Cardiovascular System

Chapter focus

This chapter introduces the structure and function of the cardiovascular system and examines its responses to sport and exercise.

All human movement, whether movement of the body around an athletics track or the movement of blood around the body, is dependent on energy. The body's ability to provide sufficient energy will limit the rate at which movement can occur, e.g. how fast an athlete can run or cycle. This energy is contained in the food we eat and is stored throughout the body until it is needed. The energy in these stores can be released via several metabolic pathways; a specific series of processes which result in energy that can be used by the body's cells; we examined this in Chapter ten. Which pathway is used depends on: the substrate used (carbohydrate, fat or protein), the rate at which energy is needed and the availability of oxygen. The main role of the cardiovascular system is to provide the oxygen needed in these metabolic pathways and to remove the by-products of metabolism such as carbon dioxide. In addition, it plays a vital role in the transport of many substances around the body including hormones and substrates. In this chapter we examine the structure and function of the cardiovascular system including the blood vessels and blood.

Learning Outcomes (LO)

This chapter is designed to help you be able to:

1) Describe the anatomy and structure of the heart and blood vessels;
2) Describe the conduction system of the heart;

3) Identify the main features of an electrocardiogram;

4) Understand the control of cardiac output during physical activity;

5) Understand the terms systolic and diastolic blood pressure;

6) Identify the components of blood.

The Heart

The heart, which is about the size of your fist, is the organ that is responsible for pushing blood around your body which it does 24 hours a day, seven days a week for your entire life, potentially resulting in over three billion heart beats. At its most simple the heart can be considered as a four chambered organ which functions as two parallel pumps (Figure 12.1). The four chambers are the left and right atria (a tre-a) and left and right ventricles (ven tri-kel), the atria are receiving chambers while the ventricles expel the blood from the heart. The right side receives blood from the body via the vena cava (great vein) which carries blood from the body's tissues. This blood is low in oxygen (O_2) and high in carbon dioxide (CO_2) as it has delivered the O_2 to the working cells and picked up the CO_2 which is a by-product of metabolism. Once the blood has arrived at the right atrium it travels via the tricuspid atrioventricular (a tre-o-ven-trik yu-lar) valve into the right ventricle where it is ejected into the pulmonary artery which transports the blood to the lungs. Here, CO_2 is removed and O_2 added. Once the blood has travelled through the lungs it is returned to the heart via the pulmonary veins where it enters the left atrium.

Pulmonary - related to the lungs

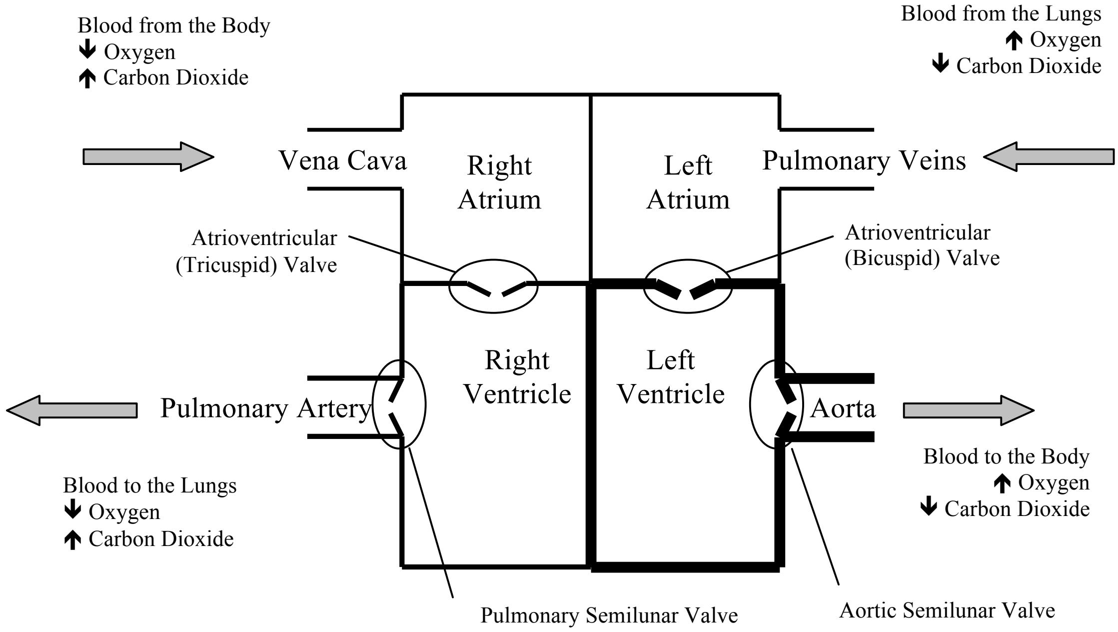
The blood is now high in O_2 and low in CO_2, having entered the left atrium it flows through the bicuspid atrioventricular valve into the left ventricle where it is pumped to the rest of the body (Figure 12.1) via the aorta. Since the left side of the heart has to pump blood to the whole body the muscle here is far larger than that of the right.

