1.2.1 The heart

Monitoring the heart

How the heart works

The heart pumps blood all around your body. In fact, the heart is really two pumps, side by side. Look at Figure 1. The right side of the heart receives deoxygenated blood that has been round the body, and pumps it to the lungs. The left side of your heart receives oxygenated blood from the lungs and pumps it all around the body.

Blood enters the heart into the atria. It is then pushed into the ventricles. The ventricles pump the blood out of the heart. The heart muscle contracts and relaxes continuously throughout life. The two atria contract together, then the two ventricles contract together.

The cardiac cycle

The first stage of the cardiac cycle is diastole. This is when the heart muscle is relaxed, and the atria of the heart, and then the ventricles, are filling with blood.

There are valves between the atria and the ventricles, called the atrio-ventricular valves. As the atria fill with blood, the blood pushes the atrio-ventricular valves open and enters the ventricles (Figure 4(a)).

The next stage of the cardiac cycle is atrial systole. The muscular wall of the atria contracts. This pushes the blood from the atria into the ventricles, so that the atria are now emptied. This pushes the atrio-ventricular valves fully open.

The next stage of the cardiac cycle is ventricular systole. The muscular walls of the ventricles contract. The atrio-ventricular valves are forced shut (Figure 4(b)). You will see that they can only open one way. When there is a greater pressure in the ventricles than in the atria, the atrio-ventricular valves close. They are prevented from going ‘inside-out’ by the tendons that attach them to the wall of the ventricles. These tendons are called chordae tendinae. The pressure in the ventricles forces the blood out of the ventricles.

The blood in the right ventricle is pumped through semi-lunar valves into the pulmonary artery. The blood in the left ventricle is pumped through semi-lunar valves into the aorta. The pressure of the blood in the ventricles pushes these valves open. These valves prevent any backflow into the heart.

Following ventricular systole, the heart muscle relaxes. This is diastole. The chambers of the heart refill. The cycle repeats itself about 75 times every minute.

Examiner tip

Make sure that you can explain the pressure that causes the valves in the heart to open and close. The valves do not move on their own.

Examiner tip

Use the diagrams in Figure 3 to describe the sequence of events in the cardiac cycle. Make sure you include the names of the chambers and the valves. Include the pressure differences and the effects these have on the valves.
Case study

Martin visited his GP because he had a bad, chesty cough. His doctor examined his chest. He told Martin
that he would need some antibiotics to clear up the infection, and then added, ‘By the way, did you know
that you have a very slight heart murmur?’ Martin was not aware of this, and was a little worried at first.
His GP reassured him. ‘It’s only a very slight heart murmur. This means there is a very tiny hole in one of
your heart valves. Clearly it’s caused you no problems up until now. I’ll refer you to a specialist to get it
checked out. However, I’d like to assure you that most minor heart murmurs like this cause no problems
at all, and don’t need any treatment.’

Pressure and volume changes in the heart

Figure 5 shows the pressure and volume changes in the
heart during one cardiac cycle.

You will see that the pressure in the ventricle increases a
lot when the muscular wall of the ventricle contracts. As
the ventricle contracts, the pressure of blood inside it
increases. When the pressure of blood in the ventricle
exceeds the pressure in the artery, blood is forced out and
the volume of the ventricle decreases.

The pressure in each atrium increases a little as it fills with
blood, and then as it contracts, but it never gets very high.
This is because the atrium only needs to pump the blood
into the ventricle.

The pressure in the aorta does go up and down, but you
will see that it never goes very low. This is important,
because the blood in the aorta has only just left the heart. It
needs to have enough pressure to get round the body and
back to the heart again.

Questions
1 Explain why the wall of the left ventricle is thicker than
   the wall of the right ventricle.
2 Use Figure 5 to estimate the heart rate, in beats per
   minute, for this person.
3 Figure 5 shows the pressure changes in the left side of
   the heart. Suggest where the line showing pressure in
   the right ventricle would be.
Cardiac muscle

The wall of the heart is made up of a very special kind of muscle called cardiac muscle. It is special because it does not need any stimulation from a nerve to make it contract. We say that it is myogenic.

There is a group of specialised cardiac cells in the wall of the right atrium called the sino-atrial node (SAN). These cells generate electrical impulses that pass rapidly across the walls of the atria from cell to cell. As a result, the atrial walls contract, causing atrial systole.

The impulses cannot pass straight on from the atria to the ventricle walls, because there is a ring of fibrous tissue preventing this. The only way that impulses can pass from the atria to the ventricles is by a group of specialised muscle cells called the atrio-ventricular node (AVN), which acts as a relay point. There is a slight delay here, allowing enough time for the atria to empty completely.

From the AV node, impulses pass very quickly down heart muscle fibres called the bundle of His that spread down the septum between the two ventricles. This means that impulses soon reach the bottom of the ventricles. After this, the fibres divide into right and left branches at the tip (base) of the ventricles. They then spread throughout the muscular walls in Purkyne tissue. The impulse causes the muscular ventricle walls to contract. This is ventricular systole.

After this, there is a short time when no impulses pass through the heart muscle. This allows the muscle to relax and diastole to occur.

