

CHAPTER 2

Cardiovascular System

Basic structure of the heart

The heart is a hollow organ located in the centre, and extending to the left of, the thoracic cavity. With the sternum and ribs to the front and the thoracic spinal column behind, the heart is well protected from physical trauma. Within the heart there are four chambers. The two upper chambers are termed atria and the lower chambers ventricles. These chambers are simply named according to the side of the heart they are on, so they are the right and left atria, and the right and left ventricles. Valves separate the atria from the ventricles and the ventricles from the aorta and pulmonary artery. The left and right sides of the heart are separated by the cardiac septum. This means that blood from the right side cannot mix with blood from the left side and vice versa.

The wall of the heart is in three layers

The inner layer of the heart is called the endocardium and is composed of smooth squamous epithelium. When an epithelium is lining internal structures it is referred to as an endothelium. This endothelium allows the smooth

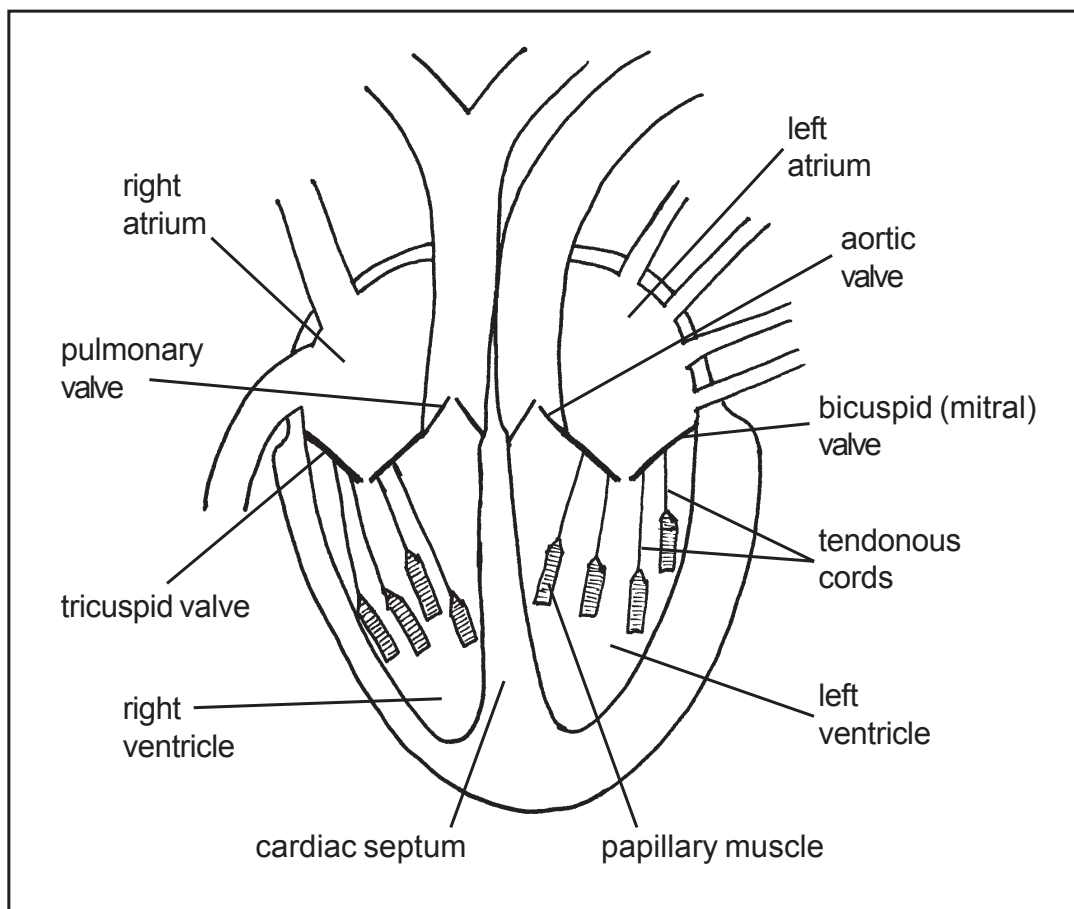


Diagram 2.1

The basic structures of the heart. The muscular wall of the left ventricle is thicker than that of the right ventricle. The walls of the atria are relatively thin.

uninterrupted flow of blood through the heart. Endocardium also covers the heart valves. The importance of the smooth lining provided by the endocardial endothelium is highlighted if it becomes infected, a condition termed endocarditis. Usually caused by a *Streptococcus*, this condition causes inflammation of the endothelium followed by deposits of the blood clotting protein fibrin, causing the build up of 'vegetation'. If this material is dislodged it will enter the circulatory system as emboli which can lodge in the small arterial supply of any part of the body.

The myocardium is the middle layer of the heart wall and is composed of specialised cardiac heart muscle. All of the energy for the pumping action of the heart is generated by the contraction of the myocardium. This cardiac form of muscle is only found in the heart and is composed of specialised cells called cardiomyocytes. Myocardial muscle is striped or striated in nature but, unlike skeletal muscle, is involuntary. As the myocardium must contract approximately 72 times per minute it uses a lot of nutrients and oxygen.

The outer layer of the heart is termed the pericardium and is composed of two layers. An inner layer is composed of serous membrane which is adherent to the outside of the myocardium. This is referred to as the visceral pericardium or epicardium. The outer pericardial layer is composed of tough fibrous tissue, which is itself lined internally with another layer of serous membrane. A serous membrane is a membrane which secretes serous lubrication fluid, in this case to allow the heart to move within the fibrous pericardial sac with minimal friction between layers. This allows the heart to expand and contract smoothly during a normal cardiac cycle. The fibrous layer is protective and prevents the heart over expanding. If fluid or blood collects under the fibrous pericardium the pressure can squash the heart and may cause death. This condition is termed cardiac tamponade.

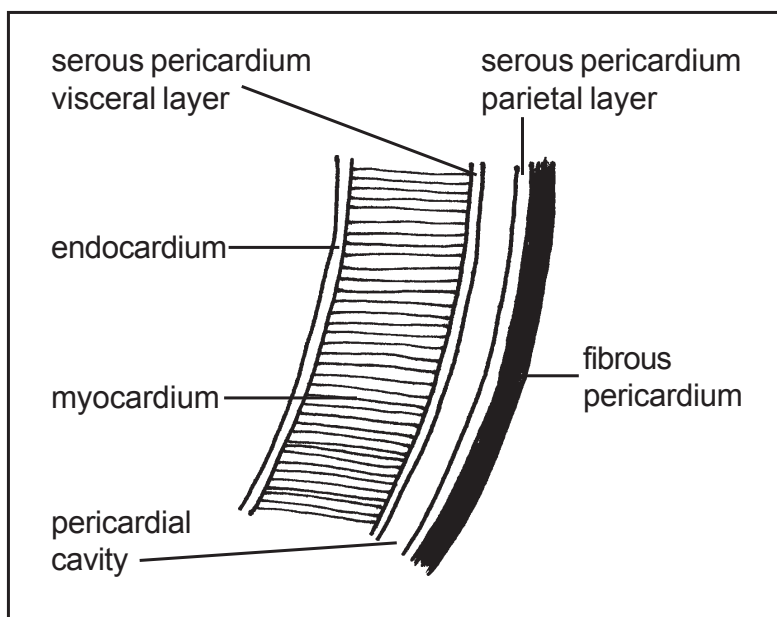


Diagram 2.2

The three layers which compose the wall of the heart, endocardium, myocardium and pericardium.

Heart valves ensure one way flow of blood

Valves are essential to control the direction of blood flow through the heart, opening and closing as a result of pressure changes in the blood. A valve will only allow the blood to flow in one direction.

The atria and ventricles are separated by valves collectively referred to as atrioventricular valves. On the right side, the atrioventricular valve is called the tricuspid valve. This is because it is made up of three separate cusps. The bicuspid valve is between the left atrium and ventricle and is composed of two cusps. Often the bicuspid valve is referred to as the mitral valve as an alternative name. These valves allow the free flow of blood from the atria into the ventricles but close during ventricular contraction to prevent blood passing from the ventricles back into the atria.

Atrioventricular valves are attached to the ventricular wall by strong tendons called chordae tendineae or tendonous cords. These prevent the valves opening upwards, i.e. the wrong way. The tendonous cords are themselves connected to the wall of the heart via specialised muscle bundles called papillary muscles. Papillary muscles contract at the same time as the ventricular wall. As they contract they pull on the tendonous cords which tightly close the valves, preventing any possible regurgitation of blood from the ventricles back into the atria.

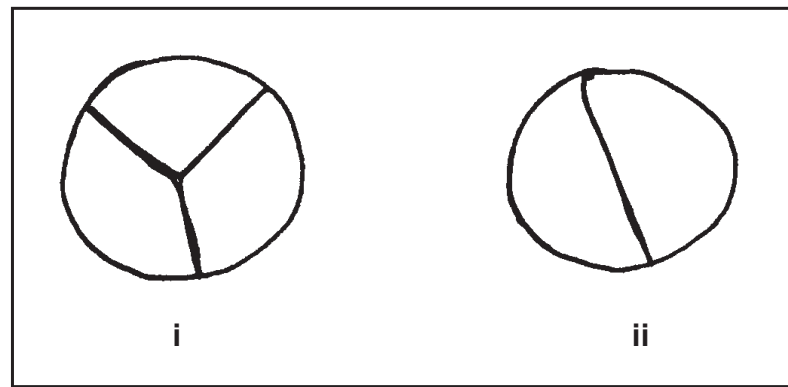


Diagram 2.3

- (i) View of the closed tricuspid valve from above.
- (ii) View of the closed bicuspid (mitral) valve from above.

Between the left ventricle and the aorta is the aortic valve (in some texts you may see this referred to as the aortic semilunar valve). Between the right ventricle and the pulmonary artery is the pulmonary valve (also sometimes referred to as the pulmonary semilunar valve). When the ventricles are contracting the aortic and pulmonary valves open to allow the free flow of blood into the aorta and pulmonary artery. At the end of ventricular contraction these valves close to prevent blood flowing from the aorta and pulmonary artery back into the ventricles.

