BIOLOGY

BREATHING & CIRCULATION

Blood

- Blood cell types
- The structure of red blood cells in relation to their transport function
- The relationship between size and surface area to volume ratio

Blood vessels

- Blood vessels as organs
- The structure of arteries, arterioles and veins in relation to their function.

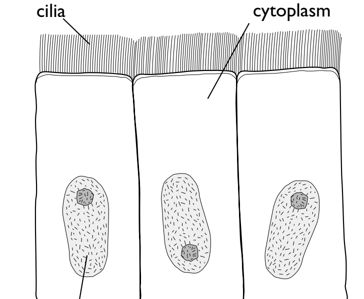
EPITHELIAL TISSUE

A **tissue** is a group of similar cells, specialised to perform the same function. Epithelial tissues cover both external and internal surfaces, and typically form sheets of large surface area but of thin cross-section. The cells are held together by an intercellular cement, and by tight junctions between adjacent membranes. At their base the cells are fixed to a basement membrane. They have one free surface which is often highly specialised with, for example, microvilli or cilia.

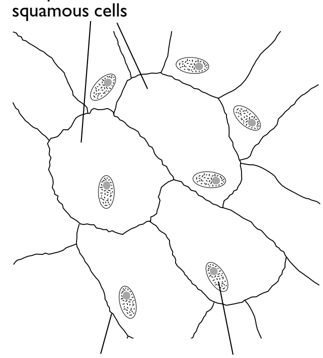
Epithelia may have a protective function, as in the skin, protecting underlying regions from the entry of pathogens and from the damaging effects of abrasion, desiccation and ultraviolet light, in these cases they are multilayered (compound). In the bronchial tubes, the epithelial lining is **ciliated** to move trapped foreign particles and prevent their entry into the lung, whilst in the alveoli, the epithelium is adapted to facilitate gas exchange.

Gas exchange in the human lungs occurs over a surface formed by around 700 million tiny air sacs (**alveoli**), each constructed out of epithelial cells. This gives an estimated total surface area of 70-90m^2. The **bronchiole**, leading to the alveolar air sac, in common with all the air passages, is lined by **ciliated** and **glandular epithelia.** Foreign particles are trapped by mucus secreted by the glandular cells and moved up the respiratory tubes towards the mouth by the beating action of the cilia. The surfaces of the alveoli are further protected by phagocytic cells called macrophages which move over them in amoeboid fashion, engulfing bacteria and other particles. Each air sac is constructed from **squamous** (flattened) epithelial cells allowing the shortest possible diffusion distance between the air space and the blood capillaries.

T.S. simple ciliated columnar epithelium



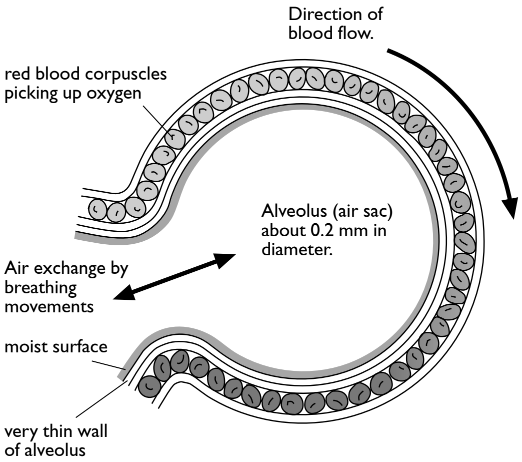
Surface view of simple squamous epithelium



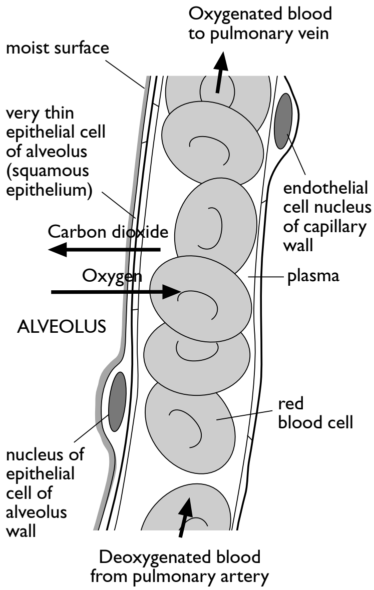
In section squamous cells look like slender rods thickened where the nucleus is located

Each alveolus is surrounded by a network of capillaries which together form the **alveolar-capillary complex**. As this name suggests, the endothelium lining of the capillaries is attached to the thin squamous epithelium of the alveolus via a shared basal membrane. The air inside the alveolus and the blood in the capillaries is thus separated by a distance of just the thickness of two layers of very thin cells. This is one feature that helps rapid diffusion of oxygen from alveolus to blood and carbon dioxide from blood to alveolus. Other features include the large surface area already mentioned, and the steep diffusion gradients which are maintained between the blood and the alveolus due to the constant movement of the blood and the constant ventilation of the lungs.

The presence of a phospholipid material called **pulmonary surfactant** ensures that the tiny air sacs do not stick together like wet panes of glass when they collapse, but slide over each other maintaining a clear airway. Phospholipids act like a detergent, reducing the surface tension of fluids at the alveolar surface.



Gas exchange alveolus/capillary



BLOOD

Blood Cell types

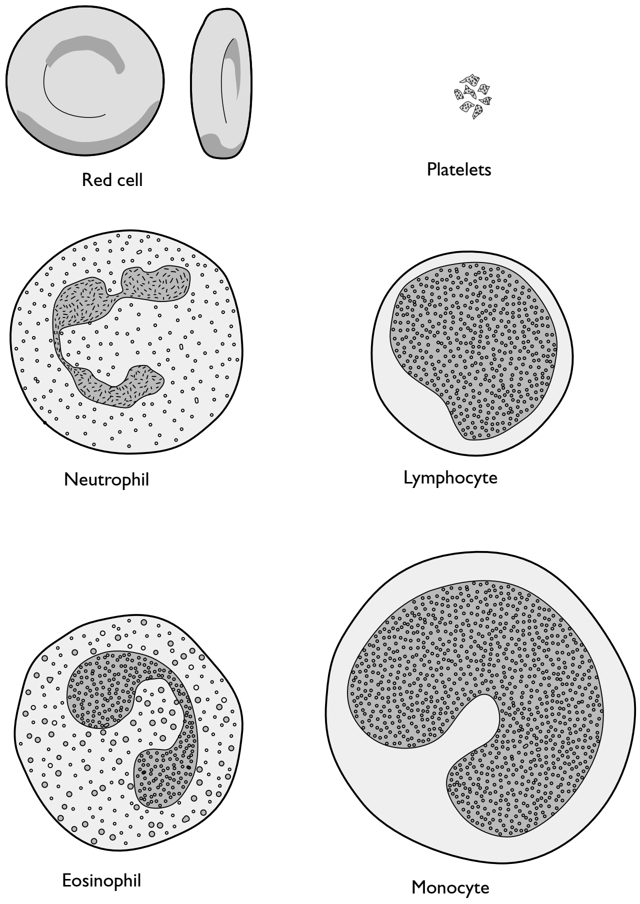
Blood is a specialised tissue containing a number of different cell types

The structure of red blood cells in relation to their transport function

Of the cellular components, red blood cells (erythrocytes) are by far the most numerous. Red blood cells lose their nucleus and most of the cytoplasmic organelles in their process of maturation, and become 'corpuscles' with a flexible membrane, filled with the oxygen carrying pigment haemoglobin. The loss of the nucleus accounts for their biconcave shape which increases their **surface area to volume ratio**. This ratio is of the utmost importance for any cell or group of cells exchanging materials with their surroundings. In general, as the volume of a cell increases so its surface area to volume ratio decreases. This principle is illustrated by the fact that the surface area to volume ratio halves as the sides of a cube are doubled from 1 to 2 cm.

The total surface area of the red blood cells in man is about 3500 m^2 and this helps the exchange of gases between the red cells and the tissues. The biconcave shape also gives them some resilience in absorbing water without bursting should the plasma become temporarily diluted for any reason, and the flexible membrane enables them to 'squeeze' through capillaries.

Blood components



BLOOD VESSELS

Blood vessels as organs

An organ may be defined as a structure consisting of several tissues which together perform a complex function (examples include the stomach, brain and lung). Blood vessels are organs whose function is the circulation of blood throughout the body. The blood circulates around a continuous system of blood vessels, from the heart in the arteries and arterioles, into the capillary beds supplying the tissues, and back to the heart in the venules and veins.