Recording an electrocardiogram

An electrocardiogram (ECG) is used to monitor heart function. A cardiology technician will ask the patient to remove his clothes from the waist upwards. Then the technician will place electrodes on the arms, legs and chest. A special ECG cream is used between the electrodes and the skin. The patient is asked to lie down and remain completely relaxed, because any movement will interfere with the recording. The machine records for about 5 minutes. It gives a recording from each electrode.

Look at Figure 3a. This shows a normal ECG for a person with a healthy heart. The line represents the electrical activity in the heart during the cardiac cycle.

You will see that the P wave occurs shortly before the pressure in the atria increases. This means that the P wave represents the impulses passing from the SAN to the AVN, through the walls of the atria, leading to atrial systole.

The QRS wave occurs just before the pressure in the ventricle increases. This shows you that the QRS wave shows the electrical activity in the ventricles that results in ventricular systole. In other words, the QRS wave shows the electrical impulses passing down the bundle of His and along the Purkyne fibres.

The T wave is a short phase that occurs as the ventricles recover.

Abnormal ECGs

Sometimes people have a problem with the electrical activity in the heart. In these cases, the ECG produced will change.

Look at Figure 3. The ECG in 3b shows ventricular fibrillation. You will see that this ECG looks very different. There is no P wave and no QRS wave. This is because the muscle in the heart wall is not contracting in a coordinated way. It is likely that a person with an ECG like this has had a myocardial infarction (heart attack) and they will almost certainly be unconscious. This person needs urgent medical attention or he will die.
The ECG in 3c shows atrial fibrillation. There is a small and unclear P wave. The deep S wave in 3d indicates ventricular hypertrophy, which is an increase in muscle thickness.

A heightened P wave can indicate an enlarged atrium. A raised S-T segment can indicate a myocardial infarction (see spread 2.4.1.1).

Figure 3 Normal and abnormal ECGs

(a) Normal ECG

(b) Tachycardia

(c) Bradycardia

(d) Ventricular fibrillation

(e) Heart block

Figure 4 ECGs

Questions
1. Explain the advantage of impulses passing very quickly down the bundle of His and Purkyne tissue.
2. Explain why there is a short interval between the P wave and QRS wave in a normal person.
3. Use the scale on Figure 4 to calculate the heart rate in beats per minute of the ECGs in (a), (b) and (c).
Changes during exercise

The **stroke volume** is the volume of blood pumped out of the left ventricle in one cardiac cycle. This is normally 60–80 cm³.

The **cardiac output** is the volume of blood pumped out of the left ventricle in one minute. This figure is normally 4–8 dm³ min⁻¹.

Therefore, cardiac output = stroke volume × heart rate.

Another effect of strenuous exercise is that body muscles contract more strongly. The muscles compress the veins and this increases the rate at which deoxygenated blood returns to the heart. The vena cava contains more blood than before, so the heart rate increases. The increased volume of blood in the heart also stretches the heart muscle. This makes the heart muscle contract more strongly. The result of this is that the stroke volume increases. If an athlete undergoes training, her stroke volume will be permanently higher than that of a non-athlete.

Look at Figure 1. You can see that a trained athlete has a greater stroke volume than a non-athlete when their heart rates are the same.

Measuring pulse rate

The heart rate can be measured by counting how many ‘pulses’ are felt in an artery per minute. This is because every time the left ventricle contracts, a ‘pulse’ of blood pushed out into the aorta.

Your pulse can be measured anywhere where you can press an artery against a bone. What you can feel is the expansion of the artery wall as the pulse of blood (the pressure wave) passes through. Pulse rate is usually measured using the ‘radial’ pulse in the wrist.

If you are measuring the pulse rate of another person, wash your hands carefully before you start.

- Find the position of the radial artery.
- Press firmly against the radial artery with the second and third fingers (because your thumb and first finger have a pulse).
- Count the number of pulses in 1 minute. Alternatively, count the number of pulses in 30 seconds, then multiply by 2 to give a pulse rate in beats per minute.

There are other places where you can measure a pulse. You can see some of these in Figure 2.

There are also meters that give you a reading of your pulse rate. These can be useful to measure your pulse rate before, during and after exercise.
Table 1 shows the normal resting pulse rate for people of different ages.

<table>
<thead>
<tr>
<th>Person</th>
<th>Resting heart rate/beats per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babies 0–12 months</td>
<td>100–160</td>
</tr>
<tr>
<td>Children aged 1–10</td>
<td>60–140</td>
</tr>
<tr>
<td>Children aged 10+ and adults</td>
<td>60–100</td>
</tr>
<tr>
<td>Highly trained athletes</td>
<td>40–60</td>
</tr>
</tbody>
</table>

Table 1  Normal resting pulse

The effect of exercise on heart rate

The effects of exercise on the heart rate of two boys were investigated. Both boys started to ride on an exercise bike at 2 minutes and stopped exercising at 7 minutes. They wore heart rate monitors. The graph in Figure 3 shows how their heart rate changed before, during and after exercise.

Figure 3  Effects of exercise on the heart rate of two boys

- Name the units that should be present on the y-axis.
- One of the boys is a highly trained athlete. Which boy is it? Explain your answer.
- How could you improve the reliability of this investigation?