Cardiac massage is a technique that can be used when the heart is not able to contract independently. This takes advantage of the valves within the heart only allowing blood to flow in the correct physiological direction through the heart. In cardiac massage the heart is compressed between the thoracic vertebral column and the sternum. As the pressure in the heart increases, blood will open the valves and be forced through the heart and out into the aorta and pulmonary artery. Good cardiac massage will therefore generate a cardiac output which may be detected as a central pulse. This cardiac output will perfuse the vital organs of the body such as the lungs, brain, kidneys and the heart itself. This can be maintained until additional treatments restore a normal cardiac rhythm.

Blood flow through the heart

The heart is the pump which generates the flow of blood through the arterial and capillary systems of the body.

Atrial function

Atria act as receiving chambers for the venous blood which is returning to the heart via the large veins. When the ventricles are not contracting blood returning to the heart, via the large veins, will pass directly through the atria, through the atrioventricular valves and will start filling up the ventricles.

However, when the ventricles are contracting blood returning to the atria will not be able to pass directly into the ventricles. Therefore during ventricular contraction returning blood is stored in the atria. Once the ventricles have completed a contraction, the atrioventricular valves will open and the blood stored in the atria will rapidly pass into the ventricles. One tenth of a second before the onset of the next ventricular contraction, when the ventricles are already about 85% full of blood, the atria contract and complete the filling of the ventricles. This final filling of the ventricles by atrial contraction is termed atrial kick. This effect is very important during exercise, when the volumes of blood returning to the heart are increased. Both atria contract essentially at the same time.

Ventricular function

Ventricles are pumping chambers which pump blood into the arteries. The left ventricle pumps blood into the main artery supplying blood to the body. This large vessel is referred to as the aorta. The right ventricle pumps blood into the main artery supplying blood to the lungs which is called the pulmonary artery (pulmonary always means to do with the lungs). Very shortly after the atria finish contracting, ventricular contraction begins. The ventricles start to contract from the cardiac apex, towards the base. This has the effect of directing blood towards the atrioventricular valves. In addition to contracting inwards the left

ventricle shortens, pulling the cardiac apex towards the valves. As the ventricles start to contract, the pressure of the blood they contain increases. This increase in intraventricular pressure has the effect of closing the atrioventricular valves preventing blood from being pumped from the ventricles back into the atria. Both ventricles contract essentially at the same time.

It is interesting to note that ventricular contraction does not completely empty the ventricles. At the start of ventricular contraction (in a resting adult) a ventricle will contain 120mls of blood. During ventricular contraction 70mls of this will be ejected. This leaves 50mls of blood in the ventricle at the end of a contraction.

The cardiac cycle

A cardiac cycle is one complete contraction and relaxation of the heart. It describes the events which take place during one heart beat. The heart contracts at a regular rate from about eight weeks after conception until the death of the individual. Resting heart rate varies with the age of the person from about 140 at birth to around 110 at age two, 80 at age ten to around 70 in adults.

Systole and diastole

Systole refers to contraction of the myocardium. Atrial systole describes contraction of the atrial myocardium and ventricular systole is contraction of the ventricles. Diastole refers to the rest of the time when the myocardium is not contracting and therefore describes the resting phase of each cardiac cycle. In a cardiac cycle ventricular systole immediately follows atrial systole.

During ventricular diastole the ventricles fill with blood prior to the next contraction. There is then a period of systole when the ventricles are actively contracting. During a cardiac cycle ventricular systole takes 0.3 seconds and ventricular diastole about 0.5 seconds. As heart rate increases, for example during exercise, the length of diastole decreases.

Systolic blood pressure is generated as a result of ventricular contraction during ventricular systole. As the left ventricle pumps blood around the whole body, relatively high pressures must be generated. However, as the right ventricle only has to pump blood to the lungs only relatively low pulmonary arterial blood pressures are required. This explains why a typical blood pressure in the systemic circulation is 120/80 mmHg whereas in the pulmonary circulation it is 25/8 mmHg. The first figure represents the blood pressure in the arteries during ventricular systole and is referred to as the systolic pressure. The second figure is the pressure in the arteries when there is no active ventricular contraction during diastole. This second pressure reflects the elasticity of the arterial system and is termed the diastolic pressure. These principles explain why the wall of the left ventricle contains a much greater muscle mass than the right ventricle. The atrial walls are also relatively thin, as they only have to pump blood from an atrium into a ventricle.

Heart sounds

Both atrioventricular valves close at the same time, making a sound referred to as a 'lub'. The closure of the two arterial semilunar valves makes a 'dub'. These are termed the first and second heart sounds, so the normal heart should make a lub dub, lub dub, lub dub. Heart sounds can easily be heard with a stethoscope. Additional sounds may be abnormal and are often caused by disturbances in the smooth flow of blood. An abnormal heart sound, referred to as a 'whoosh', is often heard in septal defects where there is a communication between the right and left sides of the heart (a hole in the heart). The resultant mixing of oxygenated and deoxygenated blood reduces the efficiency of the circulatory system. In this case some oxygenated blood is returned to the lungs and some deoxygenated blood is pumped into the systemic circulation. Such conditions are usually congenital and often require surgical correction.

Blood circulation through the lungs and around the body

The heart is actually two pumps in one; there is a body pump and a lung pump. The left side pumps blood to the body (the systemic circulation) and the right side to the lungs (the pulmonary circulation).

As the left ventricle contracts blood is ejected into the aorta. From the aorta blood passes, via the arterial system, to perfuse all the tissues of the body. As the blood circulates through the capillaries of the body it gives up oxygen to the tissues. Veins then collect the blood and return it towards the heart. The systemic veins drain blood into two large central veins called the superior and inferior vena cava. These two veins drain the top and bottom halves of the body respectively. The superior and inferior vena cava then drain directly into the right atrium.

From the right atrium the blood passes through the tricuspid valve into the right ventricle. When the right ventricle contracts this causes the closure of the tricuspid valve and the opening of the pulmonary valve. This means blood will be pumped into the pulmonary artery, and on to the lungs. Back flow from the pulmonary artery into the right ventricle is prevented by the pulmonary valve. Shortly after leaving the right ventricle, the pulmonary artery divides into two main branches, one to each lung.

Blood is pumped to the lungs to be oxygenated and to excrete (excrete just means to get rid of) carbon dioxide. Haemoglobin in red blood cells absorbs oxygen from the lungs. This oxygenated blood will then return to the left side of the heart via the pulmonary veins. The four pulmonary veins, two from each lung, drain blood into the left atrium. From the left atrium, blood passes through the bicuspid valve into the left ventricle.

The order of the circulation of the blood can therefore be summarised as follows; left ventricle - aortic valve - aorta - body - vena cava - right atrium - tricuspid valve - right ventricle - pulmonary valve - lungs - pulmonary vein - left

atrium - bicuspid valve - left ventricle. Both sides of the heart contract together, simultaneously pumping blood to lungs and body.

Arterial blood in the systemic circulation is bright red because it is rich in oxyhaemoglobin which is a bright red pigment. This is because the blood has passed through the lungs and is fully oxygenated. An oxygen saturation probe indicates that arterial blood in a healthy person is usually 98-99% saturated with oxygen. However, in the pulmonary arteries, the blood is on the way to the lungs to be oxygenated, after giving up much of its oxygen to the tissues of the body. This is why blood in the pulmonary arteries is dark red and deoxygenated. Blood in the systemic veins is dark red, compared to blood in the pulmonary veins which is bright red and fully oxygenated.

Circulation of blood through the coronary arteries

The first two arteries to leave the aorta are the right and left coronary arteries. These subdivide and supply blood to all of the smaller coronary arteries which perfuse the myocardium with blood. As this blood perfuses the myocardium it supplies the nutrients and oxygen essential for energy production and contraction. Disease of these arteries is termed coronary artery disease and is the single most common cause of death in most developed countries. This disease occurs when the lumen of the arteries is clogged up with a fatty cholesterol based material called atheroma. Because the atheroma blocks off part of the lumen, less blood is able to get through to the myocardium. This reduction in blood supply is called ischaemia. In addition, the atheroma increases the probability that a blood clot may form in the lumen of the artery, a pathological condition referred to as thrombosis. Clinically these consequences of atheroma may cause angina and myocardial infarction.

The internal electrical conducting system

The cardiac cycle is controlled by specialised conducting tissue in the heart. Inside the right atrium is an area of specialised cardiac muscle tissue termed the sinoatrial (SA) node. Because this controls the pace of the heart it is sometimes called the pacemaker. This area generates the initial electrical impulse which stimulates myocardial contraction. From the SA node an impulse spreads to both atria stimulating their contraction. The impulse travels across the atria via specialised conduction pathways termed the internodal tracts; this is because they are between the SA node and the atrioventricular (AV) node.