◆ CHECKPOINT SUMMARY

- In multicellular organisms cells are organised into tissues. A tissue being an association of similar cells specialised and coordinated to a particular function. Some functions being more specialised than others
- Examples of tissues in mammals include squamous epithelium covering surfaces e.g. in the kidney tubule and the alveoli of the lungs, ciliated epithelium lining the trachea and bronchi, cerebro-spinal canal, and oviduct
- Some tissues consist of only one type of cell. e.g.ciliated epithelium, whilst others consist of several variants of similar types of cells
- Cells in the same tissue develop from the same original cell type, even though the fully differentiated cells may appear very different
- Different tissues become 'organised' into organs specialised to particular functions, e.g. a lung is an organ and consists of squamous epithelium, ciliated epithelium, connective tissue, blood vessels etc.
- Blood consists of fluid plasma with red blood cells, white blood cells (or white cells) and blood platelets
- Plasma has 10% materials in suspension and solution
- Plasma proteins wide variety of functions and act to buffer changes in pH
- Materials carried in solution not strictly part of the plasma
- Red blood cells lose nucleus in development and become biconcave corpuscles of haemoglobin
- Large surface area to volume ratio individually due to biconcave shape, and huge total surface area due to small size (6-8 μm) and huge numbers
- Red blood cell volume 30-50% of total blood volume
- Males higher blood count/haemoglobin than females
- White cells of which there are several types form basis of immune system
- Platelets are fragments of white cells.

Arteries, arterioles and veins

The arteries close to the heart have a large cross sectional area, and thick elastic walls. Arteries are stretched by the cardiac output when the heart contracts, and they recoil as the arterial blood pressure drops when the heart relaxes between beats. The recoil of the elastic artery walls assists the circulation of the blood around the body, helps smooth the flow between contractions of the heart, and helps to maintain the blood pressure. This stretching and recoiling of the arteries is felt as the pulse in places where arteries come close to the surface of the body (the inside of the wrist, the side of the neck, and in the temple).

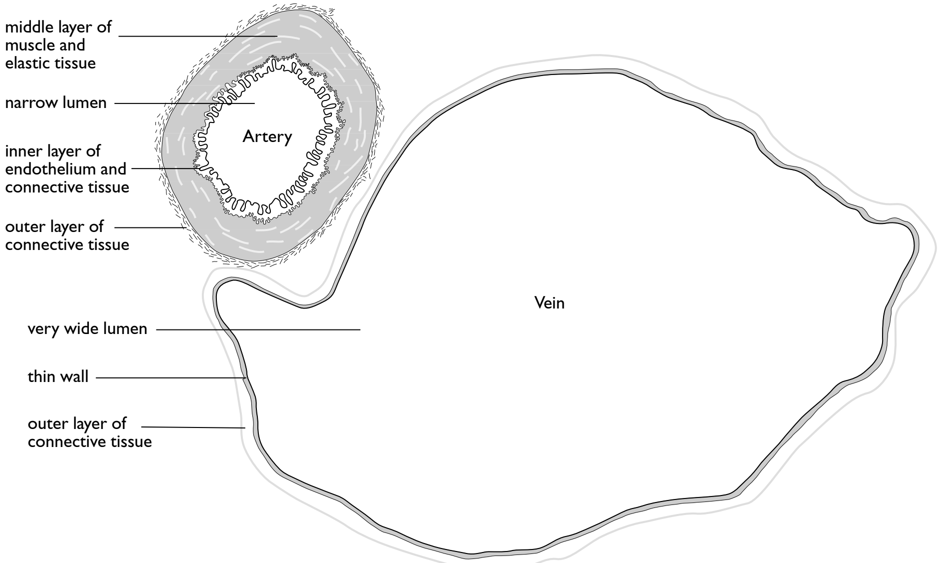
Further from the heart, the arteries branch into the smaller arterioles. The arterioles penetrate all tissues of the body and connect to beds of finely branching capillaries.

From the capillary beds **venules** join together to form **veins**, which return the blood to the heart. The individual veins have a larger cross section area than the comparable arteries, and as there are more veins than arteries, the veins also have a greater total cross sectional area. The walls of the veins are thinner and less elastic than those of the arteries, and in the veins of the legs and arms there are semi-lunar or pocket valves at intervals along their length. These valves oppose any back flow of blood under gravity, and ensure one-way flow of blood back to the heart.

The thin walled veins with their large cross section area present little resistance to the flow of the blood, and although after the blood has passed through the capillaries, the blood pressure in the veins is low, it still helps move the blood in the veins back to the heart. Because the blood in the veins is under low pressure, and their walls are thin, the veins are easily compressed by the smallest movements of the surrounding structures, particularly the skeletal muscles. As the muscles contract and relax during exercise they exert a massaging effect on the deep veins, especially for example in the legs, when running, swimming, or cycling. This massage effect of the 'muscle pump' is random and in no particular direction, but the pocket valves in these veins ensure that the flow is one-way, back to the heart.

◆ CHECKPOINT SUMMARY

- ◆ Elasticity of arteries important in smoothing flow of cardiac output. Expansions and contractions is felt as the pulse
- ◆ Finer branches and arterioles main site of generation of resistance to blood flow
- ◆ Capillary beds supply all tissues providing large surface areas for exchanges by diffusion and short diffusion distances
- ◆ Capillaries have large total cross sectional surface areas. Therefore resistance to flow, blood pressure and rate of flow all drop in capillaries
- ◆ Diameter of capillary same as red blood corpuscles thus forcing them to pass through capillaries in single file, bringing all close to tissues
- ◆ Plasma minus proteins is exuded through thin walls to bathe tissues directly.
- ◆ Thin walls and large lumen of veins offer little resistance to flow of blood back to heart, and allow ease of massage by surrounding muscles
- ◆ Pocket valves ensure one way flow back to heart
- ◆ Venous blood is under low pressure but the flow is fast enough to ensure return of blood to heart at same rate as blood flow in the arteries.

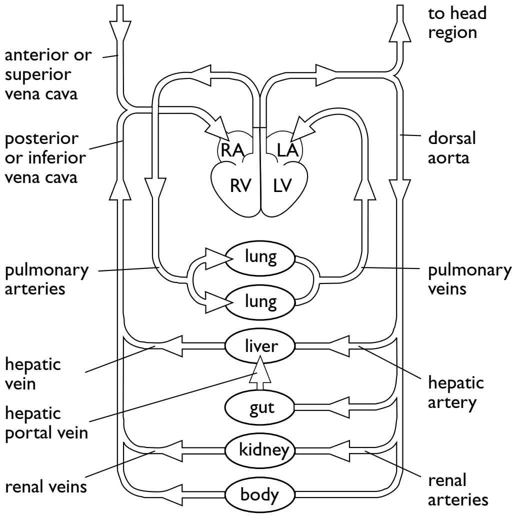


The blood system as a mass flow system

Contents

CIRCULATION

Transported materials are carried around the whole closed circulatory system, accumulating in high concentrations in those regions where they are absorbed or produced (**sources**) and reaching their lowest concentrations in areas where they are being used up or excreted (**sinks**). The overall flow of materials is from source to sink. This is described as **mass flow**. Arteries and arterioles deliver materials to the tissues, venules and veins carry blood back to the heart for oxygen uptake at the lungs and recirculation, but the important exchange of materials between blood and body tissues occurs in the capillary beds.

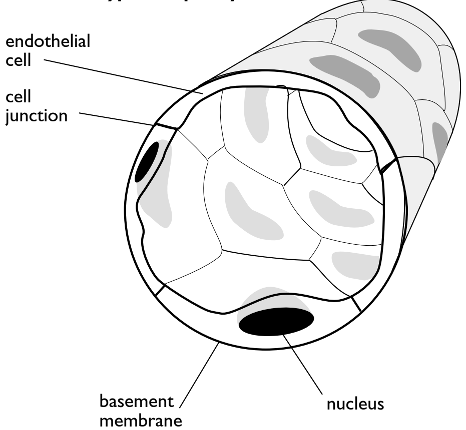


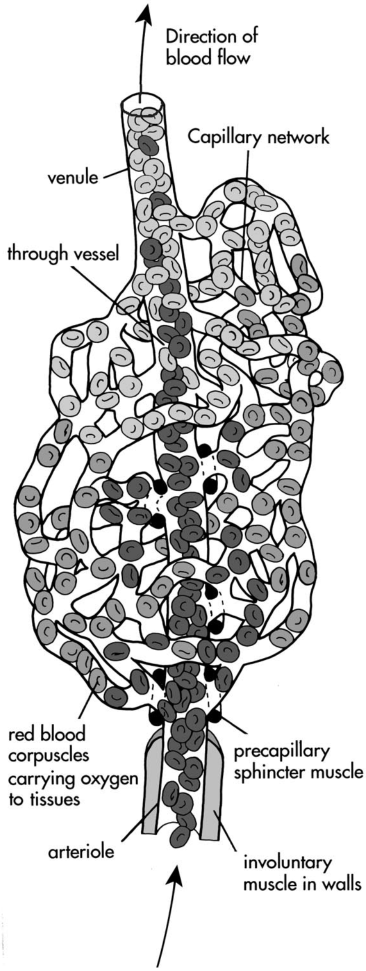
CAPILLARIES

The structure of capillaries and their importance in metabolic exchange

The capillaries form a fine network which penetrate all tissues. They have the smallest diameter of all blood vessels, about 7 micrometres (0.007 mm), which is the same as that of the red blood cells. For this reason the red cells are forced to move slowly through the capillaries in single file, ensuring a short diffusion distance between the corpuscles and the tissues. Capillary walls are just one cell thick, which further aids exchanges by diffusion between the blood and the tissues. The huge number of capillaries provide a very large surface area across which these exchanges occur. As more capillaries open up in working muscles, the surface area between the blood and tissues is increased, and the diffusion distance between the two is decreased, resulting in more rapid and efficient exchanges between them.