The Heart Wall

The heart is surrounded by a layer of connective tissue called the pericardium (per i-kar de-um; peri = around; cardium = heart) which protects and anchors it in position. The inner portion of the pericardium comprises two layers separated by the serous (ser us) fluid which reduces friction to ensure the two layers glide over each other. This low friction environment is essential to protect the heart wall during the movement produced as the heart beats; without

it the heart would rub against its surrounding structures with every beat resulting in damage to the heart tissue.

Figure 12.1: Chambers, valves and main blood vessels of the heart



Critical thinking activity 12.1

To highlight the importance of this low friction environment make a fist with your right hand, now wrap your left hand around your right tightly. Now pump your right fist as if it were your heart, you will soon notice the heat generated as the skin of your hands rub together and if you do this for a couple of minutes you could end up with a blister.

Inside the protective layer of the pericardium is the heart wall which comprises three layers. The outer layer is the epicardium (ep i-kar de-um; epi = on), next is the myocardium (mi o-kar de-um; myo = muscle) which is the heart, or cardiac, muscle, forming the bulk of the heart, and finally there is the endocardium (en do-kar de-um; endo = within). The myocardium is the part of the heart which produces the beat and, like skeletal muscle is striated or striped and has the same mechanism of contraction (see Chapter 11). There are, however, several key differences between the two. When you stimulate skeletal muscle you activate the number of motor units you need to produce the desired force. The heart, however, contracts all its muscle fibres in every beat. The reason for this is that while skeletal muscle fibres are insulated from each other so that the electrical stimulation of one fibre does not stimulate the adjacent fibre, the fibres of the heart are connected by ‘gap junctions’ so that once started, the electrical signal sweeps across the whole heart resulting in a co-ordinated beat.

Key Point 12.1

The heart beat is said to be an all or nothing event at the organ level, i.e. the whole heart either beats or it does not beat at all whereas skeletal muscle is an all or nothing event at the motor unit level, i.e. while all the fibres in a single motor unit will be stimulated other motor units within the same muscle are not necessarily stimulated.

Another key difference between skeletal and cardiac muscle is the way they re-form ATP. As discussed in Chapter ten the body’s tissues and particularly skeletal muscle, can derive energy from both anaerobic (without O_2) and aerobic (with O_2) pathways. The heart muscle is, however, far more reliant on aerobic metabolism and it is vital that the blood supply, and therefore the O_2 delivery, to the myocardium is maintained. If the blood supply is interrupted it can result in a myocardial infarction (mi o-kar de-al infark shun) or heart attack. The final layer of the heart wall, the endocardium, is in direct contact with blood as it passes through the heart chambers and it extends into the lining of the blood vessels which deliver the blood to, and carry blood away from, the heart.

Heart Valves

Blood flows through both sides of the heart in one direction due to a series of four valves, two on each side. These valves are situated between the atria and the ventricles, the atrioventricular valves, and at the point at which blood leaves the ventricles and enters the main arteries, the semilunar valves (Figure 12.1). On the right hand side of the heart, the atrioventricular valve has three flaps and is known as the tricuspid valve while the left hand side equivalent has two flaps and is known as the bicuspid or mitral valve. As blood flows through the atria and fills the ventricles the pressure in the ventricles increases, the atria then contract resulting in a final rush of blood into the ventricles, further increasing the pressure. The atria then relax and the ventricles contract, the increase in pressure in the ventricles snaps the valves shut stopping blood flowing back into the atria. This snapping shut of the atrioventricular valves results in the first of the heart sounds, the ‘lub’ of the ‘lub-dub’ you can hear when you place your ear against someone’s chest or when you use a stethoscope. The second sound, the ‘dub’, is caused by the semilunar valves snapping shut after the ventricles relax following their contraction which pushes blood from the heart. Once closed, the semilunar valves stop blood flowing back into the ventricles from the main arteries.

