**Human Circulatory System**

Small organisms don’t have a bloodstream, but instead rely on the simple diffusion of materials for transport around their cells. This is OK for single cells, but it would take days for molecules to diffuse through a large animal, so most animals have a circulatory system with a pump to transport materials quickly around their bodies. This is an example of a mass flow system, which means the transport of substances in the flow of a fluid (as opposed to diffusion, which is the random motion of molecules in a stationary fluid). The transport of materials in the xylem and phloem of plants is an other example of mass flow. Mass flow systems work together with the specialised exchange systems (such as lungs, gills and leaves), which we saw in module 1.

Humans have a double circulatory system with a 4-chambered heart. In humans the right side of the heart pumps blood to the lungs only and is called the pulmonary circulation, while the left side of the heart pumps blood to the rest of the body – the systemic circulation. The circulation of blood round the body was discovered by William Harvey in 1628. Until then people assumed that blood ebbed and flowed through the same tubes, because they hadn't seen capillaries.



# The Heart



The human heart has four chambers: two thin-walled atria on top, which receive blood, and two thick-walled ventricles underneath, which pump blood. Veins carry blood into the atria and arteries carry blood away from the ventricles. Between the atria and the ventricles are atrioventricular valves, which prevent back-flow of blood from the ventricles to the atria. The left valve has two flaps and is called the bicuspid (or mitral) valve, while the right valve has 3 flaps and is called the tricuspid valve. The valves are held in place by valve tendons (“heart strings”) attached to papillary muscles, which contract at the same time as the ventricles, holding the vales closed. There are also two semi-lunar valves in the arteries (the only examples of valves in arteries) called the pulmonary and aortic valves.

The left and right halves of the heart are separated by the inter-ventricular septum. The walls of the right ventricle are 3 times thinner than on the left and it produces less force and pressure in the blood. This is partly because the blood has less far to go (the lungs are right next to the heart), but also because a lower pressure in the pulmonary circulation means that less fluid passes from the capillaries to the alveoli.

The heart is made of cardiac muscle, composed of cells called myocytes. When myocytes receive an electrical impulse they contract together, causing a heartbeat. Since myocytes are constantly active, they have a great requirement for oxygen, so are fed by numerous capillaries from two coronary arteries. These arise from the aorta as it leaves the heart. Blood returns via the coronary sinus, which drains directly into the right atrium.

# The Cardiac Cycle

When the cardiac muscle contracts the volume in the chamber decrease, so the pressure in the chamber increases, so the blood is forced out. Cardiac muscle contracts about 75 times per minute, pumping around 75 cm³ of blood from each ventricle each beat (the stroke volume). It does this continuously for up to 100 years. There is a complicated sequence of events at each heartbeat called the cardiac cycle.

Cardiac muscle is myogenic, which means that it can contract on its own, without needing nerve impulses. Contractions are initiated within the heart by the sino-atrial node (SAN, or pacemaker) in the right atrium. This extraordinary tissue acts as a clock, and contracts spontaneously and rhythmically about once a second, even when surgically removed from the heart.

The cardiac cycle has three stages:

1. **Atrial Systole** (pronounced sis-toe-lay). The SAN contracts and transmits electrical impulses throughout the atria, which both contract, pumping blood into the ventricles. The ventricles are electrically insulated from the atria, so they do not contract at this time.
2. **Ventricular Systole**. The electrical impulse passes to the ventricles via the atrioventricular node (AVN), the bundle of His and the Purkinje fibres. These are specialised fibres that do not contract but pass the electrical impulse to the base of the ventricles, with a short but important delay of about 0.1s. The ventricles therefore contract shortly after the atria, from the bottom up, squeezing blood upwards into the arteries. The blood can't go into the atria because of the atrioventricular valves, which are forced shut with a loud "lub".
3. **Diastole.** The atria and the ventricles relax, while the atria fill with blood. The semilunar valves in the arteries close as the arterial blood pushes against them, making a "dup" sound.

The events of the three stages are shown in the diagram on the next page. The pressure changes show most clearly what is happening in each chamber. Blood flows because of pressure differences, and it always flows from a high pressure to a low pressure, if it can. So during atrial systole the atria contract, making the atrium pressure higher than the ventricle pressure, so blood flows from the atrium to the ventricle. The artery pressure is higher still, but blood can’t flow from the artery back into the heart due to the semi-lunar valves. The valves are largely passive: they open when blood flows through them the right way and close when blood tries to flow through them the wrong way.



The PCG (or phonocardiogram) is a recording of the sounds the heart makes. The cardiac muscle itself is silent and the sounds are made by the valves closing. The first sound (lub) is the atrioventricular valves closing and the second (dub) is the semi-lunar valves closing.

The ECG (or electrocardiogram) is a recording of the electrical activity of the heart. There are characteristic waves of electrical activity marking each phase of the cardiac cycle. Changes in these ECG waves can be used to help diagnose problems with the heart.