The AV node collects an impulse from the atria and passes it on to the bundle of His (or atrioventricular bundle) in the cardiac septum. The AV node is the only pathway the impulses can travel in order to spread from the atria to the ventricles; the rest of the tissue in the plane of the valves is electrically insulating. In the cardiac septum the bundle of His divides into two, forming the right and left bundle branches, which carry the electrical impulse to the right and left ventricles. The result of this arrangement is that an impulse is

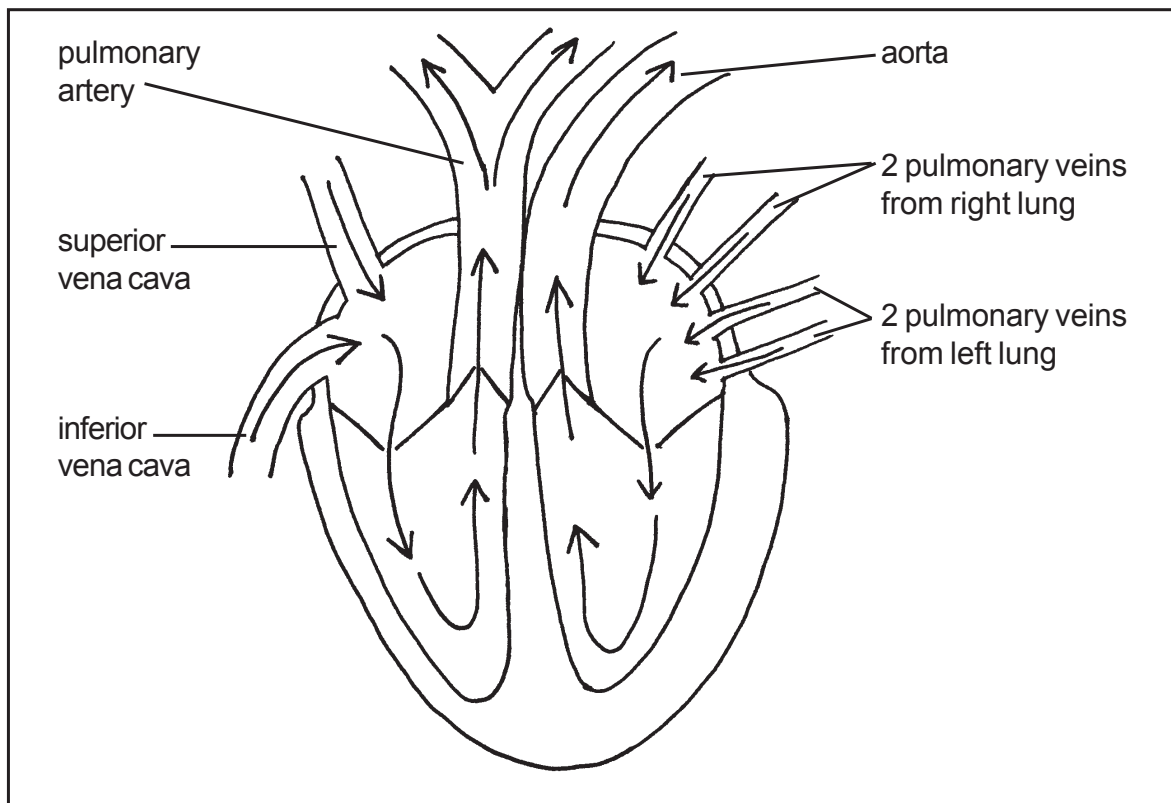


Diagram 2.4

The major blood vessels associated with the heart. Arrows indicate direction of blood flow.

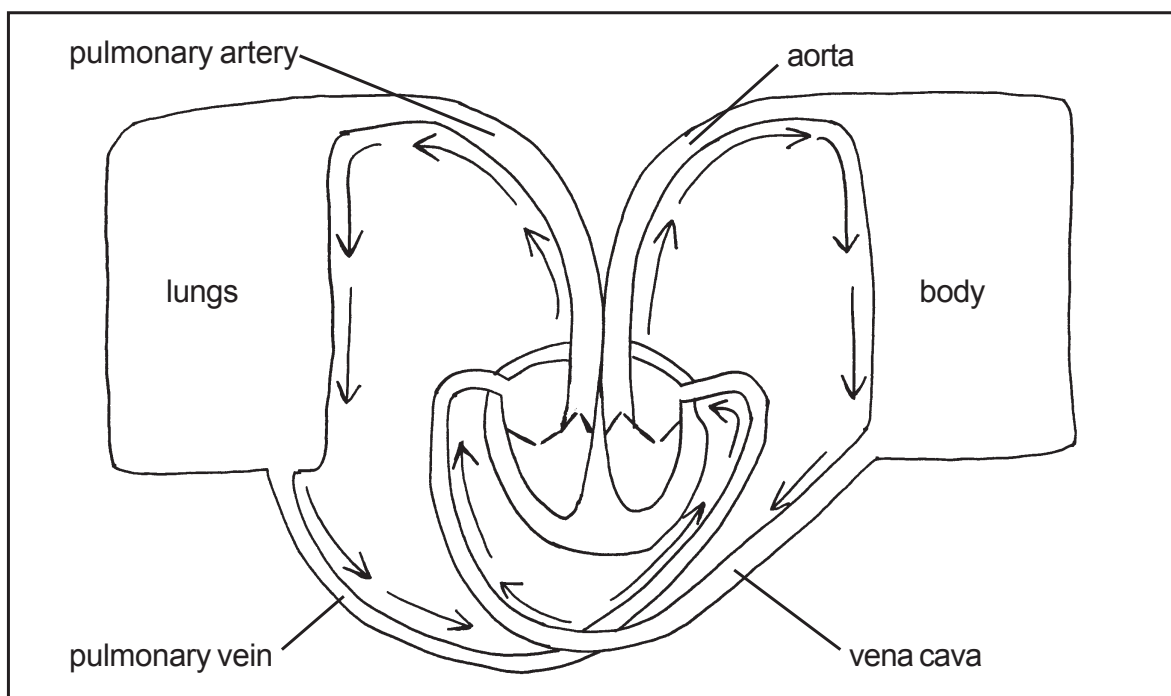


Diagram 2.5

This simplified diagram shows the flow of the blood through the heart and around the body and the lungs. You may find it helpful to colour these diagrams in. The tradition is red for oxygenated blood and blue for deoxygenated.

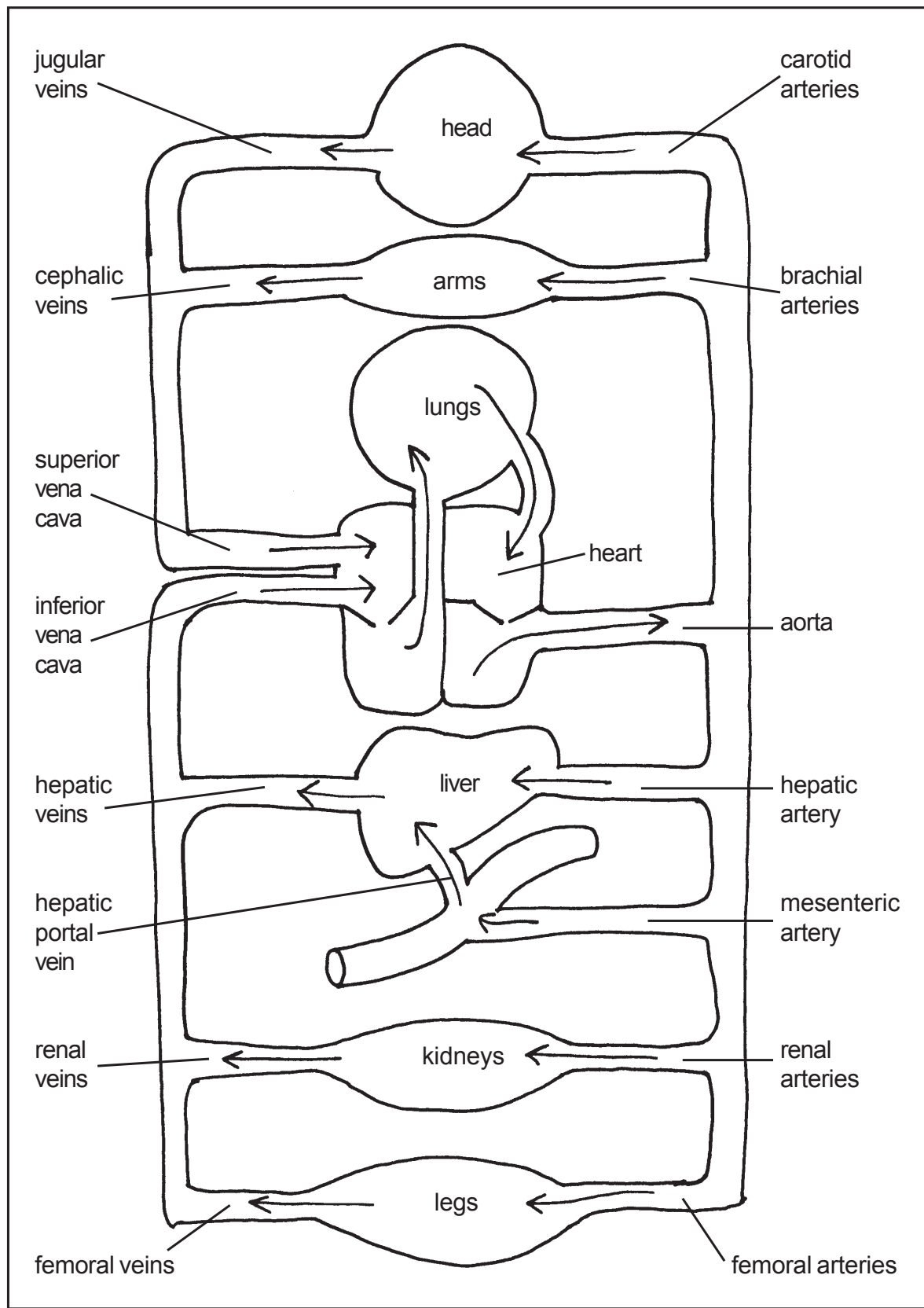


Diagram 2.6

This diagram shows more detail of the flow of blood around the systemic circulation. Arrows indicate direction of blood flow.