Section of typical capillary





The formation of tissue fluid and its return to the circulatory system

Tissue fluid is formed when plasma, minus most of its proteins, is pushed out under pressure through the capillary walls. Depending on the degree of activity and health and fitness, most of the tissue fluid is reabsorbed back into the blood capillaries. Tissue fluid bathes each cell and is the medium for the exchange of materials between the individual cells and the blood system.

The tissue fluid which is not reabsorbed into the blood capillaries, especially any proteins, enters the lymphatic capillaries, which are found in all tissues, and becomes lymph. If the lymphatic capillaries did not drain the tissues, the blood protein would accumulate in the tissue fluid and, due to its osmotic effect, would hold increasing amounts of water in the tissues. Lymph has a higher protein content than the tissue fluid.

The blind-ended lymphatic capillaries lead into wider lymph vessels which are similar in structure to the veins, having thin walls with pocket valves. Contraction of skeletal muscles massages the vessels and the valves ensure unidirectional flow. This aids the draining of tissue fluids.

During exercise the blood pressure may increase, and more tissue fluid is exuded; the lymph vessels are massaged more vigorously, and therefore the tissue fluid is drained more quickly. All these factors increase the speed of supply of oxygen and nutrients to, and removal of waste products from, the tissues.

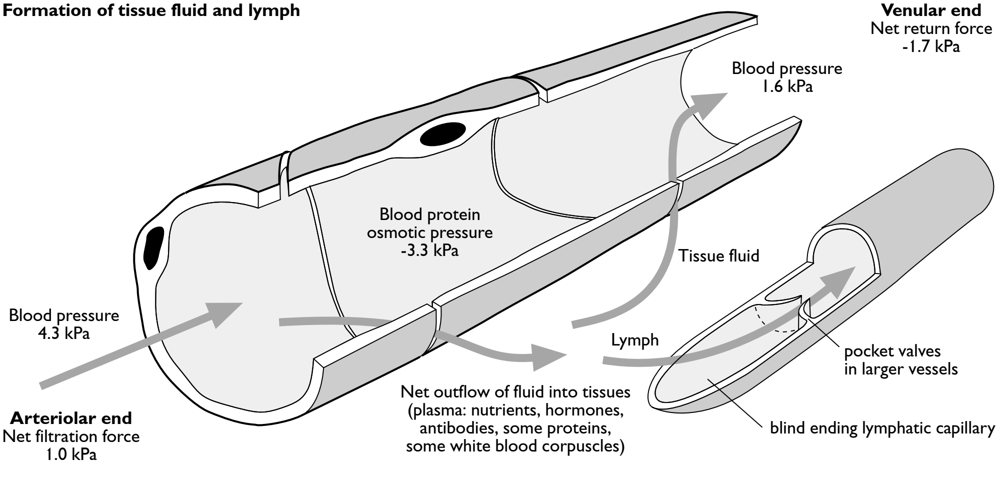
At intervals in the system are swellings called lymph nodes, which play an important role in the defence of the body against infection (ref 3HB 12.3).

The lymph is returned to the circulation in the anterior venae cavae.

◆ CHECKPOINT SUMMARY

- ◆ Closed double mammalian circulation more efficient than open single circulation
- ◆ Open circulation has blood returning to heart in large open blood spaces (haemocoel), slow flow and low pressure
- ◆ Single circulation blood only passes through heart once on each complete circulation of the body
- ◆ Means that blood passes through two sets of capillaries on each circulation, respiratory surface and body tissues
- ◆ Large resistance to overcome before blood returns to heart, resulting in slow flow and low pressure in veins which are typically large blood sinuses to lower resistance to flow
- ◆ Closed systems blood almost entirely restricted to vessels: arteries, arterioles, capillaries, venules, veins
- ◆ Tissue fluid exuded to bathe tissues directly
- ◆ Double circulation blood passes through heart twice on each circulation
- ◆ Pressure relatively low to lungs
- ◆ Pressure raised for systemic circulation to body giving high pressure and fast flow.

Formation of tissue fluid and lymph



LUNG FUNCTION

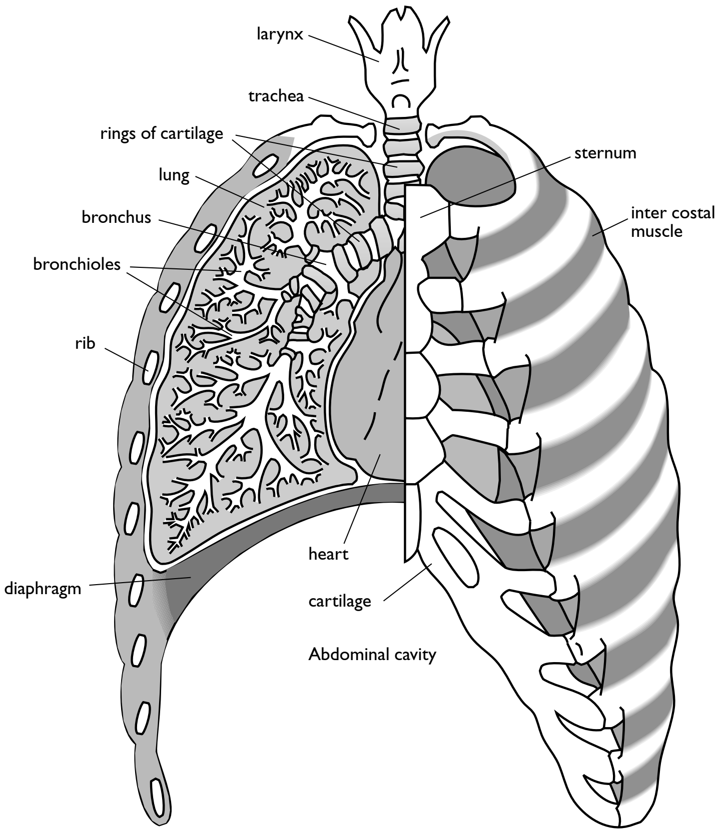
Structure of human gas exchange system

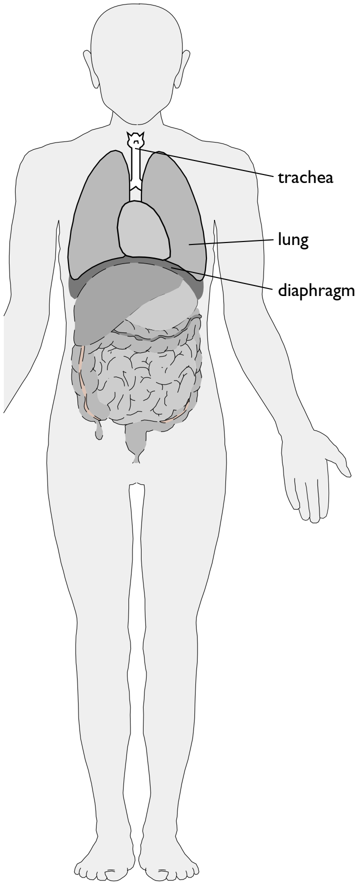
Together with the heart, the lungs fill all the available space in the air tight **thoracic (chest) cavity** bounded by the ribs and the muscular sheet known as the **diaphragm**. Air passes into a series of tubes which make up the respiratory system having first been warmed and moistened in the nasal cavity. The **trachea, bronchi and bronchioles** form a system of branching air tubes referred to as the 'bronchial tree'. The wall of the trachea and bronchi is composed of an **epithelial** layer, **connective tissue**, **smooth muscle** and **cartilage**, and a tough outer coat. Bronchioles differ in that they lack cartilage.