Key Point 12.2

Sometimes the valves of the heart do not seal properly and blood can flow in the wrong direction, this can be due to a heart abnormality or heart disease. If this occurs there is a surgical procedure in which the valves can be replaced with synthetic valves or the valves from a pig’s heart.

Blood Supply to the Heart

One thing to remember about the heart is that while there is always a large volume of blood travelling through it, it is not this blood that delivers O_2 to its own tissue. The blood supply (and therefore O_2 and nutrient supply) to the heart's tissue is delivered by a special set of blood vessels which make up the coronary circulation. The arteries of the coronary circulation leave the aorta as soon as it leaves the left ventricle, they then wrap around the heart delivering blood to its tissue.

Arteries – blood vessels which take blood away from the heart

After the blood has delivered its O_2 to the heart tissue it is taken directly back to the heart chambers via the cardiac veins which empty directly into the right atrium.

Veins – blood vessels which take blood toward the heart

Key Point 12.3

The term Coronary Heart Disease (CHD) refers to damage and deterioration of the heart's blood supply or, if the arteries are damaged this is known as Coronary Artery Disease (CAD). In the UK 25% of men and 17% of women die from CHD making it the country's biggest killer.

Conduction System

For the heart to pump effectively contraction of the myocardium needs to be co-ordinated, this is orchestrated by the heart's conduction system. While skeletal muscle needs to be stimulated by a nerve, the heart's ability to contract is intrinsic, this means that you could disconnect the heart from all nervous connections and it would continue to beat. Even so it still has a large number of nerves connected to it which play key roles in regulating its activity.

There are specialist cells within the heart called autorhythmic cells and as the name suggests these cells have the ability to set a rhythm automatically. They are found in several clusters throughout the heart and each cluster has its own rhythm. It is this rhythm that sets the pace of the heart beat. Since the different clusters of these autorhythmic cells have different rates it is always the cells with the fastest rhythm that will set the rate at which the heart beats or, the Heart Rate (HR).

In a healthy heart the cells with the fastest rate, or rhythm, are found in the Sinoatrial (SA) Node at the top of the right atrium. The rhythm of these cells would trigger a heart beat every 0.6 of a second and result in a heart rate of 100 beats per minute (bpm). However, the nerves which are connected to the heart slow this rhythm down so that the heart actually beats at a rate of approximately 75bpm when resting. Resting heart rate is, of course, very variable and depends on the fitness level and health of the individual. Resting heart rates of below 30bpm have been recorded in elite endurance athletes while heart disease patients can have resting values above 100bpm. The SA node initiates the heart beat by sending an electrical impulse across the left and right atria (Figure 12.2) which causes them to contract, forcing the blood into the ventricles. The electrical stimulus can’t travel across into the ventricles from the atria as there are no gap junctions in the cells which separate them so the impulse has to be transmitted via the atrioventricular (AV) node. Once the impulse has reached the AV node it is transmitted down the AV bundle and the two bundle branches which run down to the bottom of the heart before splitting into the purkinje fibres which carry the impulse into the myocardium to stimulate ventricular contraction.