Questions

1. A person has a stroke volume of 74 cm³ and a cardiac output of 5700 cm³ when he is at rest. Calculate his heart rate in beats per minute.
2. Following vigorous exercise, the same person has a heart rate of 195 beats per minute and a cardiac output of 18900 cm³. Calculate his stroke volume.
3. Suggest why a trained athlete has a greater stroke volume than a non-athlete when their heart rates are the same.
4. Explain why it is an advantage to an athlete to have a greater stroke volume than a non-athlete when their heart rates are the same.
### Types of blood vessel

**Arteries** carry blood away from the heart. Away from the heart, they divide into smaller vessels called **arterioles**. In turn, arterioles lead into tiny blood vessels called **capillaries**, which exchange materials between the blood and the tissues. Blood leaving the capillaries drains into vessels called **venules**. Venules join up to form **veins**, which carry blood back to the heart.

**Arteries**

Look at Figure 1a. This shows the structure of an artery. You can see that it has a thick wall with smooth muscle and elastic tissue in it. This is because the arteries carry blood away from the heart. The blood is under high pressure. Every time the heart beats, a surge of blood passes through the artery. This causes the artery wall to bulge a little. As this happens, the thick elastic layer allows the artery wall to stretch and spring back. This process is called **elastic recoil**. This helps to keep blood pressure high and helps to smooth out blood flow. When you measure your pulse, you can feel these surges in pressure.

There is also a tough fibrous layer around the outside of the artery. This protects the artery from damage as we move around and our skeletal muscles contract and relax. The **lumen** is the space through which the blood flows. You can see that it is relatively small, keeping the blood under pressure. The lining of the artery, the **endothelium**, is a thin, smooth layer. This helps the blood to flow along with as little friction as possible.

**Veins**

Figure 1b shows a vein. You can see that it has a much thinner layer of muscle and elastic tissue than the artery. This is because the blood in the vein is under much lower pressure. The lumen of the vein is larger than the lumen of the artery, so the blood is under less pressure and it flows more slowly. The vein also has a thick fibrous layer to protect it from damage. It has a smooth endothelium to reduce friction as blood flows along it.

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**Figure 1** Structure of **a** an artery, **b** a vein and **c** a capillary. The diagram of the capillary is drawn to a much larger scale.
A special feature of veins is that they contain valves. You can see how these work in Figure 2. Valves help the blood to keep flowing in one direction only, back to the heart. This happens even in veins in the legs and arms, where blood flows against the force of gravity. As our skeletal muscles contract, they squeeze the veins. This raises the pressure in the veins, which shuts the valves behind and opens the valves ahead, so making sure that the blood keeps flowing back towards the heart.

**Capillaries**

Look at Figure 1c. This shows a capillary. It is not drawn to the same scale as the artery and the vein. A capillary is a tiny blood vessel, only 7–10 μm wide. This is actually about the same diameter as a red blood cell. Red blood cells can pass through capillaries, but they have to be squeezed through. This means they pass through one at a time, allowing more efficient exchange between the blood and the tissues.

The capillary wall is made of a single layer of thin, flattened endothelium cells. In fact, the capillary wall is like the layer of cells that lines the artery and the vein. Because the capillary wall is very thin, it allows exchange between the blood and the tissues. There are also tiny gaps between the endothelium cells. These also allow substances to be exchanged between the capillaries and the tissues, and allow phagocytic white cells (phagocytes) to migrate into tissues.

**Arterioles and venules**

Look at Figure 3. You can see that the arterioles have a thin wall, mainly of muscle fibres, but with some elastic fibres. When this muscle contracts, it makes the lumen of the arteriole narrower. When it relaxes, the lumen becomes wider. This means that arterioles can increase or decrease the flow of blood to particular tissues. This is also one means of regulating blood pressure.

Venules have a very thin wall of muscle and elastic tissue. They are like small veins, and carry blood from the capillaries back to the veins.

<table>
<thead>
<tr>
<th>Artery</th>
<th>Capillary</th>
<th>Vein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transports blood away from the heart</td>
<td>Links arterioles to veins. Allows exchange of materials between the blood and tissues</td>
<td>Transports blood towards the heart</td>
</tr>
<tr>
<td>Thick wall with muscle and a great deal of elastic tissue</td>
<td>No elastic or muscle fibres</td>
<td>Relatively thin wall with only a small amount of muscle and elastic fibres</td>
</tr>
<tr>
<td>Bloodflow rapid</td>
<td>Bloodflow slowing</td>
<td>Bloodflow slow</td>
</tr>
<tr>
<td>High blood pressure – blood flows in pulses</td>
<td>Pressure of blood falling – not in pulses</td>
<td>Low blood pressure – not in pulses</td>
</tr>
</tbody>
</table>

Table 1 The main differences between arteries, veins and capillaries

**Questions**

1. The lumen of an artery is narrower than the lumen of a vein, although arteries carry the same volume of blood as veins do. Explain why their lumens are different sizes.

2. Look at Figure 4.

   (a) Explain how it is possible to identify which vessel is the artery and which vessel is the vein.

   (b) A vein is really round in cross-section. Suggest why the section through the vein in this figure is not round.

   (c) Use the magnification shown to calculate the thickness of the wall, in μm, in the artery and the vein.
The human circulatory system

The human circulatory system transports materials, such as oxygen, round the body by mass transport. Mass transport is when everything is moving in a stream in one direction. The cells, plasma and dissolved substances are all moving together in the blood.