Cartilage supports the trachea and bronchi and prevents their collapse. In the trachea the cartilage forms C-shaped rings which are arranged so that the open ends of the C are at the back of the tube, facing towards the oesophagus and the spine. These support the tube and keep it open during inspiration (breathing in). Between the ends of the Cs at the posterior (back) of the trachea, smooth muscle completes the tube. The incomplete nature of these 'rings' of cartilage allows some flexibility as the oesophagus expands when food is moving down. In the bronchi the cartilage does not form rings but instead forms plates within the smooth muscle layer to strengthen the tubes.

◆ BLOOD PRESSURE

The continuous random movement of particles of a gas means that the particles will collide with each other and with the walls of any structure enclosing them within a space, thus exerting a pressure. The number of such collisions, and therefore the pressure, is proportional to the amount of substance present. In mixtures of gases, e.g. air, each substance exerts a partial pressure in that mixture proportional to the amount of that substance in the mixture.



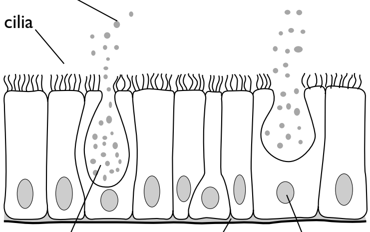


Involuntary (smooth) muscle found in the trachea, bronchi and bronchioles also helps maintain the shape of the tubes and prevents collapse of the airways. The smooth muscle receives nerve impulses from the autonomic nervous system which can regulate the diameter of the tubes. This is significant in diseases like asthma and anaphylaxis where constriction of the bronchioles occurs restricting air flow.

Epithelium lining the trachea, bronchi and bronchioles is known as the mucous membrane, and consists of ciliated columnar epithelium. This possesses: ciliated cells and goblet cells.

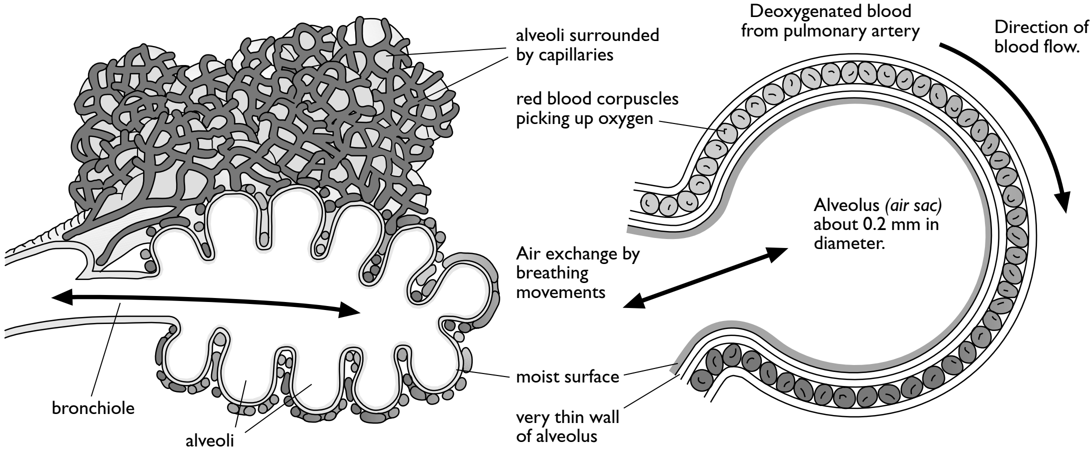
Ciliated epithelial cells have a protective function as they work in a co-ordinated fashion sweeping the mucus coat of the air passages, which contains small inhaled particles such as dust, towards the pharynx (throat) where they can be swallowed. This prevents such particles from entering the alveoli and interfering with gaseous exchange. **Goblet cells** are scattered among the ciliated cells in the trachea, bronchi and bronchioles, and are responsible for producing and secreting mucus within the respiratory tract. The layer of mucus which lines the airways traps dust and bacteria.

Respiratory ciliated columnar epithelium



Alveoli or air sacs make up the mass of the lungs. The ends of the bronchioles terminate in tubes, only 1-2mm in diameter, known as alveolar ducts which lead to the small chambers used for gas exchange (alveoli). Although each alveolus is very small, the large numbers of alveoli (around 700 million) provide an enormous surface area for gas exchange: something in the region of 70-90m^2 in an adult lung.

Blood vessels of the pulmonary circulation supply the alveoli. Deoxygenated blood enters the lung via the pulmonary artery which initially splits into right and left branches and then follow the airways, branching through the tissue of the lung.



The exchange of respiratory gases in the lungs

Gas exchange occurs by diffusion between the air in the alveoli of the lungs and the blood in the capillaries. The rate of diffusion of a substance is dependent upon the difference in its concentration in two separated regions (the concentration gradient), the distance separating them, and the surface area, a relationship expressed in the following equation known as **Fick's law** (see 10.3).

$$\text{Rate of diffusion} = \frac{\text{surface area x difference in concentration}}{\text{thickness of the exchange surface}}$$

This gives a rough guide to the speed with which oxygen diffuses from the watery lining of an alveolus to the blood in a lung capillary. In principle, the greater the surface area, the greater the concentration difference, and the thinner the separating layers, the more rapid the diffusion.

The relative amounts of oxygen and carbon dioxide in the air breathed in and out are measured as 'partial pressures' in units of kiloPascals (kPa).

The partial pressure of a gas is a better measure of the amount of gas present than its percentage composition. Although the percentage of oxygen remains the same (21%) in air under different conditions, the **amount** of oxygen does not. At atmospheric pressures less than at sea level e.g. at altitude, there is still 21% oxygen in air, but as the air is less dense there is a smaller amount of oxygen.

Blood entering the capillaries of the alveoli from the pulmonary (lung) arteries has a lower oxygen and a higher carbon dioxide content, than the air in the alveoli. Therefore carbon dioxide diffuses out of the blood into the alveoli, and oxygen diffuses into the blood from the alveoli, each down their partial pressure gradients.

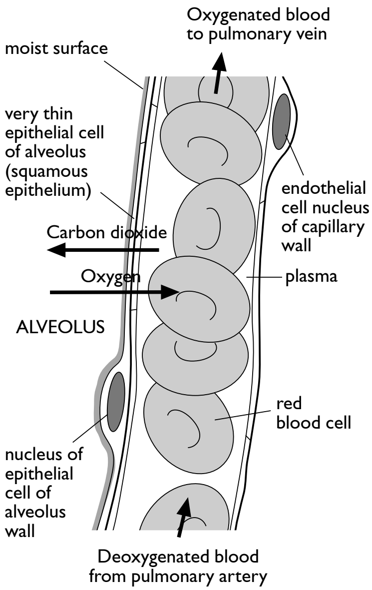
The oxygen diffusing into the blood dissolves in and diffuses through the film of moisture on the surface of the alveoli, through the thin walls of the alveoli, through the thin wall of the capillaries, through the plasma, and through the red blood corpuscle membrane to combine with the haemoglobin to form oxyhaemoglobin.

About 250 cm^3 of oxygen per minute diffuses in over the alveoli at rest, and this can be increased up to about twenty times during exercise.

Carbon dioxide diffuses in the opposite direction to the oxygen, from the blood plasma into the alveoli.

Carbon dioxide molecules are larger than those of oxygen and therefore diffuse more slowly in the gas phase, but carbon dioxide is much more soluble than oxygen and therefore diffuses about twenty times more readily in solution than oxygen across the capillary-alveolar barrier. This explains why, although the pressure gradient of carbon dioxide is only 6 mm Hg compared to 60 mm Hg for oxygen, sufficient exchange of CO_2 still occurs.

Gas exchange alveolus/capillary



◆ CHECKPOINT SUMMARY

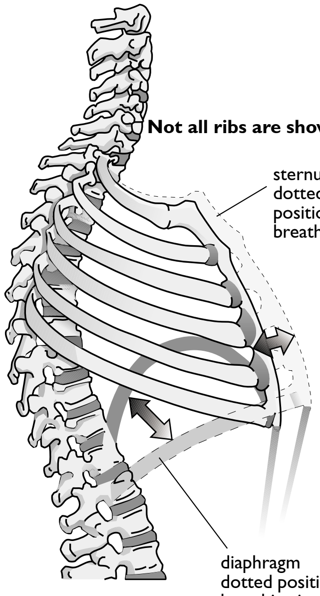
- ◆ Gas exchange occurs over large surface area of alveoli which is a product of their relatively small size and large number
- ◆ Diffusion gradients of oxygen and carbon dioxide dependent upon partial pressures of gases on either side of diffusion surface
- ◆ Diffusion surface composed of thin squamous epithelium ridged around the sandwiched capillaries
- ◆ Surface water an inevitable consequence of a permeable surface exposed to air, decreases diffusion of oxygen more than the diffusion of carbon dioxide
- ◆ Air in alveoli remains fairly constant in composition independent of breathing cycle.
- ◆ Diffusion gradients maintained by circulating blood and ventilation of the lungs
- ◆ As demand for oxygen increases so does steepness of diffusion gradients and speed of circulation thus meeting extra demand.