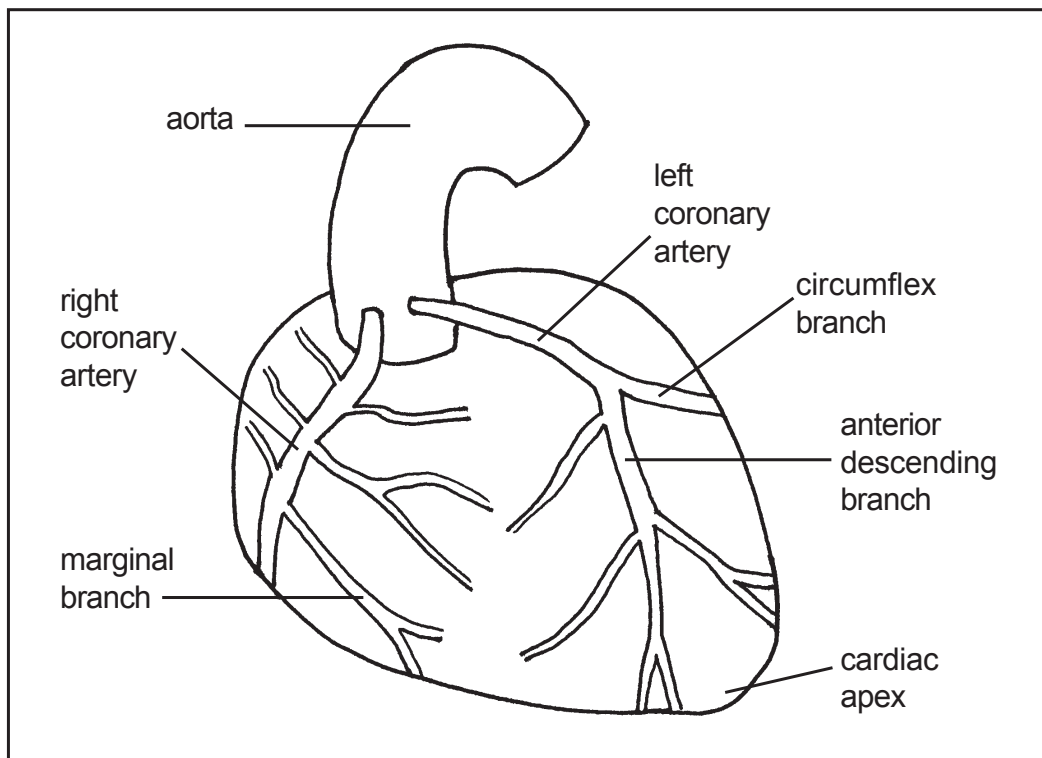


Diagram 2.7

The main coronary arteries as seen from the front. Coronary arteries are relatively thin arteries, partly explaining why they are prone to blockage in coronary arterial disease. The circumflex branch of the left and the right coronary artery carry on around the back of the heart to perfuse the posterior wall with blood.

carried rapidly down through the cardiac septum. Finally the impulse innervates the ventricular myocardial muscle via the small Purkinje fibres (or conduction myofibres). This means that ventricular contraction will start from the cardiac apex and work towards the base, pushing the blood upwards, towards the arterial valves. It is this internal conducting system which is responsible for the initiation and phases of the cardiac cycle.

Unlike other muscles the myocardium internally generates the electrical impulses which lead to muscle contraction. As mentioned, this electrical activity originates from the sinoatrial node. However, outside factors will influence the heart rate and strength of contraction. Adrenaline will increase heart rate, as will stimulation by the sympathetic nervous system. This is why heart rate, and the strength of contractions, will increase during exercise, excitement or as a result of anxiety. Parasympathetic stimulation will slow the heart rate and so reduce cardiac output. When we are relaxed the parasympathetic nervous system will slow the heart rate and reduce the strength of individual contractions. The internal generation of the electrical activity required for cardiac contraction explains why a donated heart will carry on contracting after a heart transplant operation.

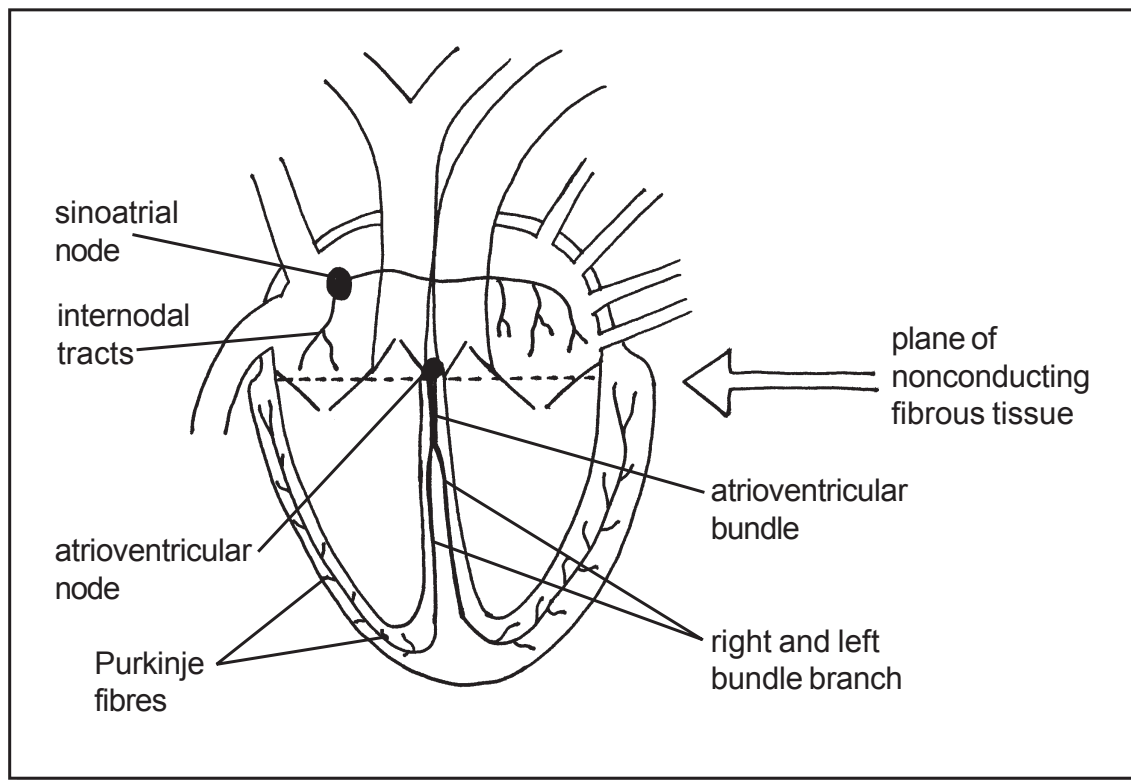


Diagram 2.8

The components of the cardiac internal conducting system. The sinoatrial node generates a new electrical impulse prior to every cardiac cycle. Firstly this impulse causes atrial contraction. As an electrical impulse cannot be transmitted through the non-conducting fibrous tissue of the valvular plane it passes down to the ventricles via the AV node. This same impulse then causes ventricular contraction.

The PQRST as seen using an electrocardiograph

When the myocardium is stimulated by an electrical impulse the myocardial cells will depolarise. This means the electrical polarity across all of the individual cell membranes will reverse. At rest any muscle cell is negatively charged on the inside and positive on the outside. Arrival of an electrical impulse will reverse this resting potential causing the cells to depolarize, becoming positive on the inside and negative on the outside. It is this depolarisation of the myocardial cells which initiates their contraction. The collective electrical activity of the myocardial cells depolarizing, and then repolarizing, may be detected with electrodes on the surface of the body. In health the contraction of the myocardial muscle cells will occur essentially at the same time as the cells depolarize. This means we can directly relate the electrical patterns we can detect on the surface of the body with the contractions of the myocardium. This is the principle of the electrocardiogram (ECG). When this is recorded three characteristic electrical phases can be clearly seen.

Firstly there is a P wave. This is the electrical activity, as detected on the surface of the body, as a result of the depolarization of the atrial myocardium.

Secondly there is the larger QRS complex caused by the depolarization of the larger muscle mass of the ventricular myocardium. This complex is associated with ventricular contraction. Thirdly there is a T wave. This is not associated with any muscular contraction but arises as the ventricular muscle repolarizes to an electrically resting state. Finally, there is a short gap before the next atrial contraction at the start of the next cardiac cycle.

A normal cardiac cycle must have a PQRST phase in that order. In health the occurrence of these phases of the cycle is fairly regular and the rate is usually between 60 and 100 per minute. So a normal rhythm has a PQRST, in the correct order, is regular, with a rate between 60 to 100 cycles per minute. This normal rhythm is called a sinus rhythm because the cardiac rhythm is controlled by the sinoatrial node in the right atrium.

If the phases of the cardiac cycle occur regularly, and in the correct order, at a rate of less than 60 times per minute, the rhythm is termed sinus bradycardia. This is normal in people who are physically fit or who are very relaxed. If the rate is over 100, with a regular PQRST in the right order, this is termed a sinus

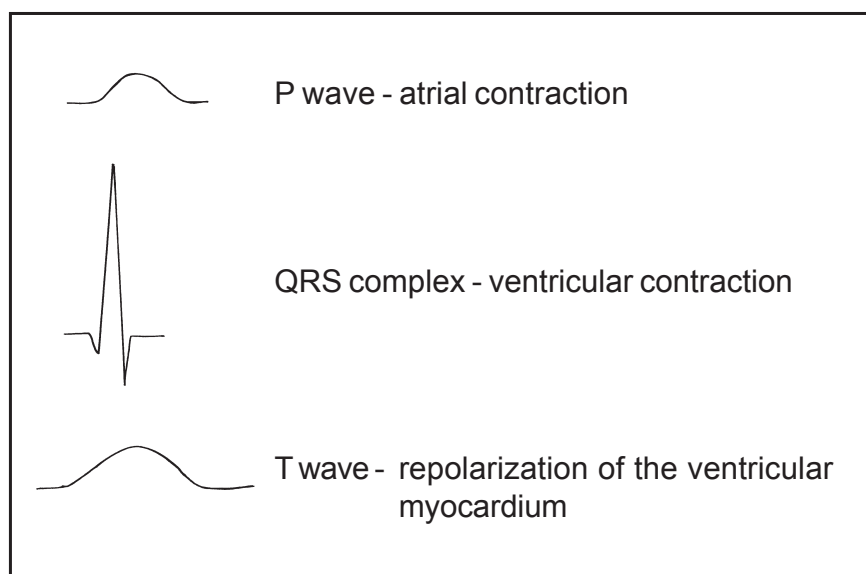


Diagram 2.9
The components of the cardiac cycle and the events the electrical activity represents.