Very small organisms, with very few cells, do not need a circulatory system as each cell in the organism is very close to the medium in which they live so oxygen and nutrients can be absorbed over their whole body surface by diffusion. Larger organisms like humans cannot do this because the diffusion path would be so long that substances wouldn’t move fast enough. We need a blood system to carry substances such as oxygen and glucose to respiring cells.

Examiner tip
You should be prepared to describe the meaning of ‘double’ and ‘closed’ circulatory systems but you should also be able to explain the advantages of both systems. The advantage of a double circulatory system is that blood pressure can be maintained at a high level around the body. If blood had to travel directly to the body from the lungs, without first returning to the heart, then the resistance to flow in the lungs would mean that blood pressure round the body would be much lower even if the heart was pumping as hard as it could. A double circulatory system also means that oxygenated and deoxygenated blood don’t mix. The outcome of the double circulatory system is, therefore, that oxygen delivery to respiring cells is optimised.

The advantages of a closed system? Again, a closed system also means that high pressure can be maintained, but it also means that a lower volume of transport fluid (blood in this case) is needed. Furthermore, it allows a more complete separation of function between organs.

Examiner tip
There is a clear link here with 1.2.2.3 – the section on measuring blood pressure. From Figure 2 you should be able to estimate the pressure during systole (when the ventricles are contracting) and diastole (when the ventricle is relaxing and the pressure is due to the elastic recoil of the artery wall). This is why blood pressure measurements are always given as two figures – the systolic pressure and the diastolic pressure. Asking you to read this from a graph is a common exam question. The fluctuations in pressure decrease in the arterioles and this illustrates part of their function – to smooth out the blood flow.

Look at Figure 1. This shows the human circulatory system. You will see that it is a closed system. This means that blood stays in the blood vessels all the time. Blood does not leave the blood vessels at any time, except when the body is injured.

The human circulatory system is also a double circulation. This means that there are two ‘circuits’. The pulmonary circulation goes from the heart to the lungs and back to the heart. The systemic circulation goes from the heart to the body organs and then back again. When blood passes round the body once, it goes through the heart twice.

Deoxygenated blood that has come from the tissues returns to the right atrium of the heart via the vena cava. It passes into the right ventricle, and gets pumped to the lungs through the pulmonary artery. Oxygenated blood from the lungs returns to the left atrium of the heart. It passes into the left ventricle. From here, it is pumped to the body in the aorta.
Blood pressure in different blood vessels

Figure 2 shows how the blood pressure changes as the blood passes through the different blood vessels in the systemic circulation. Pressure is high in the arteries, as the blood has just left the heart. It is under pressure because the left ventricle contracts very strongly. The pressure in the arteries shows small ‘up and down’ movements. This is because the pressure drops slightly during **diastole**, when the ventricle muscle relaxes, and then increases again at ventricular **systole**.

The ‘up and down’ movements decrease as blood passes through the arteries and into the **arterioles**. This is because the **elastic recoil** of the elastic tissue in the artery wall smooths out the flow. Pressure drops slowly as the blood moves through the arteries and the arterioles because it is slowed down by resistance to bloodflow, mainly due to friction.

Exchanging materials

The rate of blood flow drops considerably as it passes through the many capillaries. This gives plenty of time for exchange of materials and a large surface area over which the exchange can occur.

The blood at the arteriole end of the capillary network is under much higher pressure than the blood at the venule end. This higher **hydrostatic pressure** forces water and small soluble molecules out of the blood plasma. The loss of these materials from the capillaries causes much of the loss of pressure in the capillaries. The water, with dissolved nutrients and oxygen, forms a liquid called **tissue fluid**. This bathes the cells, bringing oxygen and nutrients such as glucose and amino acids, and removing waste materials such as carbon dioxide. These materials are exchanged between the tissue fluid and the body cells by diffusion across the **plasma membranes**.

Red blood cells and larger molecules such as plasma proteins remain in the capillary. Although these proteins exert an osmotic ‘pull’ on water, tending to keep it in the capillary, this force is smaller than the hydrostatic ‘push’ of the blood pressure, so there is an overall or net ‘push’ which tends to force water and dissolved solutes out through the capillary walls.

At the venule end of the capillary, the blood has a much lower water potential than the tissue fluid. This is because dissolved proteins are still present, but more water has been lost. The inward ‘pull’ is now much greater than the outward ‘push’ of the blood pressure. So at the venule end, water from the tissue fluid returns to the blood capillary by **osmosis** down a **water potential** gradient along with solutes.

Some of the tissue fluid does not return directly to the blood. The rest of the tissue fluid drains into a separate set of vessels – the **lymph vessels**. Lymph is not pumped through the lymph vessels. Instead, they have a series of valves, like the ones in veins, to prevent backflow. Lymph is squeezed along the vessels as skeletal muscles contract. Eventually the lymph is returned to the blood at a vein in the neck region.

Questions

1. Explain the advantage to a human of having a double circulatory system, rather than a single circulatory system.
2. Give one difference between blood plasma and tissue fluid.
3. Give two differences between tissue fluid and lymph.
Blood pressure

You have already seen that blood needs to flow through the circulation at a certain pressure. If the pressure is too low, exchange of nutrients and oxygen within the tissues will not happen efficiently. Also, key organs such as the kidney will not function. This is why blood pressure measurement is one of the key ‘obs’ or observations recorded by GPs and on hospital charts. Blood pressure must increase when we exercise, as our tissues need more glucose and oxygen at this time and more carbon dioxide will need to be removed.