> *Key Point 12.4*
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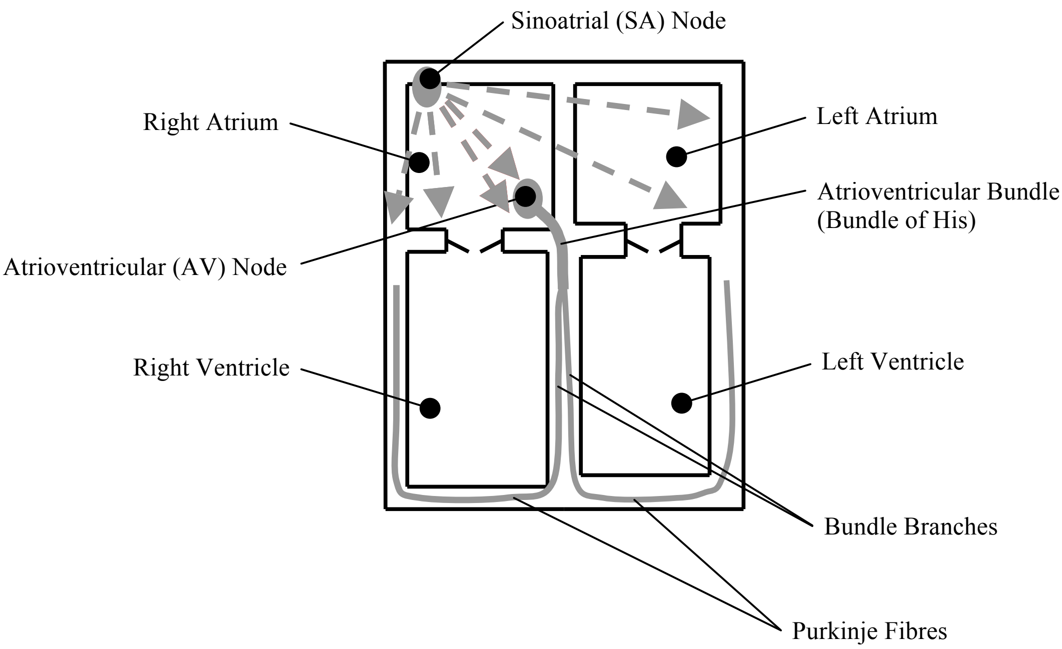
> Since the SA node sets the rhythm of the heart it is known as the heart's pace maker. In some diseases the pace maker can be damaged and stops working, so an artificial pace maker is fitted surgically.

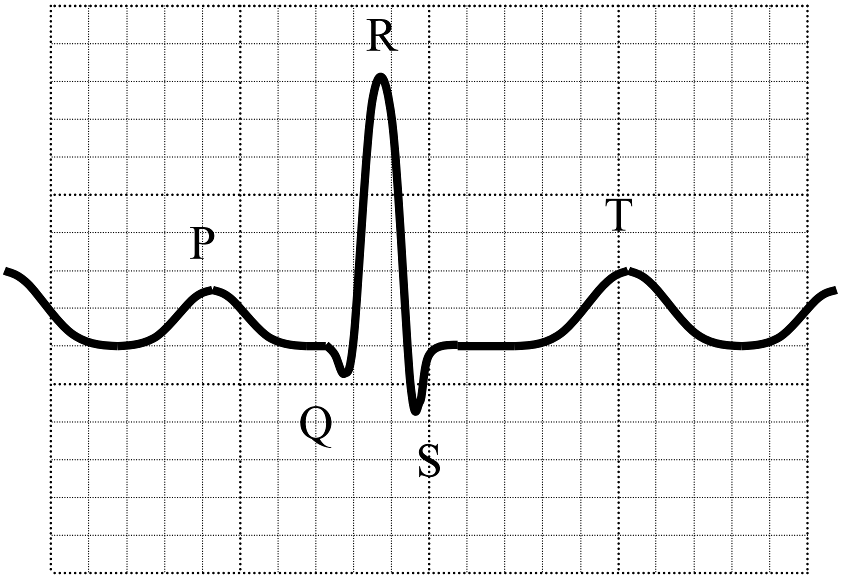
Figure 12.2: Intrinsic conduction system of the heart



Electrocardiography (ECG)

The electrical impulse which causes the heart to beat can be detected on the surface of the body by a piece of equipment known as an electrocardiograph (e-lek-tro-kar de-o-graf). This plots the electrical changes during the heart beat, producing an electrocardiogram (ECG) (Figure 12.3). The normal ECG pattern comprises three waves: the P wave, QRS Complex and T wave, each of which is associated with specific events during a single heart beat. The SA node initiates the heart beat by sending a signal across the atria, this is seen on the ECG as the P wave. There is then a short pause while the impulse travels down the AV bundle, the bundle branches and finally the purkinje fibres. The QRS complex results from the contraction signal sweeping across the ventricles. Finally, the ventricles need to reset before the next beat, this results in the T wave.

Figure 12.3: The electrocardiogram (ECG)



Key Point 12.5

The ECG can be used in medical screening to identify numerous heart abnormalities. For example, a missing P wave indicates that the SA node is not functioning and the second fastest set of autorhythmic cells, the AV node, instead sets the heart rate at 40-60bpm.