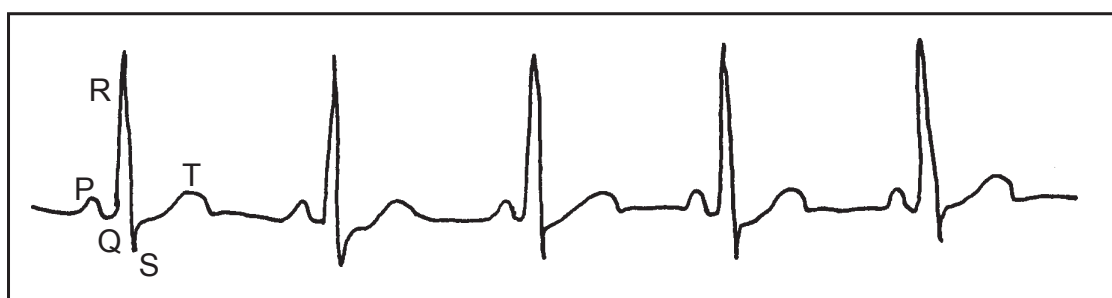


Diagram 2.10
A normal ECG recorded from one of my students.

tachycardia. A sinus tachycardia is of course normal during exercise. The terms P,Q,R,S and T do not stand for anything and have no intrinsic significance what so ever. They are arbitrary names given to specified phases.

Effects of exercise

Exercise increases heart rate, which is the number of times the heart beats per minute. It also increases stroke volume which is the amount of blood pumped out per cardiac contraction. These two factors combine to increase cardiac output, which is defined as the volume of blood pumped out from the left ventricle per minute. To be precise, cardiac output equals heart rate multiplied by stroke volume. At rest a normal stroke volume will be around 70mls. If the heart rate is 72 beats per minute this would give a cardiac output of 70×72 which equals a cardiac output of 5040 mls. As an average adult has about 5 litres of blood in total, the cardiac output figure means the entire volume of the blood circulates through both the body and lungs once per minute.

With increasing levels of physical activity cardiac output will progressively rise. This will increase the rate at which blood circulates around the lungs and body tissues and so increase the delivery of oxygen and nutrients to active muscles. During vigorous exercise an average adult might be able to increase their cardiac output to 20 or 25 litres per minute for a period of time. A trained athlete will be able to achieve a cardiac output of 35 or even 40 litres per minute for a short time.

Regular exercise is good

Regular exercise is very good for humans; it lowers the levels of sugar (glucose) in the blood and increases levels of the protective HDL (high density lipoprotein) cholesterol. Exercise will increase metabolic rate and sustained exercise will burn up excess body fat preventing obesity. Although exercise raises blood pressure at the time, it lowers blood pressure overall. It makes the heart muscle stronger and helps to keep the coronary arteries patent. These factors mean regular exercise helps to protect against heart attacks and strokes. Recent findings indicate that regular exercise reduces the risks of developing some forms of cancer. Exercise tones and strengthens many muscles in the body and as exercise applies forces through the bones of the skeleton it will increase bone strength. Exercise in childhood and young adult life will build up bone mass and make osteoporosis less likely in later life. Regular exercise is an effective treatment for depression. If people are immobilised and unable to exercise they may suffer from numerous complications such as blood clots in the veins of the legs and lungs, pressure sores, depression, constipation, pneumonia and atrophy of bones and muscles. This is why everyone should try to exercise for a least half an hour every day unless there is some medical reason not to.

Blood vessels

The main types of blood vessels are: arteries, arterioles, capillaries, venules and veins.

Arteries

An artery is any vessel which carries blood away from the heart. Essentially arteries are tubes which supply an area of tissue with blood. This is vital; if an area is deprived of a regular blood supply the tissues will die because all of the oxygen and nutrients the cells require are transported to them in the blood. Larger arteries divide into smaller arteries so the whole of the body can be perfused with blood.

Arteries have fairly thick walls because the blood they carry is at relatively high pressure. If an artery is cut the blood initially come out in spurts. This form of arterial bleeding represents the pressure changes in the arterial system as the left ventricle contracts and relaxes. Fortunately, most arteries are deep in the body for protection. Because the arteries carry blood directly from the heart, a pulse can be felt every time the heart contracts.

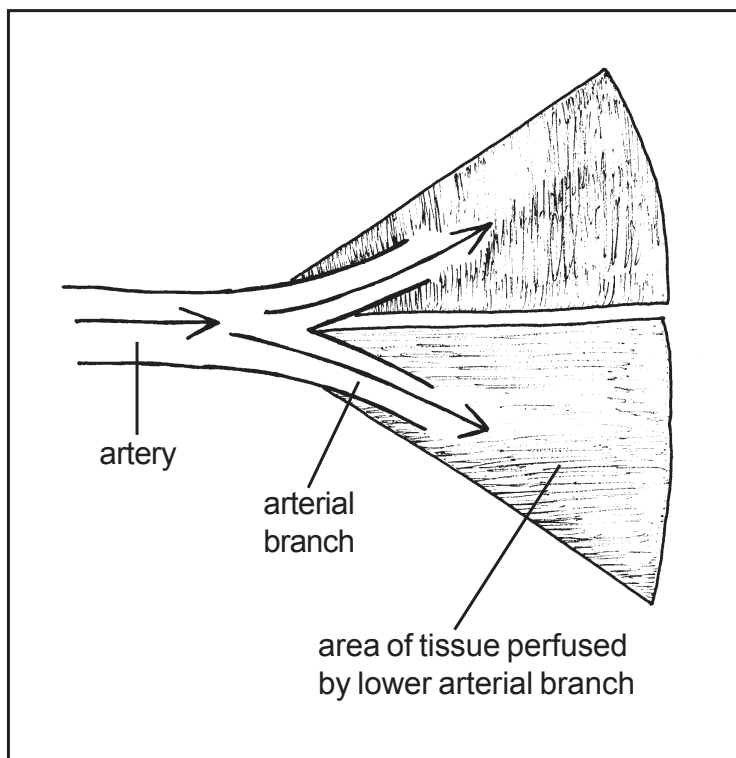


Diagram 2.11

An artery supplying an area of tissue with blood. Often an arterial branch will supply a wedge shaped area of tissue.

Arterial walls consist of three layers or coats usually described as an outer, middle and inner tunica (tunica is a word which means coat). Firstly the tunica externa (also called tunica adventitia) is the external or outer layer; this is composed mostly of connective tissues, containing collagen and elastic fibres.

Secondly the tunica media is the middle layer; this contains elastic fibres and smooth muscle. The third inner layer is called the tunica interna (or intima); this is a flat layer of smooth squamous endothelium to allow smooth flow of blood. The hole in the middle of any vessel is referred to as the lumen.

All of the systemic arteries carrying blood to the body branch from the aorta. The carotid arteries can be felt in the neck and supply the head with blood. Blood pressure is usually recorded from the brachial artery supplying the arm. The femoral pulse can be felt in the groin. Behind the knee, the pulse of the popliteal artery can be felt. The most common pulse felt in clinical practice is the radial; this is where the radial artery passes over the radius. However, in many clinical emergency situations it may not be possible to feel the radial pulse, so we should always assess a central pulse, usually the carotid or femoral. Other main arteries include the intercostal arteries to the intercostal muscles, the hepatic artery to the liver, and the renal arteries to the kidneys.

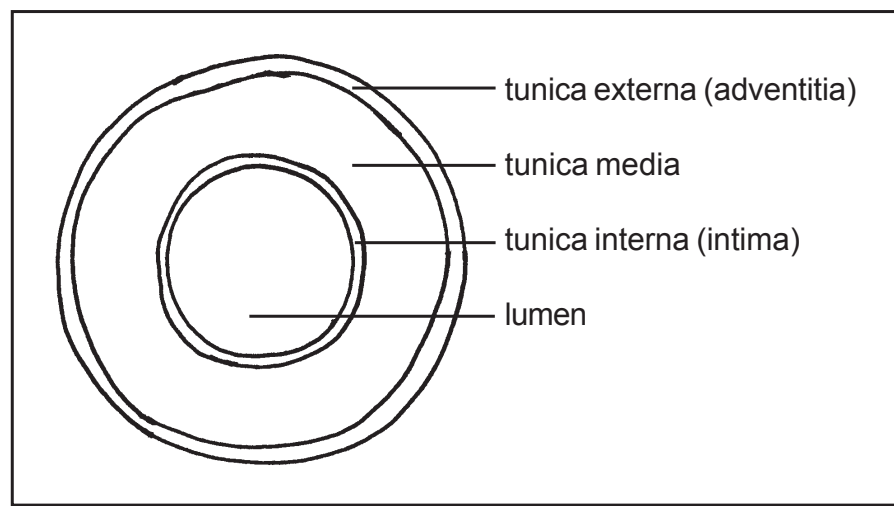


Diagram 2.12

Cross section of an artery to show the three layers and lumen.

Arterioles

Small arteries divide into even smaller arterial vessels called arterioles. These vessels are almost microscopic and carry blood into the microscopic capillaries. Arterioles contain circular smooth muscle fibres in their walls which allow them to dilate and constrict. This vasodilation and vasoconstriction allows for the regulation of the flow of blood through a tissue (vaso means to do with blood vessels). For example, after a heavy meal the arterioles to the gut will dilate, increasing the volumes of blood perfusing the capillaries of the gut wall. During exercise the arterioles supplying the skeletal muscles will dilate to increase their blood supply. When someone is cold the arterioles supplying the skin capillary beds will vasoconstrict to reduce the amount of warm blood near the

surface of the skin. Alcohol has the opposite effect and causes peripheral vasodilation; this is why alcohol should not be given to cold people. This ability of the arterioles to alter the diameter of their lumen therefore allows for precise regulation of the volumes of blood perfusing a particular tissue at a particular time.