Blood pressure is measured by medical professionals using an instrument called a sphygmomanometer. The SI units for this are kilopascals (kPa), but most sphygmomanometers use ‘millimetres of mercury’ (mm Hg).

What is normal blood pressure?

You will remember from spread 1.2.2.2. that blood pressure fluctuates a little in the arteries. You will remember that the ‘up’ part is when ventricular systole is occurring, and the heart is pumping blood into the aorta. The ‘down’ part is when diastole is occurring, i.e. the heart muscle is relaxing.

Blood pressure is usually given as two figures, e.g. 120/70. The top figure is the systolic pressure (i.e. the pressure in the artery when the left ventricle is contracting) and the lower figure is the diastolic figure (i.e. the pressure generated by the elastic recoil ‘between beats’), both in mm Hg.

A person with normal blood pressure should have a figure of 130/85 or below, but it is better to have a blood pressure of 120/70 or below. If a person has blood pressure above 180/110, they are considered to have severe hypertension. In other words, their blood pressure is too high and the doctor may give the patient medication to reduce their blood pressure.

Normal vs. average blood pressure

A person’s blood pressure will vary throughout the day, depending on their level of activity, whether they are sitting or standing, and whether they have eaten salty food. This means that a person’s ‘normal’ blood pressure will vary within a range. We also use the word ‘normal’ to refer to populations, where the term ‘average’ might be better. Figure 1 shows how different blood pressure measurements are interpreted.

As blood pressure can vary in an individual from time to time, it is important that conditions should be standardised when taking measurements.
Questions
1 A person’s blood pressure should be measured when they are resting and relaxed. Explain why.
2 People with high blood pressure sometimes have swelling in their legs and feet. This is because tissue fluid has accumulated there. Explain how this happens.
3 Somebody with very low blood pressure will feel faint and may become unconscious. Explain why.
4 Nicotine in cigarette smoke causes the muscle fibres in arteriole walls to constrict. Explain how this causes blood pressure to increase.

Examiner tip
The sounds you hear in the stethoscope during a blood pressure measurement are called the Korotkov sounds. The diagrams explain what is happening in the artery as the cuff deflates and shows what sound this corresponds to in the ear piece of the stethoscope.
1.2.3 The lungs

The structure of the lungs
Look at Figure 1. This shows the structure of the lungs and breathing system. When we breathe in, air passes down the **trachea** into the two **bronchi**. The bronchi branch into smaller **bronchioles**, which end in clusters of air sacs called **alveoli**.

![Figure 1 The lungs and breathing system](image)

The alveoli
The alveoli are the actual site of gas exchange. They are tiny hollow sacs made of thin, flattened cells called **squamous epithelium**. An ‘epithelium’ is a lining tissue.

Figure 2 shows squamous epithelium. You can see that the cells are thin and flat. This means that there is only a short distance between the air in the alveoli and the blood in the capillary, so gas exchange is as efficient as possible.

Squamous epithelium is an example of a **tissue**.

![Figure 2 Squamous epithelium](image)

**Key definition**
A tissue is a group of similar cells specialised to carry out the same function.

**Examiner tip**
Cells need not always be the same type in a tissue. For example, ciliated epithelium tissue contains ciliated cells and mucus-secreting cells. Epithelial tissues are one of four tissue types. There is also muscle tissue and connective tissue (e.g. cartilage). The fourth type of tissue is nervous tissue, which you will meet in A2. In each case you should be able to point out how the properties of the tissue and its component cells adapt it to its function.
The trachea

The trachea has rings of cartilage around it to make sure that it stays open when you breathe in and out. It is lined with a layer of ciliated epithelium cells and goblet cells. You can see this in Figure 3.

![Figure 3 Ciliated epithelium cells and goblet cells from the lining of the trachea](image)

The goblet cells are so-called because they are shaped like a goblet. These cells produce large amounts of mucus, which is a glycoprotein. The ciliated epithelium cells have many tiny hairs called cilia. These beat together in a rhythm and move the mucus back up the trachea to the throat. Dirt and bacteria in the air that is breathed in gets trapped in the mucus. When the mucus reaches the throat, it is swallowed. This means that the dirt and bacteria are destroyed by the acid and the enzymes in the stomach.

The lungs

Look at Figure 4. This shows a photo of lung tissue. You can see that it consists of many alveoli, which are lined with squamous epithelium cells. It also contains many blood capillaries. The lung is an example of an organ. An organ is a structure made up of different kinds of tissue. The lung is an organ because it contains different kinds of tissue, such as squamous epithelium and elastic tissue (a kind of connective tissue).

Questions

1. Compare the role of the squamous epithelium cells in the capillaries and in the alveoli of the lungs.
2. Goblet cells make large amounts of mucus, which is a glycoprotein. Name the organelles that would be involved in producing this mucus.
3. Cigarette smoke damages the cilia on the ciliated epithelium cells lining the trachea. Explain why people who smoke develop a persistent chesty cough and are prone to lung infections.
A single-celled organism can take in molecules, such as oxygen, all over its surface. But the cells in a multicellular organism cannot take in oxygen through their surface unless they are on the outside. Look at Figure 1. You can see that the cells in the middle of an organism are too far from the outside. They cannot obtain the oxygen they need from the environment.