Exchanges between alveolar air and pulmonary blood at rest

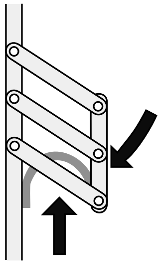
	Blood in pulmonary artery	Alveolar air	Blood in pulmonary vein
	mmHg	mmHg	mmHg
O_2	40.0	98.0	96.0
CO_2	46.0	40.0	40.0

Differences between inspired and expired air

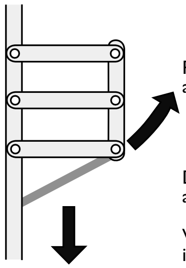
	Dry inspired air	Alveolar air	Expired air
	mmHg	mmHg	mmHg
O_2	159.6	98.0	116.2
CO_2	0.3	40.0	28.5
N_2	600.0	575	567.5



Muscles Relaxed



Muscles Contracted



VENTILATION

The mechanism of ventilation and its nervous control

For efficient gaseous exchange at the alveolar surface, air must be moved in and out of the lungs in the process called **ventilation**. This is achieved by the movements of the **intercostal muscles** of the ribs and the muscular **diaphragm,** which are controlled by the autonomic and voluntary nervous systems.

During **inspiration** (breathing in) the external intercostal muscles contract pulling the ribs upwards and outwards. At the same time the diaphragm contracts, moving downwards. Both movements increase the volume of the thorax, reducing the pressure in the thorax below atmospheric pressure causing air to enter, inflating the lungs. At rest, **expiration** (breathing out) does not involve active muscle contractions, but depends upon the elasticity of the tissues of the lungs and thorax.. The external intercostal muscles relax, allowing the rib cage to move downwards and inwards, and the diaphragm relaxes and regains its domed shape. The volume of the thorax is reduced, pressure increased above atmospheric pressure and air is forced out of the lungs. During forced breathing, for example as a result of exercise or in speech, expiration is active, with the internal intercostal muscles and abdominal muscles contracting to increase the pressure within the thorax.

Friction between the lungs and the inner surface of the wall of the thorax is reduced by the **pleural fluid** which lies between the two pleural membranes that surround the lungs.

Breathing movements result in certain volumes of air passing into and out of the lungs.

The role of the medulla and phrenic nerves in generating a basic breathing rhythm

Normally, respiratory movements are involuntary, being controlled by rhythmic discharges of nerve impulses from the respiratory control centres in the **medulla** region of the brain. From the inspiratory control centre impulses travel down the **phrenic nerves** to the diaphragm, and down the **intercostal nerves** to the external intercostal muscles causing them to contract and bring about inspiration. When the alveoli are stretched at the end of inspiration, stretch receptors in the bronchioles send impulses to the **inspiratory control centre** in the medulla, which is switched off, and the diaphragm and external intercostal muscles relax. The elasticity of the the tissues of the lungs and thorax leads to expiration as they recoil. Normally, expiration is passive but it may be assisted by nerve impulses originating in the **expiratory control centre** in the medulla which cause the internal intercostal muscles to contract.

The inspiratory control centre and expiratory control centres are antagonistic to each other, each inhibiting the activity of the other so that neither can operate at the same time. The two centres are responsible for maintaining the basic rhythm of breathing.

The rate of respiration is mainly dependent upon the carbon dioxide concentration of the blood, which has a direct effect on the respiratory centres of the medulla. Any increase in carbon dioxide levels is also detected by sensory receptors (chemoreceptors) located in the aorta and carotid arteries which inform the medulla of the need to increase the rate and depth of breathing. These sensory messages are backed up by other receptors which inform the medulla of increases in temperature and decreases in oxygen levels and blood pH.

◆ CHECKPOINT SUMMARY

- For efficient gaseous exchange at the alveolar surface, air must be moved in and out of the lungs in the process called ventilation
- Inspiration (breathing in) - the external intercostal muscles contract, pulling the ribs upwards and outwards, the diaphragm contracts, moving downwards, the volume of the thorax increases, the pressure in the thorax decreases below atmospheric pressure causing air to enter, inflating the lungs
- Expiration (breathing out) depends upon the elasticity of the tissues of the lungs and thorax. The respiratory muscles relax, the thorax and lungs recoil as a result of their elasticity and the events of inspiration are reversed
- At sea level the composition of inspired air is relatively constant, but the composition of expired air varies with the activity of the individual
- More oxygen is consumed and carbon dioxide produced as activity increases.
- Normally, respiratory movements are involuntary, being controlled by rhythmic discharges of nerve impulses from the respiratory control centres in the medulla region of the brain
- From the inspiratory control centre impulses travel down the phrenic nerves to the diaphragm, and down the intercostal nerves to the external intercostal muscles causing them to contract and bring about inspiration
- At the end of inspiration, stretch receptors in the bronchioles send impulses to the inspiratory control centre in the medulla, which is switched off, and the diaphragm and external intercostal muscles relax. The elasticity of the the tissues of the lungs and thorax leads to expiration as they recoil.

The function of the heart in the circulation of blood and in relation to the level of activity of an individual

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Heart structure

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- Pulmonary ventilation as the product of tidal volume and breathing rate
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- Nervous control of heart rate in relation to changing demands.
- Redistribution of blood flow in response to varying degrees of exercise
- The relative stability of blood supply to the brain and the increase to skeletal muscle.

HEART STRUCTURE and FUNCTION

The heart is situated in a cavity, slightly to the left of the chest mid-line, protected by the ribs and by a membrane (**pericardial membrane**) which surrounds it in a fluid filled cavity.

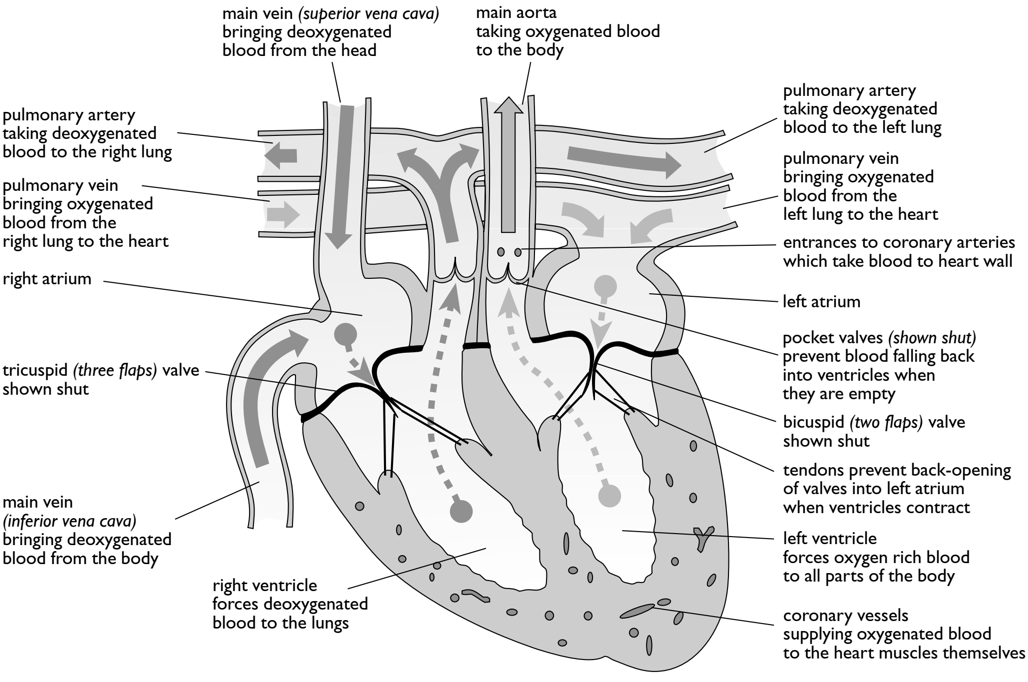
The collecting chambers of the heart, the right and left **atria** are situated at the top of the organ, receiving blood from the major veins (**venae cavae** and **pulmonary veins**). Note that diagrams of internal organs are always viewed from the front or anterior side of the body, so that the right atrium and right ventricle appear on the left side of the diagram. The atria are separated from the main pumping chambers (right and left **ventricles**) by flaps of fibrous tissue which act as one way valves, the **tricuspid valve** on the right and the **bicuspid valve** on the left. These atrio-ventricular valves are supported by tendons and muscles which prevent them blowing outwards under pressure. Inside the entrance of the main arteries which leave the heart, the aorta and pulmonary artery are two more sets of valves called **semi-lunar, or pocket valves**, the action of which is described later. Immediately above the semi-lunar valve in the aorta is the entrance to the **coronary artery** which supplies the heart itself with food and oxygen. This branches all over the surface of the heart. Deoxygenated blood is collected into the **coronary vein** which empties directly into the right atrium.