# Blood vessels

Blood circulates in a series of different kinds of blood vessels as it circulates round the body. Each kind of vessel is adapted to its function.

|  |  |  |
| --- | --- | --- |
| **Veins and Venules** | **Capillaries** | **Arteries and Arterioles** |
|  |  |  |
| Function is to carry blood from tissues to the heart | Function is to allow exchange of materials between the blood and the tissues | Function is to carry blood from the heart to the tissues |
| Thin walls, mainly collagen, since blood at low pressure | Very thin, permeable walls, only one cell thick to allow exchange of materials | Thick walls with smooth elastic layers to resist high pressure and muscle layer to aid pumping |
| Large lumen to reduce resistance to flow. | Very small lumen. Blood cells must distort to pass through. | Small lumen |
| Many valves to prevent back-flow | No valves | No valves (except in heart) |
| Blood at low pressure | Blood pressure falls in capillaries. | Blood at high pressure |
| Blood usually deoxygenated (except in pulmonary vein) | Blood changes from oxygenated to deoxygenated (except in lungs) | Blood usually oxygenated (except in pulmonary artery) |

**Arteries** carry blood from the heart to every tissue in the body. They have thick, elastic walls to withstand the high pressure of blood from the heart. The arteries close to the heart are particularly elastic and expand during systole and recoil again during diastole, helping to even out the pulsating blood flow. The smaller arteries and arterioles are more muscular and can contract (vasoconstriction) to close off the capillary beds to which they lead; or relax (vasodilation) to open up the capillary bed. These changes are happening constantly under the involuntary control of the medulla in the brain, and are most obvious in the capillary beds of the skin, causing the skin to change colour from pink (skin arterioles dilated) to blue (skin arterioles constricted). There is not enough blood to fill all the body’s capillaries, and at any given time up to 20% of the capillary beds are closed off.

**Veins** carry blood from every tissue in the body to the heart. The blood has lost almost all its pressure in the capillaries, so it is at low pressure inside veins and moving slowly. Veins therefore don’t need thick walls and they have a larger lumen that arteries, to reduce the resistance to flow. They also have semi-lunar valves to stop the blood flowing backwards. It is particularly difficult for blood to flow upwards through the legs to heart, and the flow is helped by contractions of the leg and abdominal muscles:



The body relies on constant contraction of these muscles to get the blood back to the heart, and this explains why soldiers standing still on parade for long periods can faint, and why sitting still on a long flight can cause swelling of the ankles and Deep Vein Thrombosis (DVT or “economy class syndrome”), where small blood clots collect in the legs.

**Capillaries** are where the transported substances actually enter and leave the blood. No exchange of materials takes place in the arteries and veins, whose walls are too thick and impermeable. Capillaries are very narrow and thin-walled, but there are a vast number of them (108 m in one adult!), so they have a huge surface area : volume ratio, helping rapid diffusion of substances between blood and cells. Capillaries are arranged in networks called capillary beds feeding a group of cells, and no cell in the body is more than 2 cells away from a capillary.

#

# Blood

Blood is composed of 4 components, as shown in this diagram:



There are dozens of different substances in blood, all being transported from one part of the body to another. Some of the main ones are listed in this table:

|  |  |  |
| --- | --- | --- |
| **Substance** | **Where** | **Reason** |
| Oxygen | Red blood cells | Transported from lungs to all cells for respiration |
| Carbon dioxide | Plasma | Transported from all cells to lungs for excretion |
| Nutrients (e.g. glucose, amino acids, vitamins, lipids, nucleotides) | Plasma | Transported from small intestine to liver and from liver to all cells |
| Waste products (e.g. urea, lactic acid) | Plasma | Transported from cells to liver and from liver to kidneys for excretion |
| Ions (e.g. Na+, K+, Ca2+, Mg2+, Cl-, , , ) | Plasma | Transported from small intestine to cells, and help buffer the blood pH. |
| Hormones | Plasma | Transported from glands to target organs |
| Proteins (eg albumins) | Plasma | Amino acid reserve |
| Blood clotting factors | Plasma | At least 13 different substances (mainly proteins) required to make blood clot. |
| Antigens and antibodies | Plasma | Part of immune system |
| Water | Plasma | Transported from large intestine and cells to kidneys for excretion. |
| Bacteria and viruses | plasma |  |
| Heat | Plasma | Transported from muscles to skin for heat exchange. |

# Tissue Fluid

These substances are all exchanged between the blood and the cells in capillary beds. Substances do not actually move directly between the blood and the cell: they first diffuse into the tissue fluid that surrounds all cells, and then diffuse from there to the cells.



1. At the arterial end of the capillary bed the blood is still at high hydrostatic pressure, so blood plasma is squeezed out through the permeable walls of the capillary. Cells and proteins are too big to leave the capillary, so they remain in the blood.

2. This fluid now forms tissue fluid surrounding the cells. Materials are exchanged between the tissue fluid and the cells by all four methods of transport across a cell membrane. Gases and lipid-soluble substances (such as steroids) cross by lipid diffusion; water crosses by osmosis, ions cross by facilitated diffusion; and glucose and amino acids cross by active transport.