**Surface area and volumes**

The amount of diffusion between a multicellular organism and its environment depends on:

- its surface area – in other words, the number of cells in contact with the environment
- its volume – in other words, the space occupied by all the cells that need to be supplied with molecules.

As the number of cells increases, the volume increases. The surface area also increases, but not as much. Look at Table 1. To make it easier, we can assume that an organism is shaped like a cube. Notice how the surface area:volume ratio goes down sharply as the size of the organism increases.

<table>
<thead>
<tr>
<th>Length of side/cm</th>
<th>Surface area/cm²</th>
<th>Volume/cm³</th>
<th>Surface area:volume ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
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<td>1</td>
</tr>
<tr>
<td>7</td>
<td>294</td>
<td>343</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 1  Surface area:volume ratios

**Gas exchange in the alveoli**

Look at Figure 2. This shows the structure of an alveolus in the lungs.

The alveolus wall contains some elastic fibres. These allow the alveoli to expand when breathing in, and recoil easily when breathing out. The alveoli are also lined with a watery liquid. This contains a detergent-like substance called surfactant. It lowers the surface tension of the alveoli, and therefore reduces the amount of effort needed to breathe in and inflate the lungs. It also has an antibacterial effect, helping to remove any harmful bacteria that reach the alveoli.
A good exchange surface has a large surface area, a thin surface and a steep diffusion gradient.

The lungs are adapted for efficient gas exchange because of a number of factors.

A large surface area
- The bronchioles are highly branched, giving a large number of pathways for air to enter and leave the lungs.
- There are millions of alveoli in each lung.
- The alveoli are highly folded, giving an even greater surface area.

A thin surface
- The squamous epithelium cells in the alveoli are only 0.1–0.5 μm thick, which allows rapid diffusion across them.
- The capillary wall is also made of a single layer of thin, flattened cells.

A steep diffusion gradient
- The blood circulation carries oxygenated blood away from the alveoli, and brings deoxygenated blood to the alveoli.
- Ventilation brings air rich in oxygen into the alveoli, and air with increased carbon dioxide is removed from the alveoli.
- The capillaries surrounding the alveoli are narrow, slowing down the blood flow and allowing plenty of time for efficient gas exchange.

Figure 2 The structure of an alveolus (not drawn to scale)

Questions
1. A premature baby may suffer from respiratory distress syndrome. This happens because the baby’s lungs do not contain enough surfactant. Suggest the symptoms of respiratory distress syndrome.
2. Describe in detail the path taken by a molecule of oxygen as it passes from the air in the alveoli to the haemoglobin in a red blood cell.
Lung capacity

The volume of air breathed in and out of the lungs depends on a number of factors. These include our level of activity, the size of our lungs and how healthy we are.

Look at Figure 1. This shows some of the volume changes that take place in the lungs during breathing. The actual volumes vary from one person to another.

- The **tidal volume** is the volume of air breathed in and out with a normal breath. This is usually about 0.5 dm$^3$.
- If you breathe out as much air as possible, and then breathe in as much air as possible, you will breathe in about 3.5 dm$^3$. This volume is called the **vital capacity**.
- Even when you have breathed out as much air as possible, there is still about 1.5 dm$^3$ of air left in the lungs. This is called the **residual volume**. It is important that there is some air left in the lungs when you breathe out, or the walls of the alveoli would stick together and it would be difficult to re-inflate the lungs.

**Using a spirometer**

Lung volumes can be measured using a piece of apparatus called a **spirometer**. You can see a spirometer in Figure 2.

**Flow rates**

Medical practitioners may also wish to measure the rate at which air can be expelled from the lungs when a person forcibly breathes out. This can help them to diagnose and monitor conditions such as asthma.

- The **forced expiratory volume per second** (FEV$_1$) is the volume of air that can be breathed out in the first second of forced breathing out.
- The **peak expiratory flow rate** (PEFR) is the maximum rate at which air can be forcibly breathed out through the mouth.

These volumes can be measured using a **peak flow meter**.
Using a spirometer

A person breathes in air through a tube connected to a container of oxygen that floats in a tank of water. You can see this in Figure 2.

The floating container rises and falls as the person breathes in and out. The rise and fall is related to the volume of air the person is breathing in and out.

The container has an arm attached to it, with a pen on the end. The pen draws a trace on some graph paper on a rotating drum. You can see a trace in Figure 3.

The air breathed out passes through a chamber containing soda lime, which absorbs the carbon dioxide in the air breathed out before it returns to the oxygen chamber. This stops the person re-breathing carbon dioxide, which would increase their breathing rate.

As the oxygen in the chamber is gradually used up, the volume of oxygen in the chamber reduces gradually. You can see this happening as the trace gradually goes down in Figure 3.

Note that you can also measure lung volumes using a digital spirometer.

Using a peak flow meter

- Stand up straight and make sure that the indicator is at the bottom of the meter.
- Take a deep breath and fill your lungs completely with air.
- Place the mouthpiece in your mouth and close your lips firmly around it.
- Blow air out of your mouth into the meter as hard as you can in one blow.
- Record the reading on the meter.
- Re-set the meter and take two more readings. Record the highest reading.

Some peak flow meters and digital spirometers will also measure FEV₁.