Arterioles and control of blood pressure

Blood pressure is determined by two factors; the cardiac output and the peripheral resistance. As discussed cardiac output describes the volume of blood discharged into the systemic circulation over one minute. If cardiac output increases, this has the effect of increasing flow rate and so will increase blood pressure. This is analogous to turning a tap where a small turn will result in a small flow of water with low volumes and pressure. However, if the tap is turned up the flow rate and pressure will increase.

The other factor in determining blood pressure is the resistance generated by the arterial system to the cardiac output. Blood pressure is determined by the cardiac output multiplied by the peripheral resistance. It is this peripheral resistance, generated mostly at the level of the arterioles, which is the main factor determining blood pressure. This means that arteriole tone is vital in the regulation of blood pressure. Widespread constriction of the arterioles will narrow the total lumen of the arterial system which in turn will increase resistance to blood flow. The resistance to blood flow offered by the arterioles is termed peripheral resistance. Conversely if the arterioles are dilated, there will be less resistance to blood flow and peripheral resistance will be reduced. If peripheral resistance is increased blood pressure will also be increased. Conversely, if peripheral resistance is lowered, due to vasodilation, blood pressure will be lowered.

The relative tone of the arterioles, and so systemic blood pressure, is regulated via two separate mechanisms. Firstly neuronal reflexes maintain blood pressure on a short term basis. This effect will increase blood pressure over a second or two to meet the current requirements of the body. For example, blood pressure will be increased if we stand up in order to ensure the brain is perfused with blood. This short term vasomotor control is coordinated by a specialised area in the medulla oblongata (part of the brain stem) called the vasomotor centre. The second mechanism is the renin-angiotensin mechanism. This hormonal regulation is the main factor determining long term blood pressure control and is discussed in chapter 10.

Efficient regulation of blood pressure is essential for life. If blood pressure is too low, tissues will not be adequately perfused. For example, if the brain is acutely hypoperfused a person will lose consciousness and faint. If the blood pressure perfusing the kidneys is inadequate they will not be able to generate glomerular filtrate and so will not produce urine. However, chronic high blood pressure will lead to atheroma formation in larger arteries and thickening of the

walls in smaller arteries. The walls of blood vessels will be weakened leading to aneurysm and possible haemorrhage. Sustained high blood pressure can also lead to heart failure, renal damage leading to renal failure and retinal damage leading to blindness.

Capillaries

Capillaries are the smallest blood vessels and are microscopic. They receive blood from the arterioles. Capillaries are the only part of the circulatory system where there is exchange of materials from the blood to the tissues or from the tissues to the blood; all other vessel walls are too thick to allow diffusion. Capillaries however, are able to facilitate this exchange because they are only one squamous cell thick. This means the diffusional distance between the blood and the tissue cells is very small, allowing relatively free diffusion. The cells which comprise the capillary walls are called endothelial cells. Exchange of material between the blood and tissue fluid is aided by small gaps which are present between some of the capillary endothelial cells. These gaps are called capillary pores.

Living tissue contains millions of capillaries arranged in beds. A capillary bed refers to a system of capillaries perfusing a particular area of tissue. For example, finger nail beds are pink because of the colour of the blood passing through a capillary bed. If you press on your finger nails the beds turn white.

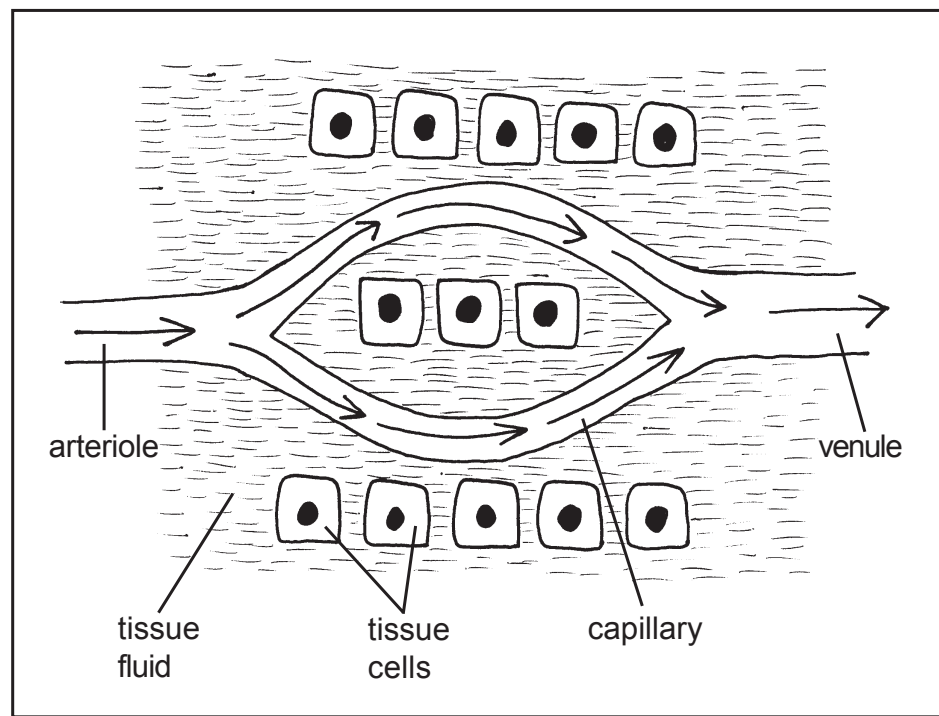


Diagram 2.13

An arteriole divides into a group of capillaries which perfuse some tissue cells.

This is because the pressure of the nail from above has squeezed the blood out of the capillary bed, so the pink colour is lost. Overall the capillaries form a massive surface area between the blood and the tissues. It has been suggested the total area of capillary wall in an adult is 6000 square metres.

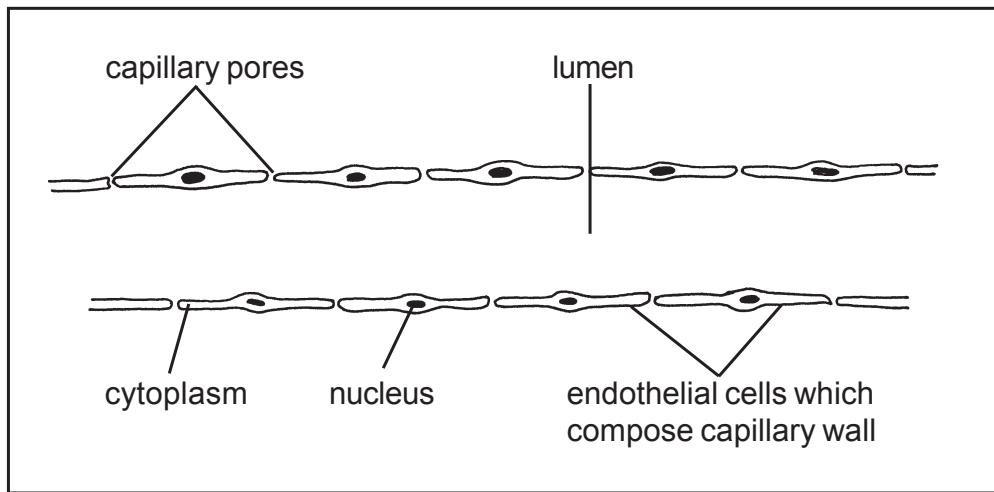


Diagram 2.14

A magnified view of a capillary wall made up of individual endothelial cells.

Tissue fluid formation and reabsorption

As can be seen from diagram 2.13, the cells of a tissue are bathed in tissue fluid. This is essential to keep the cells moist and to prevent them drying out. In addition, tissue fluid is the essential medium for diffusion between the blood and capillaries. Substances diffuse from the blood, through the tissue fluid, before reaching and diffusing into cells. The same is true for substances the cells excrete. These waste products must diffuse into the tissue fluid before they can diffuse through the capillary wall into the blood.

It is the capillaries which are responsible for the formation of the tissue fluid. At the arteriole end of the capillary, because the blood has recently left the arterial system, the blood pressure is still relatively high. Because the pressure in the capillary is greater than in the tissue fluid, water molecules, which are small enough to fit through the capillary pores, are forced out from the capillary blood into the tissue spaces. Larger components of the blood such as cells and plasma proteins, which are big molecules, remain in the capillaries. Once formed, tissue fluid bathes and flows over the individual tissue cells.

At the venous end of a capillary blood pressure is lower because the blood is nearing the lower pressure venous system. Because blood plasma contains large protein molecules, the plasma generates an osmotic potential which tends to draw in water. At the venous end of the capillary, the osmotic potential is greater than the blood pressure which is trying to force water molecules out of the capillary. The net effect of this is that water molecules are osmotically drawn

back into the blood at the venous end of the capillary. The overall result of this process of tissue fluid formation and reabsorption is that there is a flow of fresh tissue fluid over the tissue cells, from the arterial to the venous end of the capillary. This flow helps keep tissue cells nourished and oxygenated as well as removing toxic waste products.

When the levels of protein in the blood are very low, such as in severe malnutrition, the plasma is no longer able to generate the osmotic potential required to reabsorb tissue fluid. This is why people with severe protein deficiencies develop oedema (the retention of fluid in the tissues).