Cardiac Output

We have now examined the basic structure of the heart and how the heart beats to push blood around the body. We now examine how the amount of blood being delivered to the body can be manipulated. When you start to exercise the amount of O_2 needed by your muscles will increase very rapidly so you will start to breathe more deeply and move more air into the lungs so that O_2 can be taken by the blood and delivered to the working tissue around the body. The heart will also have to work harder to increase the rate at which blood is pumped around the body. The amount of blood leaving the heart in one minute is called the Cardiac Output (CO) which is a product of HR and Stroke Volume (SV). At rest if an individual's heart rate was 60bpm and they pumped out 83ml of blood every beat their CO would be 60bpm × 83ml/beat = 4980ml/min. Cardiac output can therefore be changed by changing either HR or SV, so for a fixed CO a larger heart with a larger SV would result in a lower HR. This is why endurance athletes have lower resting heart rates because one of the changes that occurs with training is an increase in heart size and SV (Table 12.1).

Stroke Volume – the amount of blood pushed from the heart in a single beat

Key Point 12.6

Units for Cardiac Output:

CO = 60beats/min× 83ml/beat

$$\frac{\text{Beats}}{\text{Minute}} \times \frac{\text{ml}}{\text{Beat}}$$

$$\frac{\cancel{\text{Beats}}}{\text{Minute}} \times \frac{\text{ml}}{\cancel{\text{Beat}}} = \frac{\text{ml}}{\text{Minute}}$$

= 4980ml/min = 4.98L/min

Table 12.1: Determinants of cardiac output in athletic and sedentary individuals

		Athlete	*Sedentary*
Heart Rate	(bpm)	45	75
Stroke Volume	(ml/min)	111	67
Cardiac Output	(L/min)	5	5

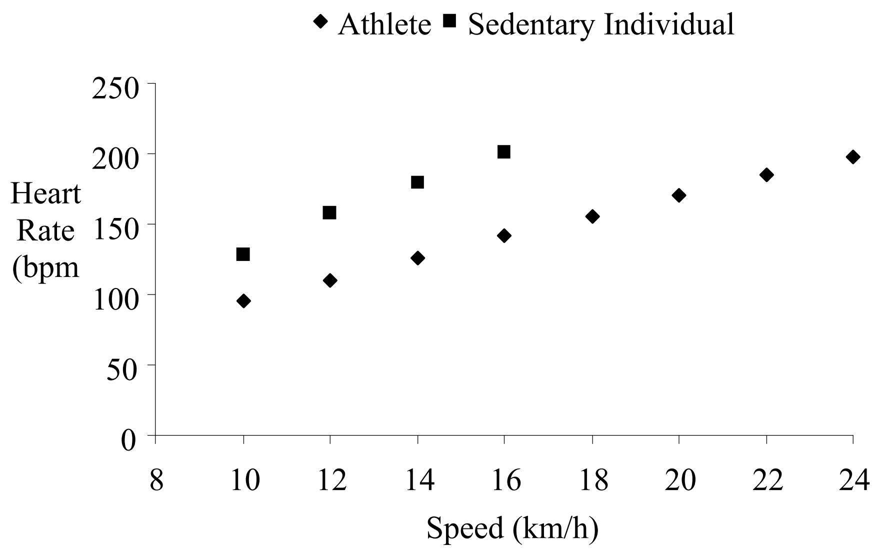
The energy required when you start to exercise increases the demand for O_2 therefore the heart will have to increase CO. It can do this by increasing either the HR or the SV, but in practice both occur. The increase in CO is controlled very carefully so that it matches the increase in required O_2 and this is where the athlete and the sedentary individual differ greatly as the athlete can increase their CO to a far greater extent resulting in greater work capacities. After long periods of training athletes can increase their CO by five to seven that at rest, so while at rest a typical CO value is 5L/min, during maximal exercise an athlete's heart can pump out 25 – 35L/min.