3. At the venous end of the capillary bed the blood is at low pressure, since it has lost so much plasma. Water returns to the blood by osmosis since the blood has a low water potential. Solutes (such as carbon dioxide, urea, salts, etc) enter the blood by diffusion, down their concentration gradients.

4. Not all the plasma that left the blood returns to it, so there is excess tissue fluid. This excess drains into lymph vessels, which are found in all capillary beds. Lymph vessels have very thin walls, like capillaries, and tissue fluid can easily diffuse inside, forming lymph.

Exercise and Heart Rate

The rate at which the heart beats and the volume of blood pumped at each beat (the stroke volume) can both be controlled. The product of these two is called the cardiac output – the amount of blood flowing in a given time:



As the table shows, the cardiac output can increase dramatically when the body exercises. There are several benefits from this:

* to get oxygen to the muscles faster
* to get glucose to the muscles faster
* to get carbon dioxide away from the muscles faster
* to get lactate away from the muscles faster
* to get heat away from the muscles faster

But what makes the heart beat faster? It is clearly an involuntary process (you don’t have to think about it), and like many involuntary processes (such as breathing, coughing and sneezing) it is controlled by a region of the brain called the medulla. The medulla and its nerves are part of the autonomic nervous system (i.e. involuntary). The part of the medulla that controls the heart is called the cardiovascular centre. It receives inputs from various receptors around the body and sends output through two nerves to the sino-atrial node in the heart.



**How does the cardiovascular centre control the heart?**

The cardiovascular centre can control both the heart rate and the stroke volume. Since the heart is myogenic, it does not need nerve impulses to initiate each contraction. But the nerves from the cardiovascular centre can change the heart rate. There are two separate nerves from the cardiovascular centre to the sino-atrial node: the sympathetic nerve to slow the heart rate down and the parasympathetic nerve to speed it up.

The cardiovascular centre can also change the stroke volume by controlling blood pressure. It can increase the stroke volume by sending nerve impulses to the arterioles to cause vasoconstriction, which increases blood pressure so more blood fills the heart at diastole. Alternatively it can decrease the stroke volume by causing vasodilation and reducing the blood pressure.

**How does the cardiovascular centre respond to exercise?**

When the muscles are active they respire more quickly and cause several changes to the blood, such as decreased oxygen concentration, increased carbon dioxide concentration, decreased pH (since the carbon dioxide dissolves to form carbonic acid, see p xx) and increased temperature. All of these changes are detected by various receptor cells around the body, but the pH changes are the most sensitive and therefore the most important. The main chemoreceptors (receptor cells that can detect chemical changes) are found in:

* The walls of the aorta (the aortic body), monitoring the blood as it leaves the heart
* The walls of the carotid arteries (the carotid bodies), monitoring the blood to the head and brain
* The medulla, monitoring the tissue fluid in the brain

The chemoreceptors send nerve impulses to the cardiovascular centre indicating that more respiration is taking place, and the cardiovascular centre responds by increasing the heart rate.



A similar job is performed by temperature receptors and stretch receptors in the muscles, which also detect increased muscle activity.

Exercise and Breathing

Both the rate and depth (volume) of breathing can be varied. The product of these two is called the ventilation rate – the volume air ventilating the lungs each minute:



When the body exercises the ventilation rate and depth increases so that

* Oxygen can diffuse from the air to the blood faster
* Carbon dioxide can diffuse from the blood to the air faster

Again, this is an involuntary process and is controlled by a region of the medulla called the respiratory centre, which plays a similar role to the cardiovascular centre. The respiratory centre receives inputs from various receptors around the body and sends output through two nerves to the muscles around the lungs.



**How does the respiratory centre control ventilation?**

Unlike the heart, the muscles that cause breathing cannot contract on their own, but need nerve impulses from the brain for each breath. The respiratory centre transmits regular nerve impulses to the diaphragm and intercostal muscles to cause inhalation. Stretch receptors in the alveoli and bronchioles detect inhalation and send inhibitory signals to the respiratory centre to cause exhalation. This negative feedback system in continuous and prevents damage to the lungs.

**How does respiratory centre respond to exercise?**

The process is the same as for heart rate, with the chemoreceptors in the aortic and carotid bodies detecting an increase in respiration.



Again, the stretch receptors in the muscles give a more rapid indication of muscular activity, allowing an anticipatory increase in breathing rate even before the carbon dioxide concentration the blood has changed.

One difference between ventilation and heartbeat is that ventilation is also under voluntary control from the cortex, the voluntary part of the brain. This allows you to hold your breath or blow out candles, but it can be overruled by the autonomic system in the event of danger. For example if you hold your breath for a long time, the carbon dioxide concentration in the blood increases so much that the respiratory centre forces you to gasp and take a breath. Pearl divers hyperventilate before diving to lower the carbon dioxide concentration in their blood, so that it takes longer to build up.

During sleep there is so little cellular respiration taking place that it is possible to stop breathing for a while, but the respiratory centre starts it up again as the carbon dioxide concentration increases. It is possible that one cause of cot deaths may be an underdeveloped respiratory centre in young babies, which allows breathing to slow down or stop for too long.