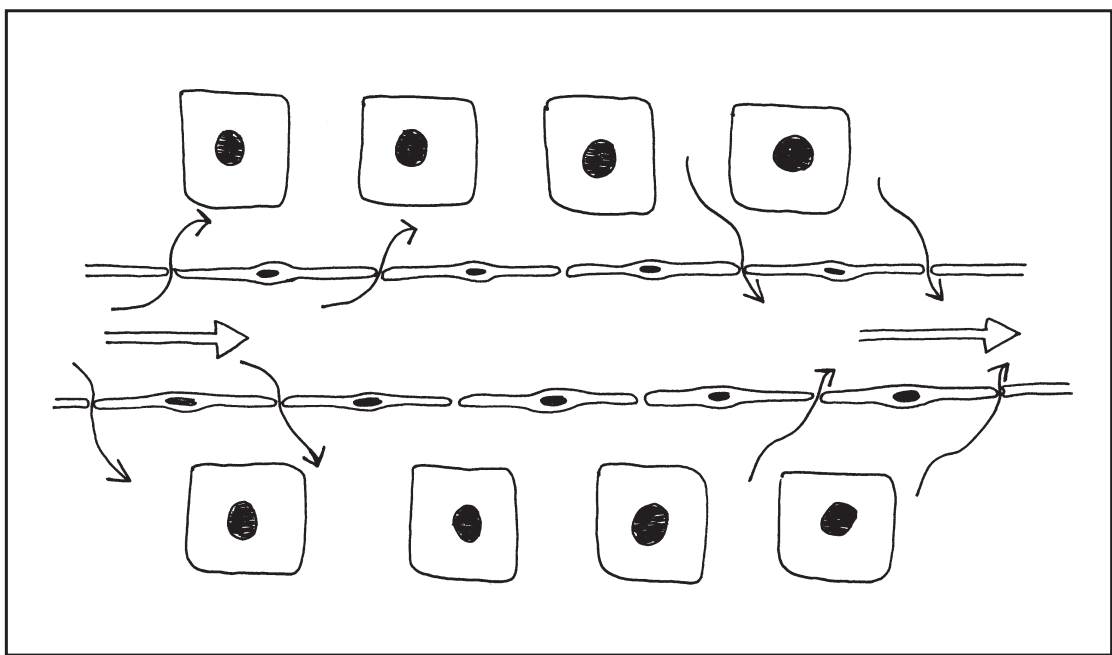


Diagram 2.15

Formation and reabsorption of tissue fluid. Water is exuded from the arterial end of the capillary, washes over the tissue cells and is reabsorbed at the venous end of the capillary. Dark arrows represent tissue fluid movement; white arrows indicate direction of blood flow.

Gaseous exchange between capillary blood and tissue cells

Capillaries are the site of gaseous exchange between the blood and tissues. All living tissues need a constant supply of oxygen to allow mitochondria to produce the energy essential for life. In the systemic circulation, arterial blood arrives from the arterioles containing high concentrations of oxygen. Because the tissues have been using up oxygen, the concentration in tissue cells is relatively low. This means there will be a diffusion gradient, between the high level of oxygen in the blood, and lower level in the tissues. The result of this is that oxygen will diffuse from the blood into the tissue cells.

The same principle of differential concentrations of dissolved gas also determines the movement of carbon dioxide. Ongoing metabolism in the cells produces carbon dioxide, the concentration of which will therefore rise. Arterial blood arrives from the arterioles containing very low concentrations of carbon dioxide. This means there is a concentration gradient from the cells to the blood, resulting in the diffusion of carbon dioxide from tissue cells into the blood. By these mechanisms the cells maintain oxygenation and dispose of waste carbon dioxide.

In addition to gaseous exchange, nutrients that cells require diffuse from the blood to the cells through the capillary walls and tissue fluids. Nutrients include amino acids, fatty acids, glucose, minerals and vitamins. As well as producing waste carbon dioxide, cells produce other chemical wastes as a result of their metabolic processes. These include waste nitrogen containing toxic molecules such as ammonia. If these are allowed to accumulate in the tissues they would eventually poison the cells.

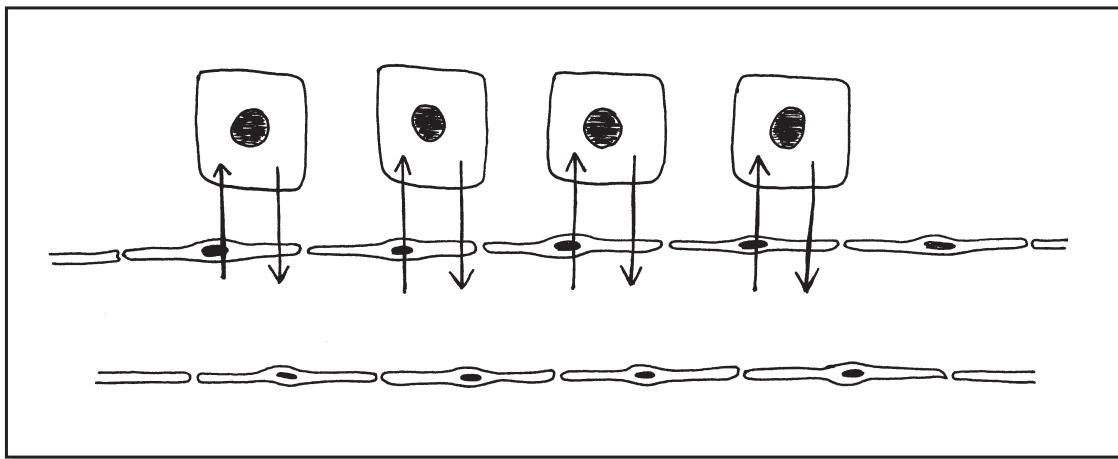


Diagram 2.16

Gaseous exchange between blood and tissues, oxygen diffuses from capillary blood to tissue cells and carbon dioxide from tissue cells to blood.

Veins

A vein may be defined as any vessel which carries blood towards the heart. Veins have the same basic three layered structure as arteries, with a central lumen, tunica interna, media and externa. Because the pressure of blood in the veins is lower than in arteries, the walls are thinner. Unlike arteries veins have valves within their lumen to prevent back flow of blood. Systemic veins carry deoxygenated blood and the pulmonary veins carry oxygenated blood. Because systemic veins carry deoxygenated blood at relatively low pressure, venous bleeding is seen as the oozing of dark red blood. This is opposed to the spurting of bright red blood from a freshly cut artery.

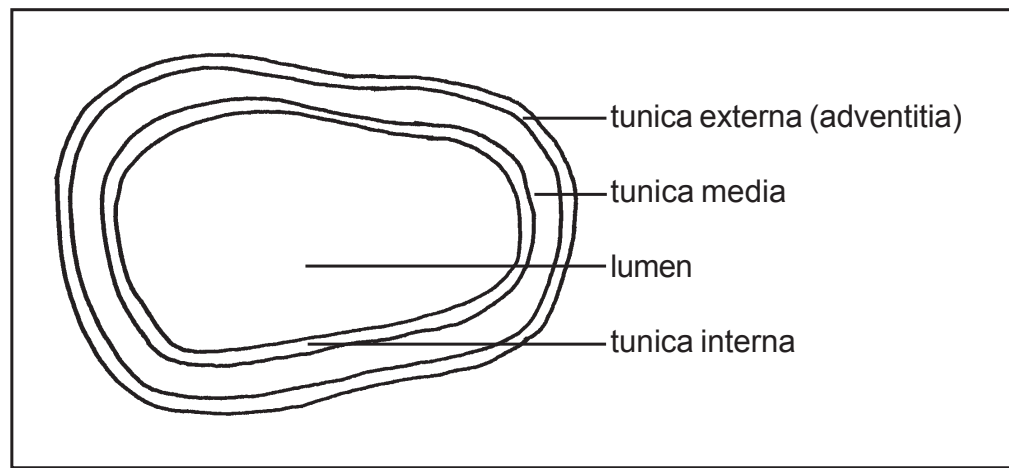


Diagram 2.17
A cross section of a vein.

Deep and superficial venous systems

Veins are often described as existing in two systems; the superficial and the deep venous systems. Superficial veins can be seen and palpated under the skin. These veins are therefore external to the muscles. Deep veins are found deeper in the body, often in muscles. Between the superficial and the deep venous systems are small veins called perforator veins, so called because they perforate the muscle fascia. Venous blood flows from the superficial veins, through the perforator veins, into the deep veins. Once the blood is in the deep venous system it can be rapidly returned to the heart.

If a tourniquet is applied to an arm this will obstruct the normal venous return from the limb. Providing the pressure applied by the tourniquet is less than arterial blood pressure, blood will still be pumped into the arm. This means that blood will accumulate in the arm and the superficial veins will become full and dilated. In clinical practice these superficial veins are very useful for gaining venous access. Once a vein has been cannulated blood samples may be taken or intravenous fluids or drugs given.

Mechanisms facilitating return of venous blood to the heart

Blood flows along the arteries because of the pumping effect of the heart generating a blood pressure. However, once blood has passed through the capillaries, virtually all of this pressure is lost. In veins above the heart, blood can return to the right atrium under the influence of gravity, but for veins below the level of the heart, extra mechanisms of venous return are needed. The mechanisms of venous return are; contraction of adjacent muscles, contraction of adjacent arteries and negative and positive pressures set up in the thorax and abdomen during respiration. All of these mechanisms rely on the action of valves in the veins. These prevent back flow of blood from the

centre to the periphery. Any blood trying to flow backwards will have the effect of closing off the valve immediately below. The importance of venous valves is clearly illustrated in varicose veins where there is failure of the valves and pooling of blood dilates the veins.

The most dramatic mechanism of venous return is contraction of adjacent muscles. This works especially well for deep veins which run through muscles. When a muscle contracts, veins within the muscle are squeezed, this has the effect of raising the blood pressure within the lumen of the vein. This will close the valves below the area of increased pressure and force blood upwards, towards the centre of the body. This mechanism works so efficiently in the calf muscles it is referred to as the calf muscle pump. This is why it is important that patients on bed rest keep their ankles moving, this will activate the calf pump, returning blood and preventing pooling of blood in the legs.

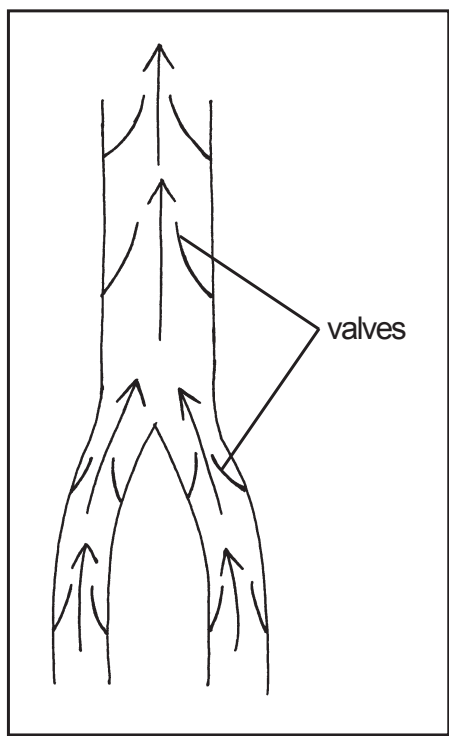


Diagram 2.18

A series of valves in peripheral veins. Blood flowing upwards will automatically open the valves whereas blood flowing backwards will close them. This arrangement means blood can only travel in one direction, from the periphery towards the heart. Arrows indicate the direction of blood flow.