The walls of the atria are less muscular than those of the ventricles, and the wall of the right ventricle is not as muscular as that of the left ventricle. These differences reflect the different amounts of work that the various chambers have to do. The atria only have to pump blood into the ventricles, and the right ventricle pumps blood to the lungs at a lower pressure, than the left ventricle which pumps blood all around the body. However, it is important to remember that the volumes of the cavities of the chambers on the right hand side of the heart are the same as those on the left hand side of the heart, otherwise the right side would not be able to supply the left side with blood.

The blood travels from the heart to the lungs and back to the heart in the **pulmonary circulation**, and then from the heart around the rest of the body and back to the heart in the **systemic circulation**. This arrangement means that the blood can be pumped through the capillaries of the delicate alveoli of the lungs at a lower pressure, than that of the systemic circulation in which a higher pressure is required for the circulation around the body. The lower pressure is a result of the less muscular wall of the right ventricle, and the lower resistance presented by the relative thinness of the elastic walls of the pulmonary arteries, and their arterioles. If the blood pressure was any higher in the pulmonary circulation (as it sometimes is in people suffering from **hypertension** or 'high' blood pressure) the lungs would be at risk of filling with tissue fluid, which would have serious consequences for gas exchange.

◆ CHECKPOINT SUMMARY

- ◆ External appearance of heart includes small 'flap-like' atria, coronary blood vessels, fat deposits, and major vessels entering and leaving
- ◆ Internal structure of two atria and two ventricles. Atria separated from ventricles by flap valves
- ◆ Chordae tendinae and muscles preventing back-opening of bicuspid and tricuspid valves when ventricles contract (ventricular systole)
- ◆ Pocket valves at base of pulmonary artery and main aorta prevent backflow of blood into ventricles when they relax (ventricular diastole)
- ◆ Atria walls thinner than ventricle walls
- ◆ Left ventricle wall thicker than right ventricle wall to pump blood around body (systemic circulation)
- ◆ Right ventricle wall thinner as only has to pump blood via pulmonary circulation around lungs, where reduced pressure prevents formation of tissue fluid in alveoli
- ◆ Volumes of both left and right ventricles the same as right ventricle supplies the left ventricle with blood via the lungs and left atrium.



The cardiac cycle

The sequence of events that occurs during the filling and emptying of the heart is known as the cardiac cycle. At a rate of 70 beats per minute (bpm) the complete cycle takes about 0.86 seconds. It is a continuous sequence of events, but for the purposes of explanation it is convenient to consider it as occurring in a series of stages. There is a point in the cardiac cycle when all the heart valves are shut, which can be taken as the starting point of the cardiac cycle.

Blood returning under low pressure in the main veins (superior and inferior venae cavae) from the upper and lower body enters the right atrium, and at the same time blood returning from the lungs in the pulmonary veins enters the left atrium.

The atria fill with blood, and the rising pressure of the blood in the atria pushes the tricuspid and bicuspid valves open, and both ventricles begin to fill. As the heart fills with blood both atria contract (**atrial systole**) forcing even more blood into the ventricles. These are now stretched, and they both contract (**ventricular systole**) forcing the blood upwards. This upsurge of blood forces the tricuspid and bicuspid valves shut. These valves are prevented from back-opening into the atria by tough tendon cords, which are held taut by contraction of the papillary muscles to which they are attached. The closing of these valves makes the first heart sound (described as 'lub').

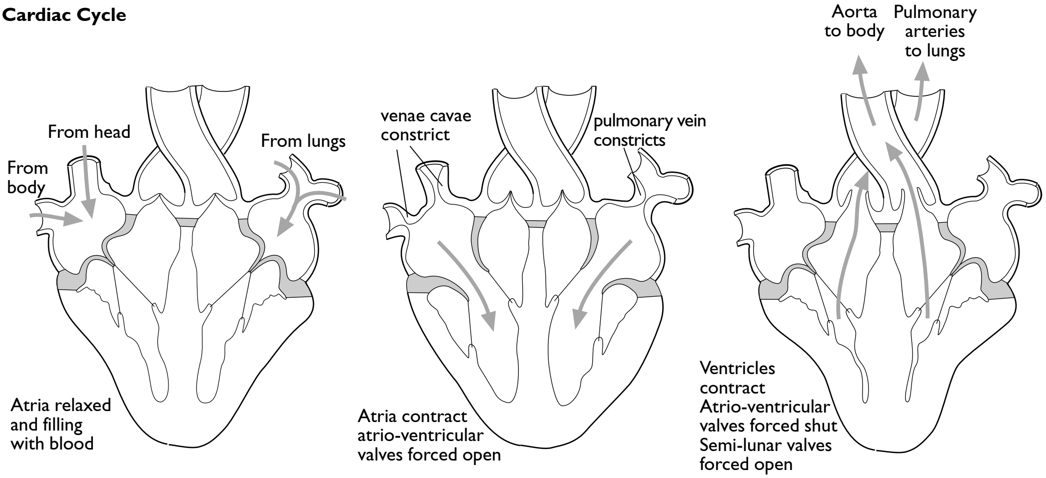
The blood is thus forced along the pulmonary artery to the lungs, and along the main aorta to the rest of the body, forcing open both sets of pocket or semi-lunar valves on the way.

When the ventricles relax (**ventricular diastole**) the blood tends to fall back down the pulmonary artery and main aorta under gravity, thus filling and shutting the pocket valves. The closing of these valves makes the second heart sound (described as 'dub'). All valves are now shut and the cycle is repeated.

◆ CHECKPOINT SUMMARY

- ◆ The events of a complete filling and emptying of the heart are known as the cardiac cycle
- ◆ It is a continuous cycle the start point of which can be taken when heart is empty and all valves shut
- ◆ Atria fill and internal pressure rises forcing bicuspid and tricuspid valves open
- ◆ Ventricles fill so that whole heart full
- ◆ Atria contract (atrial systole) so that ventricles overfilled and stretched
- ◆ Ventricles contract with a force proportional to their degree of stretch (ventricular systole)
- ◆ Blood forced up shutting bicuspid and tricuspid valves (first heart sound) and opening pocket valves as blood forced up pulmonary artery and aorta
- ◆ Ventricles relax (ventricular diastole) blood falls back in pulmonary artery and aorta shutting pocket valves (second heart sound).

Cardiac Cycle



Initiation and control of heart action

Cardiac muscle is **myogenic**, that is it can contract without nervous stimulation. Coordinating waves of electrical activity originate in a mass of specialised cardiac muscle in the right atrium, the **sinoatrial node** (SA node or 'pacemaker'). This provides the basic rhythm of the heart contractions.

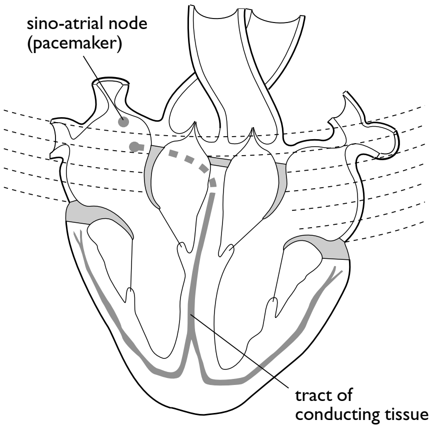
The wave of excitation spreads rapidly through the interconnected cardiac muscle fibres of the atria. However a band of fibrous connective tissue between the atria and ventricles prevents the wave of excitation spreading down into the ventricles. Another mass of specialised tissue, the **atrio-ventricular node** at the bottom of the atria is stimulated, and impulses are transmitted to the base of the ventricles in a tract of conducting tissue (modified cardiac muscle fibres and neurones) called the **bundle of His** which branches into two. The impulses radiate upwards through the cardiac muscle of the ventricles.

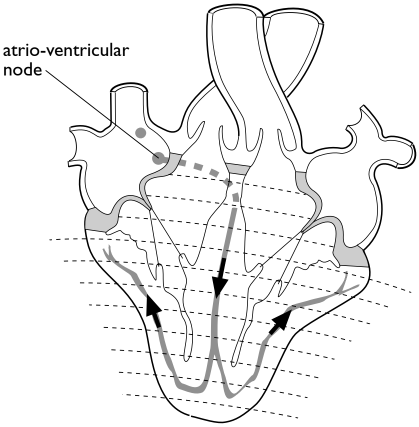
This pattern of the spread of excitatory waves through the heart, ensures that the atria contract to force the blood down into the ventricles, and that the ventricles contract to force the blood up into the pulmonary arteries and main aorta. The spread of the wave of excitation throughout the heart can be detected by electrodes attached to the skin of the chest and displayed as an electrocardiograph (ECG trace).