Heart Rate

As already stated resting heart rate is dependent on fitness level and athletes have larger hearts and greater SV than sedentary individuals. Healthy individuals will have a resting HR of 60-75bpm and a maximal HR (HRmax) which is dependent on age. As we age our HRmax will decrease by approximately 1 beat each year. A simple method of calculating your HRmax is to subtract your age from 220, so a 20 year old would have a HRmax of 200bpm. Care must be taken with this calculation as it is very approximate and five per cent of all 20 year olds will have a HRmax of less than 180 or greater than 220bpm.

Heart rate increases with exercise intensity in a linear fashion (Figure 12.4) so as exercise intensity increases so does HR until you reach your HRmax when you will be working extremely hard. Figure 12.4 shows the HR response of two 20 year olds during a treadmill exercise test. As you can see the athlete has a much lower HR at all speeds but both individuals stop exercising at a similar HRmax, 200bpm. The main difference is that the athlete can run at 24km/h before they fatigue, while the sedentary individual can only manage 16km/h.

Figure 12.4: Heart rate response to increasing treadmill speed



Anatomy of the Blood Vessels

There are three main types of blood vessel: the arteries which carry blood away from the heart at high pressure, the veins which carry blood back to the heart at a much lower pressure and the capillaries which have very thin walls to allow the exchange of materials between the blood and the body's tissues. Arteries and veins have three layers or tunics; one of the differences between the two types of blood vessel is the way in which these three layers make up the blood vessel wall. The outer most layer of a blood vessel is known as the tunica adventitia (ad ven-tish e-ah; coming from outside), it surrounds the blood vessel, protects it and anchors it to surrounding tissues. The second layer, the tunica media (me de-ah; middle) is comprised of relatively large amounts of smooth muscle and plays an important role in the redistribution of blood flow via vasoconstriction. The final layer, the tunica intima (in ti-mah; intimate), is in direct contact with the blood and its cells have very smooth surfaces to minimise friction, allowing the blood to flow easily. The hole which runs down the centre of the blood vessel, through which the blood flows, is called the lumen. While there are similarities between the three types of vessel there are also many differences as we will see below.

Vasoconstriction – reduction in the size of the blood vessel's lumen

Arteries

Arteries carry blood away from the heart, those leaving the right side of the heart carry blood low in O_2 to the lungs and those on the left carry blood high in O_2 to the rest of the body. As the heart beats it pushes blood into the arteries and if you hold your fingers over an artery and press lightly on the skin you will feel the pressure wave from the heart, known as the pulse. You can feel this at several places around the body; those most commonly used are the radial pulse on the inside of the wrist about two to three centimetres up from the thumb, and the carotid pulse in the neck on either side of the larynx.

Larynx - also known as the voice box or Adam's apple in men

Critical thinking activity 12.2

Sit or lie down for five minutes, then find your own radial pulse and count the number of beats in 60 seconds to work out your own resting heart rate. Now walk around the room for a couple of minutes and check your heart rate again, note if it has changed, if it has think about why based on what you have read above.

The artery walls are relatively elastic so that they can expand with the pressure created by the heart beat. They also have large amounts of smooth muscle to control blood flow to different organs. When an organ needs more blood they relax to increase the diameter of the lumen, or when less blood is needed they contract to reduce the diameter. The amount of blood that an organ needs depends on the circumstances, for instance, following a meal when you are relaxing the stomach needs energy to digest your meal so the arteries supplying the stomach relax and the ones supplying your muscles contract. However, if you begin exercising, the arteries supplying the skeletal muscle relax and those supplying the stomach contract switching the blood flow from the stomach to the muscle. Table 12.2 identifies the difference in CO at rest and during exercise, and the different tissues to which the blood is pumped. At rest CO is five litres with most of this going to the liver and kidneys, however, during exercise CO increases to over 25 litres and is directed to tissues which are needed during exercise. These include muscle, the heart which has to work harder to increase CO and the skin which has to produce sweat to keep the body cool.