Deep veins, arteries and nerves often run together in the body, usually in areas where they are protected from outside trauma. For example, the main vein and artery in the upper leg lie behind the quadriceps muscle and femur. This means they are protected from most blows or traumas coming from outside. This is why the upper outer aspect of the thigh is a safe site for intramuscular injections; the needle is unlikely to hit a nerve, artery or vein. Because arteries pulsate, they press on adjacent veins and so slightly squeeze them. This will increase the pressure of the blood in the lumen of the vein, so aid venous return. This is a less dramatic mechanism than skeletal muscle contraction but it is constant.

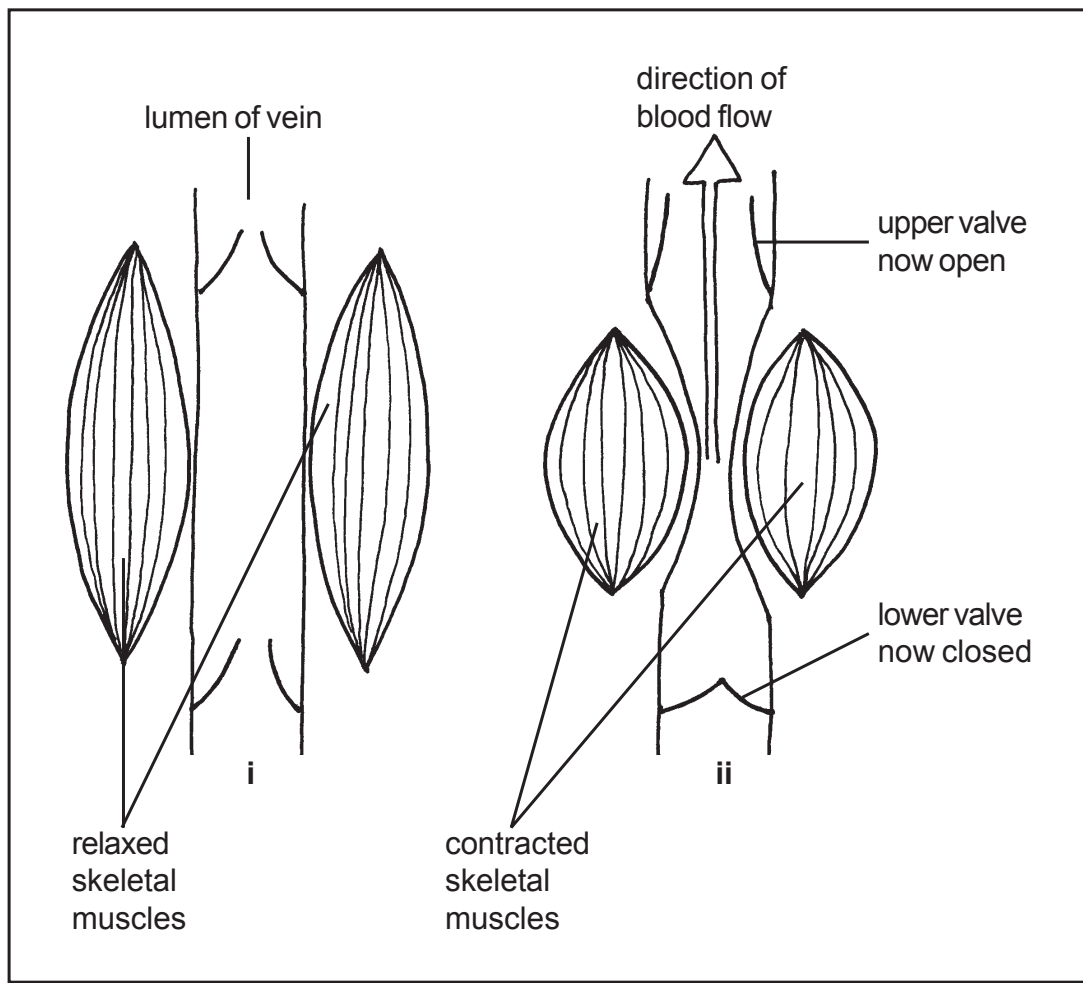


Diagram 2.19

The action of the calf muscle pump, muscle contraction shortens the muscle which squeezes the vein running through.

- (i) A deep vein in a muscle which is relaxed.
- (ii) A deep vein in a muscle which is contracting.

During inspiration the diaphragm moves down. As the diaphragm is between the thorax and the abdomen, downward movement compresses the abdominal contents. Because the inferior vena cava runs through the abdomen, this will be slightly compressed during inspiration. This pressure on the vena cava will increase the pressure of the blood it contains, closing the valves beneath, while pumping blood back into the thoracic cavity. Also during inspiration, because the diaphragm moves down, and the ribs move up and out, the pressure in the thorax is reduced. This reduction in pressure sucks blood into the thoracic vena cava from the abdominal vena cava.

During expiration, because the diaphragm moves up, the pressure in the abdomen is lowered. This allows blood from the leg veins to pass up, into the abdominal vena cava. Expiration also causes pressure changes in the thorax as the diaphragm moves up and the ribs down and inwards. This has the effect of

increasing the pressure in the thorax. This will increase the pressure on the thoracic vena cava, increasing the pressure of the blood it contains. This has the effect of squeezing blood from the thoracic vena cava back into the right atrium.

Clinical applications of venous return physiology

The mechanisms of venous return described above are one reason why patients on bed rest should be advised to take regular deep breaths, as well as keeping their ankles moving. If venous return is too sluggish there is the possibility of a blood clot forming in the deep veins, a condition referred to as deep venous thrombosis. This can be very painful, but the real danger is that a part of the blood clot may break off and form an embolus. This will travel with the venous blood back through the right side of the heart and will become jammed in a branch of the pulmonary artery. This condition is referred to as pulmonary embolism and is life threatening.

Some veins you may come across in clinical practice include the jugular in the neck and the subclavian under the clavicle. A venous cannula may be sited in the cephalic vein, over the lateral surface of the radius. The femoral veins drain blood from the legs and the main veins draining blood from the arm are the cephalic and the larger axillary vein. Renal veins carry blood from the kidneys directly to the inferior vena cava. Hepatic veins also directly drain blood from the liver back into the inferior vena cava.

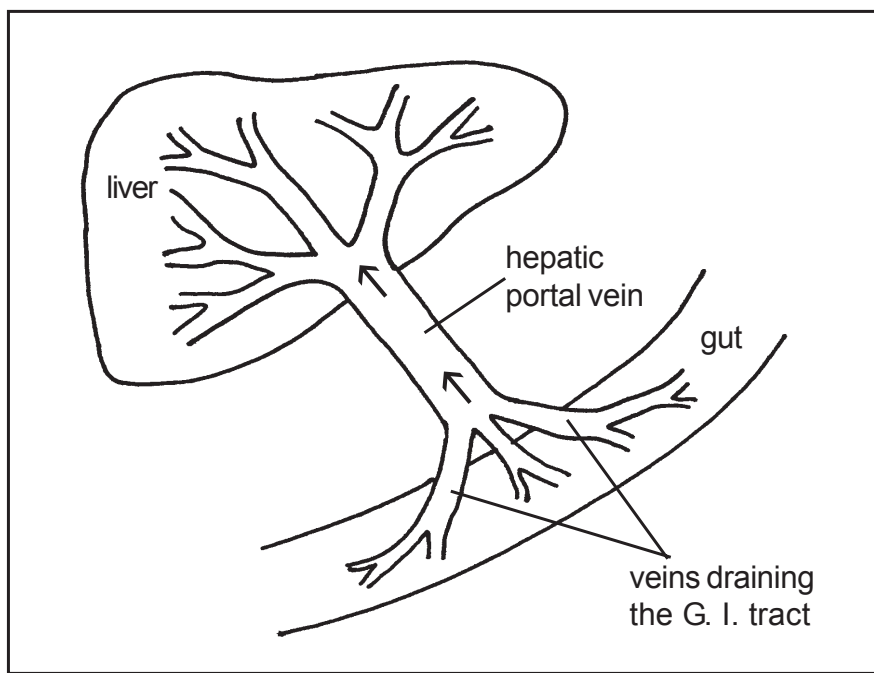


Diagram 2.20

Portal veins; Blood draining from the gastrointestinal tract carries absorbed nutrients and bacterial toxins directly to the liver for biochemical processing. Arrows indicate direction of blood flow.

Portal veins

A portal vein is one which does not drain into a larger vein but ends in capillaries. There is a portal system between the hypothalamus and the anterior pituitary to carry hypothalamic releasing hormones. As blood is passing directly from one area to another it is not diluted in the entire blood volume. This means smaller volumes of hormone may be used to generate the desired physiological effect which increases the efficiency of the process. The other main example of a portal system is the hepatic portal vein. Blood draining from the stomach, small and large intestine is collected together into this single vessel. The result of this is most of the blood drained from the gut passes directly into the liver; only once this blood has circulated through the liver does it enter the inferior vena cava via the hepatic veins. As the blood is carried directly to the liver, absorbed food products may be immediately processed by liver cells, for example, glucose can be stored as glycogen. However, the main reason for the hepatic portal system is to allow the liver to break down bacterial metabolic toxins, generated in the lumen of the gut, before they enter the systemic circulation. If these toxins freely entered systemic blood, there would be a chronic, low grade poisoning of all bodily organs.