◆ CHECKPOINT SUMMARY

- ◆ Cardiac muscle is myogenic
- ◆ Rate modified by sinu-atrial node (pacemaker) in wall of right atrium
- ◆ Waves of electrical activity spread rapidly down through cardiac muscle of atria
- ◆ Prevented from passing directly into ventricles by barrier of connective tissue, stimulus picked up by atrio-ventricular node
- ◆ Bundle of His composed of Purkyne tissue transmits stimulus to base of ventricles from where it radiates up through the walls back to the connective tissue barrier
- ◆ Detected by electrodes on the skin as an ECG
- ◆ Pacemaker influenced by sympathetic (faster) and parasympathetic (slower) nervous systems, and the hormone adrenaline
- ◆ All influences on heart rate coordinate heart rate and therefore blood supply to body (cardiac output) with demands of body.

ECG trace of electrical activity of heart





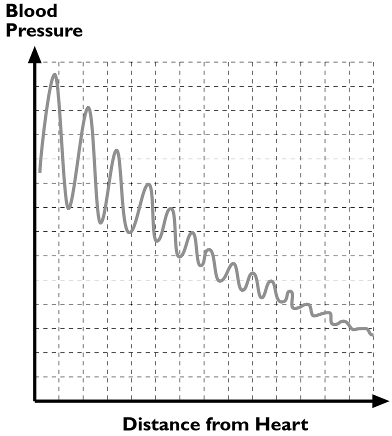
EFFECTS of EXERCISE

Cardiac output

The heart pumps blood around a complete circuit of vessels, which offer resistance to the flow of blood, therefore pressures are generated within the system. Blood pressure is usually measured in the brachial artery in the left arm using a sphygmomanometer. It is measured in mm of mercury (mm Hg). As a result of the action of the heart there are two measures of blood pressure.

Systolic blood pressure is that pressure generated when the ventricles are contracting (about 120 mm Hg in a young healthy adult). A rough estimation of systolic blood pressure can be derived from adding 100 to your age.

Diastolic blood pressure is that pressure when the ventricles are relaxing (about 80 mm Hg in a young healthy adult). With regard to checking blood pressure, the diastolic pressure gives the clearest indication of the state of the resistance offered to flow by the blood vessels (peripheral resistance), as the heart is not contracting at this time.



Blood pressure is expressed as a ratio of systolic to diastolic blood pressure e.g. 120/80 mm Hg.

The average of the systolic and diastolic pressures during a complete cardiac cycle, known as the **mean blood pressure**, determines the overall rate of blood flow through the circulation. The blood pressure drops as the blood gets further away from the left ventricle and circulates around the body. Some typical figures for the mean blood pressure (in mm Hg) whilst at rest are: arteries 100, arterioles 60, capillaries 18, veins 7, and at the entrance to the right atrium 3.

Blood pressure is generated by the **cardiac output** (heart rate x stroke volume) and the resistance to flow of the blood in the blood vessels. The resistance is often referred to as the peripheral resistance, as the major part of it occurs in the smaller vessels (mainly the arterioles) at a distance from the heart. The resistance to flow is due to the friction between the blood and the walls of the blood vessels. The friction is determined by the length, diameter, and the smoothness of the lining of the vessels; and the viscosity of the blood. The shorter the vessel, the larger the diameter and the less viscous the blood the lower the resistance. These features, particularly vessel diameter, are not fixed in an individual but change according to circumstances. Both acute (short term) and chronic (long term) changes can occur.

Arteries and arterioles (and to a lesser extent veins and venules) have involuntary muscle fibres in their walls, which when contracted constrict the vessel reducing its diameter. This can lead to short-term (acute) rises in blood pressure and can happen at times of emotional stress, or following intake of certain drugs including nicotine. The systolic and diastolic blood pressures are raised considerably during static (isometric), straining type exercises, as in weight training. This is caused by compression of the peripheral blood vessels, causing an increase in the resistance to blood flow and a demand for increased blood pressure, to maintain the circulation to the contracted muscles. Acute increases in blood viscosity, which lead to increased resistance and increased blood pressure can occur during periods of dehydration due to excess water loss in sweating, or through urine following consumption of substances that increase urine production (diuretics) such as alcohol and caffeine.

Pulmonary ventilation

Pulmonary ventilation is the product of the breathing rate (number of breaths per minute) and the tidal volume. The **tidal volume** is the volume of air breathed in and out in a single breath in a normal breathing cycle. A healthy, active mature male of average height would have a tidal volume of about 500 cm^3. Of this 500 cm^3, about 350 cm^3 reaches the alveoli where gaseous exchange occurs. The remaining 150 cm^3 fills the pharynx, larynx, trachea, bronchi, and bronchioles, which compared to the alveoli are poorly supplied with blood capillaries. This space where no gaseous exchange occurs is known as the anatomical **dead space**, and the air that occupies it as the **dead air volume**.

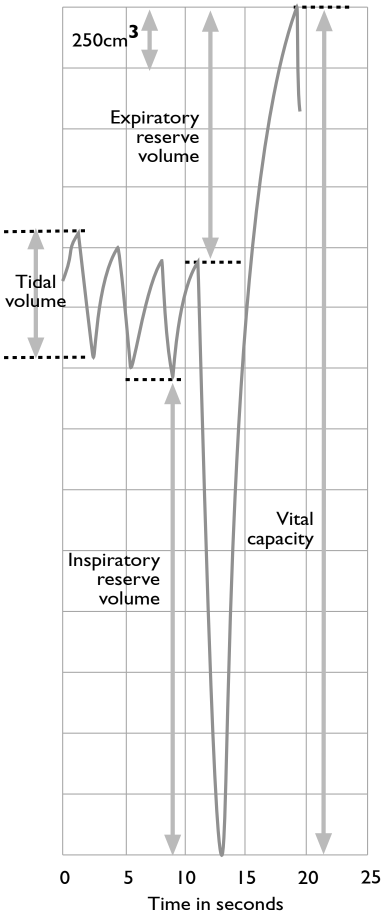
The 350 cm^3 of the tidal volume that reaches the alveoli, mixes with the 150 cm^3 of air remaining in the dead space from the previous exhalation, so that 500 cm^3 of mixed air reaches the alveoli on each inspiration. Here it mixes with the air that remains in the alveoli during quiet breathing, the **stationary air volume**, which can be up to 2500 cm^3. Thus the alveolar air consists of about 350 cm^3 of fresh air mixed with up to 2500 cm^3 of air that has undergone gaseous exchange with the blood, and 150 cm^3 of previous dead space air. Therefore the composition of alveolar air does not fluctuate widely during the breathing cycle, which in turn ensures that gaseous exchange with the blood also remains fairly constant throughout the breathing cycle. However, when the depth of breathing increases during exercise more 'fresh air' does reach the alveoli.

By breathing in as deeply as possible an extra volume of air, in addition to the tidal volume and the stationary air, can be taken into the lungs. This is the **inspiratory reserve volume** and can be up to 2000 cm^3. By breathing out as forcibly as possible after returning to normal breathing, it is possible to expel some of the stationary air in addition to the tidal volume. This is known as the **expiratory reserve volume** and can be up to 1500 cm^3. However the lungs cannot be emptied entirely, otherwise they would collapse, and this remaining air is known as the **residual volume** which can be up to 1500 cm^3.

The sum of the inspiratory reserve volume, the tidal volume, and the expiratory reserve volume is described as the **vital capacity**. The vital capacity represents the maximum total amount of air that can be moved into and out of the lungs by one inhalation and one exhalation, and is about 3000cm^3 - 4000 cm^3 in the adult male.

These volumes and the lung capacities vary considerably between individuals. They are generally smaller in females than in males, due to smaller average body size in females, and correlate closely with body size, height and surface area up to age 25. Smoking and associated lung diseases can considerably reduce lung volumes and capacities.

Vital Capacity



This trace does not show the total lung volume and residual volume, which are not easily measured. With increasing age the residual volume increases from about 20% of the total lung volume to more than 30%.

Change in cardiac output and pulmonary ventilation with exercise - nervous control of heart rate

At the onset of exercise, control centres are alerted by sensory receptors of the need for an increase in lung ventilation and cardiac output. In the case of the respiratory rate, the roles of the inspiratory and expiratory centres have been described in 10.7. Exercise causes a rise in carbon dioxide levels in the blood and tissue fluids accompanied by an increase in temperature and a decrease in oxygen levels. All of these factors combine to cause a response by the inspiratory centre in the medulla resulting in an increase in the rate of breathing.