Table 12.2: Distribution of blood flow at rest and during exercise in ml/min

	Volume of blood (ml/min)	
	At rest	*During exercise*
Muscle	1000	21000
Heart	200	1000
Skin	300	600
Brain	700	900
Kidneys	1100	250
Liver	1350	500
Other	350	780

Veins

Veins return blood to the heart so those supplying the left hand side have high levels of O_2 as the blood has just passed through the lungs. The blood in the veins supplying the right side is low in O_2 as the blood is returning from the body. The pressure in veins is much lower than in arteries therefore the walls of the veins are much thinner with relatively little smooth muscle. The low pressure also means that there is relatively little driving force to push the blood forward, so the veins have valves. These are functionally similar to the ones in the heart as they are one-way, meaning that blood can flow towards the heart but if it tried to flow in the opposite direction the valve would close to stop the flow until there was enough pressure to drive it forward again. A mechanism which helps blood return to the heart is known as the 'muscle pump'. When skeletal muscle contracts concentrically (Chapter 11) it shortens and widens; this presses against the vein, increasing the pressure, and pushing the blood forward. This is an important reason why we warm down after exercise. During physical activity the arteries increase the blood supply to the muscles and blood is helped back to the heart via the muscle pump, however, if you stop exercise suddenly without warming down the blood will not be able to return to the heart as effectively.

Capillaries

Capillaries link the arteries and the veins, and in the capillaries the blood exchanges the O_2 and nutrients it is carrying for CO_2 and other waste products produced by the body's tissues. For this exchange to occur the walls of the capillaries are very thin and have no tunica adventitia or tunica media. In the smallest capillaries the tunica intima can be made up from a single cell wrapped around the lumen which is only wide enough for blood cells to pass through individually. Even though the cross sectional area of the lumen of a single capillary is very small there are so many more capillaries than arteries and veins that if you were to combine the cross sectional areas of all the capillary lumens the total area would be far greater than that of either the arteries or the veins. This is important as it allows the blood to slow down as it moves through the capillaries giving time for the exchange of O_2 and CO_2.

Blood Pressure

As the heart beats there is an increase in pressure which pushes the blood out of the heart and into the arteries, this pressure is transferred to the artery wall and is known as Blood Pressure (BP). Blood pressure varies during the heart beat and two measures are normally taken when we record BP: systolic (sis tol-ik) and diastolic (di-as tol-ik). Systolic is the pressure exerted on the artery wall when the heart contracts, a period known as systole (sis to-le). Diastolic pressure is exerted when the heart relaxes to refill with blood between beats, a period known as diastole (di-as to-le). Typical values for a healthy adult are 120mmHg and 80mmHg for systolic and diastolic, respectively. It is important to note that these values are resting values and only in the artery of the upper arm (the brachial artery). If BP was measured in an artery closer to the heart the pressure would be greater whereas if the measurement was taken in an artery further from the heart the pressure would be less, and, BP in the veins is very low in comparison, less than 20mmHg.

Key Point 12.7

Units of BP: mmHg = millimetres of mercury

This unit expresses the pressure as an equivalent of the pressure that is exerted by a column of mercury of a given height in millimetres. For example, a typical systolic BP of 120mmHg means that the pressure the blood exerts on the artery wall is the same as that exerted by a column of mercury 120mm high.

Blood pressure is very responsive to stress, posture and physical exercise, for example, if you stand up very quickly from lying down you sometimes feel lightheaded. This is because while lying down your BP is low as the heart does not have to work hard to pump blood against gravity to your brain. When you stand up gravity has an immediate effect on the blood, pushing it down to your legs and it can take the heart several seconds to adjust to the change and increase the pressure to push the blood up to the brain; during this time you can experience dizziness. Similarly, when you start to perform exercise the heart has to work harder to pump more blood at higher pressure to the working muscles.