Normal values for PEFR

Figure 5 shows the normal range of values for PEFR for males and females of different ages.

Questions

1. Look at Figure 5.
   (a) Estimate the person’s tidal volume at rest using Figure 3.
   (b) Estimate this person’s normal breathing rate in breaths per second.

2. Asthma is a condition in which the bronchi and bronchioles constrict. Some people with asthma find that their condition is made worse when they are exposed to house dust mites. Figure 6 shows a graph of a person’s PEFR over several days.
   (a) Explain the evidence that this person’s asthma is caused by exposure to house dust mites.
   (b) Explain why PEFR is lower when a person is having an asthma attack.
Causes of respiratory arrest

Respiratory arrest is when a person stops breathing. It is possible for a person to stop breathing even though her heart is still beating. Many things can cause respiratory arrest, including:

• a respiratory disorder, e.g. severe asthma or pneumonia
• an obstruction in the trachea or bronchi, e.g. caused by choking on food or a child putting a small object into their mouth
• overdosing on drugs that suppress the respiratory system, e.g. heroin, barbiturates.

Respiratory arrest may also occur following cardiac arrest (when the heart stops beating).

Respired air resuscitation

This is a first aid procedure that you should carry out on a person who is not breathing but who still has a pulse. It is sometimes called ‘rescue breathing’.

First of all, dial 999 for an ambulance. If there is another person with you, send them to get help while you start rescue breathing. If you can, wear latex gloves and use a breathing mask.

• Roll the person on to his back, being very careful not to twist the person’s neck, head or spine. Then pull his head back and lift the chin as in Figure 1. This will open the person’s airway.
• Ensure nothing is blocking the person’s airway.
• Gently pinch the person’s nose shut, using the thumb and index finger. Then place your mouth over the person’s mouth, making a seal.
• Breathe slowly into the person’s mouth, and watch their chest to see if it rises. Pause between each breath to let the air flow out.
• If the person’s chest does not rise, tilt the head back again and try again.
• After giving two breaths, check for a pulse. If the person has a pulse, continue rescue breathing. You should give one breath every five seconds.
• If the person’s pulse stops, you should perform CPR (cardiopulmonary resuscitation, also called Basic Life Support). You can read about this in spread 2.4.1.1.

Examiner tip

Whenever breathing has stopped or the pulse is weak, cyanosis occurs. The word comes from the Greek word for dark blue – cyan. Cyanosis describes the bluish appearance of the skin especially around the lips. This is due to the build up of deoxygenated haemoglobin.

Figure 1 Opening the airway
Rescue breathing in children

This is very similar to the procedure for adults, but there are a few differences.

• To open the airway of an infant or child, you do not need to tilt the head so far back.
• Children or infants need one slow breath every three seconds.
• On a baby, you should use your mouth to make a seal over the baby’s mouth and
  nose at the same time.
• Check for a pulse after a minute of rescue breathing (about 20 breaths).

Figure 2  Rescue breathing

Questions

1. Suggest why you should use latex gloves and a breathing mask if these are available.
2. Suggest why you should avoid twisting the person’s head, neck or spine.
3. Suggest why it is important to check regularly for a pulse.
4. When you do rescue breathing, you are blowing exhaled air into the person’s lungs.
   This contains about 16% oxygen, although fresh air has 21% oxygen. Also, expired air
   has 4% carbon dioxide, while fresh air has 0.04% carbon dioxide. Explain why it is still
   helpful to blow expired air into the lungs of a person who is not breathing.
1.2 Circulatory and gas exchange systems summary

Self-check questions

Fill the blanks

1. The human heart has four chambers. ................. blood entering the heart from the vena cava enters the right .................. From here, the blood passes through ................. valves into the right .................. The right ventricle contracts to pump the blood to the ................. via the pulmonary .................. ................. blood from the lungs enters the left ................. through the ................. veins. This blood passes through the ................. valves into the left .................. When the left ventricle contracts, blood passes out of the left ventricle along the ..................

2. Atrial ................. is when the atria ................., forcing blood from the atria into the .................. During ventricular systole, the ................. contract. The pressure in the ventricles during systole causes the atrio-ventricular valves to ................. and the semi-lunar valves to .................. This forces blood out of the heart along the pulmonary ................. and the .................. During ................., the atria and the ventricles relax.

3. Heart muscle is ................. which means that it contracts without being stimulated by a nerve. The ................. node in the wall of the ................. atrium initiates the heartbeat. From here, impulses pass across the walls of the ................. to the ................. node between the atria and the ventricles. These cause the atria to contract. From the atrio-ventricular node, impulses pass along the ................. tissue to the ventricles. This causes the ventricles to contract.

4. ................. volume is the volume of blood pumped out by the heart during one cardiac cycle. Cardiac output = ................. × ................. rate. During exercise, both stroke volume and heart rate .................

5. ................. have a thick muscular wall, containing a great deal of ................. tissue. The diameter of the ................. is comparatively small. They transport blood at ................. pressure away from the ................. have thinner walls, containing some muscle and a little ................. tissue. The diameter of the ................. is comparatively large. They carry blood at ................. pressure back to the heart. They contain ................. to prevent backflow. ................. have no ................. or elastic tissue in their walls. They have permeable walls and supply materials from the blood to cells.