Increased cardiac output is initiated by nervous information from various sources including pressure receptors (baroreceptors) located in major arteries and veins, the medulla of the brain and the adrenal glands. During exercise, the heart rate is caused to increase due to stimulation of the sinoatrial node by sympathetic nerves from the medulla of the brain. This response is enhanced by secretions of the hormone adrenaline from the adrenal gland.

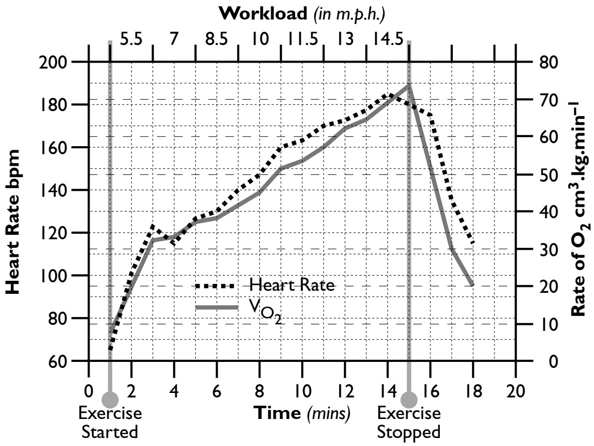
As the heart rate rises during exercise, owing to increased demand for oxygen and glucose by muscles, so too does the pulse rate. A resting pulse rate (heart rate) of around 70 beats per minute can increase to over 200 during vigorous exercise. The maximum heart rate decreases with age, so that an estimate of your maximum heart rate can be given by the result of 220 minus your age.

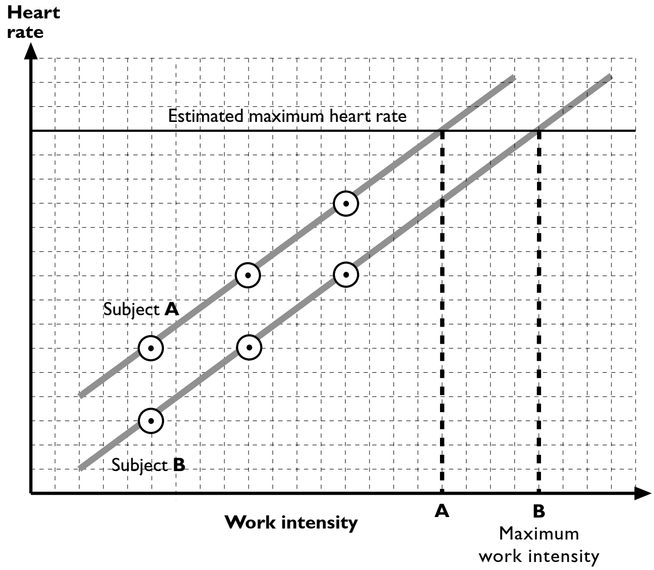
The heart rate of individuals doing the same exercise will, however, vary considerably. Heart size varies between people, being usually though not always correlated with body size. In general the larger the heart the slower the maximum heart rate, as it takes longer for a larger heart to fill with blood between contractions. It is important to note that this is usually regarded as being beneficial since the rate at which blood is pumped into arteries and hence to tissues (the cardiac output) depends not only on the heart rate, but also on the amount of blood pumped out of the ventricles on each contraction (the stroke volume). The stroke volume is determined by the extent to which the ventricles fill with blood and by the force of contraction of the ventricles which is itself related to this (the fuller the ventricles the greater the force of contraction). Cardiac output is equal to heart rate x stroke volume. Endurance training over long periods of time can lead to the enlargement of the heart - a condition known as athlete's heart.

The **resting pulse** is defined as the pulse rate measured when an individual is at complete rest. It is usually taken when an individual is lying down first thing in the morning. It represents the response of the heart to basic metabolic demands of the body at rest (mental and physical). In general the larger and more powerful the heart of an individual (perhaps as a result of endurance athletic training) the lower will be the resting heart rate. This is because more blood will be pumped out of their ventricles on each contraction (the stroke volume is larger). Thus for a given cardiac output heart rate is reduced, with some highly trained endurance athletes having resting pulse rates as low as 30 beats per minute.

It can therefore be said that as physical fitness (of the endurance type) increases, heart rate decreases, both at rest and during exercise of a given intensity. This is beneficial as it means that the heart is working less hard and has a lower oxygen demand. Another measure of fitness is the rate at which the heart rate returns to its resting rate after a set period of exercise at a given intensity, the faster the return to normal the greater the physical fitness.

Heart rate and oxygen uptake in response to exercise





Subject **B** is capable of a greater maximum work intensity

◆ CHECKPOINT SUMMARY

- Cardiac output is the product of heart rate and stroke volume
- Stroke volume is the product of the volume of the ventricle, the degree of filling, and the ejection fraction (the fraction of the blood that it contains that is pumped out)
- Pulmonary ventilation is the product of breathing rate and tidal volume (depth of breathing)
- Both cardiac output and pulmonary ventilation increase with exercise
- Increased cardiac output is initiated by sensory nerve information on increases in blood pressure, carbon dioxide levels in the blood, and decreasing blood pH
- There are so many capillaries in the body that they cannot all be supplied with blood at the same time. Consequently, there is competition for blood between different regions of the body, especially during exercise, when blood must be shunted to the working muscles, and consequently withdrawn from other regions
- For example, when the body is at rest, about 45% of the cardiac output passes through the capillaries of the gut wall and associated glands, and the kidneys
- During maximum exercise this can be reduced to about 3% of the cardiac output, as blood is redirected to the working muscles
- The blood supply to the brain and heart remains relatively stable during exercise, but increases dramatically to the working muscles from about 20 to 88%.

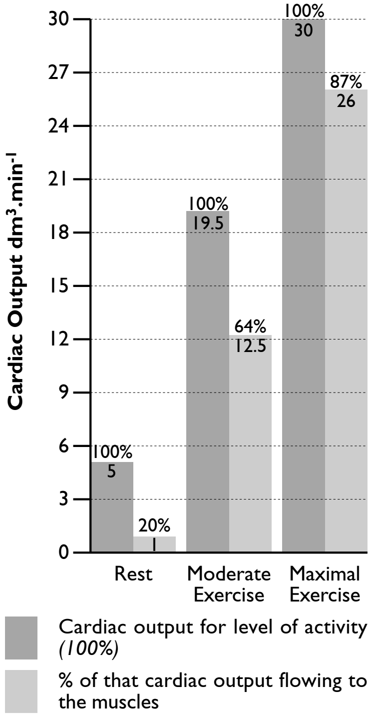
Redistribution of blood flow in response to exercise

There are so many capillaries in the body that they cannot all be supplied with blood at the same time. Consequently, there is competition for blood between different regions of the body, especially during exercise, when blood must be shunted to the working muscles, and consequently withdrawn from other regions. For example, when the body is at rest, about 45% of the cardiac output passes through the capillaries of the gut wall and associated glands, and the kidneys.

During maximum exercise this can be reduced to about 3% of the cardiac output, as blood is redirected to the working muscles. This does not necessarily lead to as large a reduction in oxygen supply to the gut and kidneys as it would seem, as these regions only use about 10 - 25% of the oxygen available in their normal blood supply. The reduced flow rate is compensated for by a greater extraction of oxygen from the blood, by these tissues. However, prolonged reduction in the blood flow to the gut and its associated glands will inevitably interfere with digestion. In short intense periods of exercise the blood flow to the skin is also reduced, even in hot conditions, as it is shunted to the muscles. However, it is increased in longer duration moderate exercise in order to promote heat loss as part of temperature control.

The shunting of blood between competing tissues is achieved by constriction and dilation of the arterioles, and of the arterio-venous vessels, which are direct connections between the arterioles and venules. The entrances to the capillary beds are controlled by circular precapillary sphincter muscles which, when contracted, shut off the capillaries and when relaxed, open them

Effect of exercise on cardiac output and redistribution of blood to muscles.



Estimated blood flow in cm^3 per minute, to different organs/systems in a trained male at rest and during maximum effort.

Estimated blood flow in cm^3 per minute

Organ system	At rest	%	Max. effort	%
Skeletal muscle	1000	20	26 000	88.00
Coronary vessels	250	5	1200	4.00
Skin	500	10	750	2.50
Kidneys	1000	20	300	1.00
Liver & gut	1250	25	375	1.25
Brain	750	15	750	2.50
Whole body	5000	100	30 000	100.00