Blood

The typical male has five to six litres of blood whereas a typical female has four to five litres; this accounts for approximately 8% of total body mass. Blood is the medium through which substances are moved around the body, this includes hormones, nutrients, proteins, cells and gases such as O_2 and CO_2. Blood has evolved some highly specialised methods of transporting these essential life materials. Firstly, let’s look at what blood is made up of; if you place a blood sample in a test tube and spin it in a centrifuge at several thousand revolutions per minute for several minutes the heaviest components of blood will be pushed to the bottom of the tube and the lighter ones will float to the top. If you then look at the tube you will see that the blood has separated out into three distinct bands. In the bottom of the tube you will see a dark red substance, these are the red blood cells or erythrocytes (e-rith ro-site; erythro = red, cyte = cell). Next is a thin layer called the 'buffy coat' which is made up of platelets and white blood cells or leukocytes (lu ko-site; leuko = white), finally floating on the top is a straw coloured liquid called plasma. The erythrocytes make up approximately 45% of blood although this does vary with training and their job is to carry O_2 and CO_2 around the body. Oxygen is carried in the erythrocytes attached to a substance called haemoglobin (he-mo-glo bin), when O_2 is attached to haemoglobin it is known as oxyhaemoglobin (ok si-he mo-glo bin). The bond between O_2 and haemoglobin is very easily formed but also easily broken. When the blood cell is in an area high in $O_{2,}$ i.e. the lungs, O_2 attaches to haemoglobin, the cells are then transported in the blood to the body's tissues, which are low in $O_{2,}$ at which point the O_2 breaks away from the haemoglobin and can enter the tissue. At the same time haemoglobin picks up CO_2 and transports it to the lungs to be expired. Erythrocytes make up 45% of blood volume but the buffy coat, which contains leukocytes and platelets, contributes less than 1%. Leukocytes form an important part of the body's immune system; they travel around the body via the blood and if they encounter any tissue that they do not recognise as belonging to the body they will destroy it. They can recognise foreign tissue including viruses and bacteria as all of your body's cells have protein markers on the cell wall which identify that cell as being a part of you; if the leukocytes can't find the markers they destroy the cell. The platelets play a vital role in forming blood clots by sticking to damaged cells. If they didn't do this the slightest cut wouldn't heal and bleeding wouldn't stop with potentially fatal consequences. The final component of blood, plasma, typically makes up 54% of blood and is itself 90% water. Its main role is to carry substances and cells around the body, in addition to erythrocytes, leukocytes and platelets; plasma also carries nutrients, hormones, waste products, proteins and gases. Plasma can also act as a medium to store and transport heat away from metabolically active tissue such as muscle during exercise. The heat can then be transferred to the skin as blood returns to the heart.

The Effect of Physical Training on Blood

Following a period of endurance training there are several changes which occur to blood. One of the first is an increase in the volume of plasma which occurs very rapidly, usually after only several training sessions. This increase in volume of plasma dilutes the number of blood cells giving the false impression of anaemia; this is known as 'athletic anaemia' or 'sports anaemia'. A consequence of the increase in plasma volume is that the amount of blood pumped out of the heart in a single beat, the SV, will increase; this in part explains the lower resting HR seen in athletes. Following a slightly longer period of training of two to three weeks the number of erythrocytes will start to increase, however, the increase in erythrocytes will never match the increase in plasma, giving athletes slightly anaemic blood. These changes together give athletes a greater O_2 carrying capacity increasing the athlete's ability to produce energy aerobically.

Anaemia – low erythrocyte count

Chapter summary

We started this chapter with the anatomy of the heart including the heart wall, chambers and blood supply (LO 1) before we moved on to the heart's conduction system (LO 2) and the ECG (LO 3). We then spent some time examining cardiac output and specifically its control by increasing or decreasing heart rate and stroke volume (LO 4). Before taking a close look at blood, its constituent parts and the role each part plays within the body (LO 6) we spent some time examining blood pressure, specifically systolic and diastolic pressures (LO 5).

Further Reading (cardiovascular system)

- Marieb, EN (2000) *Human anatomy and physiology* (7th edition). Menlo Park, California: Benjamin Cummings.
    - This is an excellent general anatomy and physiology text used by undergraduate medical students. Chapters 17, 18 and 19 provide detail on the structure and function of the blood, the heart and the blood vessels, respectively.
- McArdle, WD, Katch, FI, and Katch, VL (2006) *Exercise physiology: energy, nutrition, and human performance* (6th edition, pages 313-363). Baltimore, Maryland: Lippincott Williams and Wilkins.
    - This text book is written for undergraduate degree students and goes into some depth but the quality of the figures can help with understanding some of the key issues. Chapters 15, 16 and 17 (pages 313-363) cover the cardiovascular system and its contribution to energy delivery.
- Wilmore, JH, Costill, DL, and, Kenney, WL (2007) *Physiology of sport and exercise* (4th edition, pages 122-141 and pages 160-184). Champaign, IL: Human Kinetics.
    - This text book is written for undergraduate degree students and goes into a little more depth than we have here. The quality of the figures and graphs will help with understanding some of the key issues. Chapter 5 (pages 122-141) provides information on the cardiovascular system and Chapter 7 (pages 160-184) examines the cardiovascular system's response to exercise.