6. Squamous ................. cells in the ................. of the lung are an example of a ................., because they consist of a group of ................. cells carrying out the same function. A lung is an example of an ................. because it consists of several different kinds of tissue, all working together to carry out the same function. The respiratory tract is lined with ................. epithelium cells. These move mucus that has been secreted by ................. cells back towards the throat. In this way, dirt and ................. are kept out of the lungs.

7. The alveoli are efficient at gas exchange because they have a ................. surface area. The squamous epithelium cells are very ................. and flat, giving a short ................. pathway. The alveoli are well supplied with blood ................. and ................. keeps bringing fresh air into the lungs. This maintains a steep ................. gradient.
**Summary questions**

1. The diagram shows some cells from the lining of the respiratory tract.

   ![Diagram of respiratory cells](image)

   (a) (i) Name the type of tissue shown in the diagram. [1]
   (ii) Name structures A, B and C. [3]

   (b) Calculate the magnification of the drawing. Show your working. [2]

   (c) Explain how the tissue shown in the diagram may help to protect against lung infections. [3]

2. The drawing shows some structures involved in gas exchange in a human.

   ![Diagram of gas exchange structures](image)

   (a) Name structures A and B. [2]

   (b) Surfactant is found lining the walls of structure A. Explain the role of surfactant. [2]

   (c) Describe how a spirometer may be used to measure tidal volume. [4]

3. ![Diagram of heart](image)

   (a) Name structures A, B, C and D. [4]

   (b) Add arrows to the diagram to show the pathway of deoxygenated blood through the heart. [2]

   (c) Explain why the wall of structure D is thicker than the wall of structure C. [2]

   (d) Some children are born with a ‘hole in the heart’. This is a hole in the septum between the left and the right atria. Suggest the effects that this would have on a person with a ‘hole in the heart’. [3]
Question 1

Lymphocytes can be identified in a blood smear by using a differential stain.

(a) Describe the structure of a lymphocyte as seen in a blood smear examined using a light microscope.

Lymphocytes can also be examined using an electron microscope. A diagram of mature B lymphocyte is shown below.

![Diagram of mature B lymphocyte]

(b) Identify the structures by completing the table using EITHER the appropriate letter OR the name of the organelle.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>smooth endoplasmic reticulum</td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>nuclear envelope</td>
</tr>
</tbody>
</table>

(c) (i) What features of the cell in Figure 1.1 suggests that its main function is antibody production? [3]

(ii) Which structure in the cell will convert the antibody proteins into glycoproteins? [1]

(d) Describe how antibody molecules will be secreted from the mature lymphocyte. [4]

Question 2

Fill in the missing words in the following passage about erythrocytes and haemoglobin.

(a) Erythrocytes contain a solution of the ....................... protein haemoglobin. Haemoglobin consists of ........................... polypeptide chains. Each chain is attached to a ......................... group – a non-protein group which in this case is .......................... . The chains consist of a sequence of amino acids linked by ......................... bonds which form their primary structure. The sequence of amino .......................... is determined by DNA in the nuclei of stem cells in the .............................. . The nucleus is lost as the cells mature and are released into the plasma. [6]

(b) In the formation of a blood clot, erythrocytes become trapped in a network of insoluble protein fibres. Outline how soluble plasma proteins are converted into insoluble protein fibres when blood clotting occurs. [4]

(c) Antithrombin is a small protein molecule that inactivates enzymes in the clotting cascade. Antithrombin and enzyme molecules bind and the active site of the enzyme is blocked. The substrate cannot enter the active site and a product cannot be formed. Using examples from the clotting cascade, identify an enzyme, its substrate and its normal product. [3]
Question 3

(a) Cuff pressure > 120

(b) Time/sec mmHg

Figure 3.1

(a) Figure 3.1 (a) represents what happens in the arm when a blood pressure measurement is taken.

(i) Name the instrument which is being used to measure the blood pressure. [1]

(ii) Name the TYPE of blood vessel which is labelled A. [1]

(iii) Indicate the direction of blood flow in this vessel by placing an arrow on the diagram. [1]

(b) Line B to C on the graph indicates the pressure exerted by the cuff around the arm. This is inflated and then deflated slowly. A stethoscope is placed over the blood vessel. The noises which are detected are called the Korotkov sounds.

(i) Explain why no sounds are heard at one second. [2]

(ii) Between two and four seconds, a regular tapping noise is heard. Using the information on the graph, describe the blood flow responsible for this sound. [2]

(iii) Between four and six seconds, the sounds become softer. Using the information on the graph, explain why. [2]

(iv) Using the information on the graph – give the blood pressure reading that would have been recorded. [2]

Question 4

A spirometer was used to measure lung volumes. The measurements were carried out at two different breathing rates. The data collected was used to calculate the pulmonary ventilation rate.

(a) State two precautions that should be taken when carrying out investigations with a spirometer. [2]

(b) Pulmonary ventilation is the volume of air breathed per minute. If the pulmonary ventilation rate was 6000 cm³ min⁻¹ and the tidal volume was 200 cm³, what was the breathing rate during the experiment? [2]

(c) The volume of air arriving at the alveolar surface was only 1500 cm³. With reference to the structure of the gas exchange system, comment on the implications of so little of the air inhaled reaching the alveoli. You will gain credit for the use of figures in your answer.

Credit will also be given for good organisation and the use of technical terms. [5]