmonary artery** takes deoxygenated blood from the right ventricle to the lungs.
- **Pulmonary vein** brings oxygenated blood from the lungs to the left atrium.
- **Aorta** takes oxygenated blood from the left ventricle to the body.

Valves: the **atrioventricular (AV) valves** between atria and ventricles, and the **semilunar valves** at the base of the aorta and pulmonary artery, prevent backflow. **Coronary arteries** supply the heart muscle itself.

The cardiac cycle

Stage	What happens
Atrial systole	The atria **contract**; pressure in the atria rises above that in the ventricles, the AV valves open and blood is pushed into the ventricles
Ventricular systole	The ventricles **contract**. Pressure rises above that in the atria, so the **AV valves close** (first heart sound). Pressure rises above that in the aorta and pulmonary artery, so the **semilunar valves open** and blood is ejected
Cardiac diastole	The heart **relaxes**. The semilunar valves close (second heart sound) as pressure falls. The atria fill with blood and the AV valves open, so blood flows passively into the ventricles

> TRY IT
>
> Explain why the AV valves close at the start of ventricular systole.

When the ventricles contract, the pressure in the ventricle becomes higher than in the atrium, so blood is forced against the valve flaps, which close and prevent backflow into the atria.

Cardiac output is covered with the control of the heart. Details of myogenic stimulation are in Unit 5.

Haemoglobin and oxygen transport

Haemoglobin is a protein with **four polypeptide chains**, each with a **haem** group containing an **iron** ion that binds one O_2 molecule. Each molecule carries up to four O_2, forming **oxyhaemoglobin**.

The oxygen dissociation curve

It plots the **percentage saturation** of haemoglobin against the **partial pressure of oxygen** (p_{O_2}). The curve is **S-shaped (sigmoid)**:

- At low p_{O_2} the first O_2 binds slowly.
- Binding changes the shape of the molecule, making it easier for the next molecules to bind (**cooperative binding**), so the curve is steep in the middle.

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- At high p_{O_2} the haemoglobin is almost saturated.

In the **lungs** the high p_{O_2} means haemoglobin **loads** oxygen. In respiring **tissues** the low p_{O_2} means it **unloads** oxygen.

The Bohr effect

At high partial pressure of CO_2 (in respiring tissues), the **curve shifts to the right**. Haemoglobin has a **lower affinity** for oxygen, so it unloads more at the same p_{O_2}. CO_2 dissolves to form carbonic acid, which releases H^+, lowering the pH and changing the shape of haemoglobin.

Fetal haemoglobin

Fetal haemoglobin has a **higher affinity** for oxygen than adult haemoglobin, so its dissociation curve is to the **left**. In the placenta, oxygen is transferred from the mother's haemoglobin to the fetus's, since the fetal haemoglobin is still unsaturated at the p_{O_2} where the mother's is unloading.

Carbon dioxide transport

About 5% is dissolved in plasma, about 10 to 20% binds to haemoglobin (carbaminohaemoglobin), and about 75% is carried as **hydrogencarbonate ions** in plasma. In red blood cells, **carbonic anhydrase** catalyses $CO_2 + H_2O \rightleftharpoons H_2CO_3$, which dissociates to H^+ and HCO_3^-. The H^+ is taken up by haemoglobin (forming haemoglobinic acid), and HCO_3^- moves out in exchange for Cl^- (the **chloride shift**).

> **Learn the shifts. Right shift (Bohr effect, high CO_2, e.g. in exercise): haemoglobin releases oxygen more readily. Left shift (fetal haemoglobin, myoglobin, llama at altitude): haemoglobin has a higher affinity.**

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