INQUIRY QUESTION
How do the structures of the cardiovascular system work together to meet the demands of the body during rest and exercise?
The cardiovascular system plays an important role in the delivery of oxygen and fuels for energy production, as well as the removal of waste products during physical activity.

**KEY KNOWLEDGE**
- The structure and function of the cardiovascular system, including the structure and function of the heart and blood vessels, and blood flow around the body at rest and during exercise
- Components of blood, including red blood cells, white blood cells, platelets and plasma, and their function at rest and during exercise
- The role of the cardiovascular system in thermoregulation: homeostasis, hyperthermia and hypothermia
- Vasodilation and vasoconstriction of the blood vessels to regulate blood distribution at rest and during exercise
- The relationship between stroke volume, heart rate and cardiac output at rest and during submaximal and maximal exercise

**KEY SKILLS**
- Use and apply correct anatomical terminology to identify the structures and function of the cardiovascular and respiratory systems
- Describe the role and function of the blood
- Examine the role of the cardiovascular system in thermoregulation
- Analyse the relationship between stroke volume, heart rate and cardiac output at rest and during submaximal and maximal exercise
- Perform, measure and report on changes to the cardiovascular and respiratory systems at rest compared with exercise

**CHAPTER PREVIEW**
Functions of the cardiovascular system

The body depends on the efficient functioning of the cardiovascular system. The cardiovascular system consists of the heart and blood vessels working together to transport gases and nutrients around the body. This system has five important functions:

- It circulates blood to all parts of the body.
- It transports water, oxygen and nutrients to the cells.
- It transports wastes including carbon dioxide away from the cells.
- It helps maintain correct body temperature.
- It helps fight disease through the white blood cells and antibodies contained in the blood.

Structure of the heart

The heart is a pump designed to circulate blood throughout the cardiovascular system (figure 6.1).
- The heart has four chambers — two atria and two ventricles.
- The atria are the upper chambers that receive blood.
- The ventricles are the lower chambers that pump blood.

The septum divides the heart into two pumps.
- The left pump is the left atrium and left ventricle.
- The right pump is the right atrium and right ventricle.

The blood in the two pumps does not mix because the left pump has oxygenated blood for the body, while the right pump has deoxygenated blood that travels to the lungs for the removal of carbon dioxide.
Valves are located between the atria and the ventricles, and at the entrance to the arteries from the heart. The bicuspid valve is on the left side of the heart and the tricuspid valve is on the right side. They allow blood to travel in only one direction, stopping blood in the ventricles from flowing back into the atria.

**Functioning of the heart**
The heart is an involuntary muscle; that is, we do not have conscious control over its functioning. It works by the continual contraction and relaxation of the atria and ventricles. When the heart contracts, it forces blood out of the heart via the ventricles and into the arteries. This is called *systole*. When the heart relaxes, it fills with blood from the veins. This is called *diastole*. The **cardiac cycle** is made up of the atria contracting (systole) while the ventricles relax (diastole), and the ventricles contracting (systole) while the atria relax (diastole).

**Features of the heart**
- It is located slightly to the left of the centre of the chest (between the two lungs) and is protected by the rib cage (figure 6.2).

- The adult heart is about the size of a large fist.
- The audible sound that can be heard when listening to the heart is called the heartbeat.
- At rest, the average **heart rate (HR)** is about 72 beats per minute (see page 141 for more information). Heart rate is measured by taking your pulse.
- **Stroke volume (SV)** is the amount of blood pumped by each beat of the heart (see pages 141–2 for more information). As an individual becomes fitter, stroke volume increases from approximately 70 mL/beat to 100 mL/beat.
- **Cardiac output (Q)** is the amount of blood pumped by the heart per minute (see page 142 for more information), and is measured in litres per minute (L/min). In adult males this may be about 5 litres per minute, and in adult females about 4 litres per minute. It is calculated by multiplying heart rate (HR) by stroke volume (SV), or HR \times SV = Q. For example, 72 bpm \times 70 (mL/beat) = 5.04 L/min.
Blood vessels

In addition to the heart, the cardiovascular system has three types of blood vessels that control the direction and volume of the blood flow around the body:

- arteries (figure 6.3)
- veins (figure 6.4)
- capillaries (figure 6.5).

This network is also referred to as the vascular system.

Arteries

Arteries are large, thick-walled blood vessels that carry blood away from the heart.

**Figure 6.3** An artery has a thick, elastic, muscular wall.

**Figure 6.4** A vein has a thinner, less elastic wall than an artery wall.

**Figure 6.5** A capillary has a very thin wall that allows oxygen, carbon dioxide and nutrients to pass into the cells.

**Arteries** always carry oxygen-rich blood from the heart to the body. The aorta is the largest artery in the body (figures 6.1 and 6.7). The left ventricle pushes the blood into the aorta and on to the rest of the body. The volume of blood pumped into the arteries with each beat is quite large. The artery walls are elastic so they can expand with each heartbeat to accommodate this volume.

When you take your heart rate, you are recording the number of beats of the heart by feeling the pressure of the blood being pushed into the arterial system. The two most common points for recording a heart rate are the carotid (neck) and radial (wrist) pulse. You should always take your heart rate at only one point on the body, using a fingertip and not a thumb. A quick method of calculating your heart rate is to take it for 10 seconds, then multiply that number by six to find the beats per minute.

**Figure 6.6** shows the location of the major pulse sites on the body. These may also be emergency pressure-control points to stem blood flow after accidents that have caused high blood loss. Bleeding from an artery can be recognised by the blood spurting out with each heartbeat and by the bright red colour of this oxygen-rich blood. Factors that affect resting heart rate include:

- gender, with males usually having a lower resting heart rate than females
- temperature, with heart rate increasing as air temperature increases
- eating, which increases heart rate
- laughing, which increases heart rate
- smoking, which increases heart rate
- body position, with heart rate being higher when standing than when sitting, and higher when sitting than when lying down
- exercise, which increases heart rate in order to deliver more oxygen and nutrients around the body and to the working muscles.

Arteries reduce in size to become arterioles as the network of blood vessels works its way into the depths of the body.

**Figure 6.6** Major pulse sites in the body
Like other muscles, the heart needs a supply of oxygen and nutrients which are delivered by the cardiovascular system. There are two coronary arteries (figure 6.7), both of which branch from the aorta and spread across the heart muscle to feed all the chamber walls with nutrients. One of the most common causes of heart attack is the blockage of one or both of the coronary arteries with fatty deposits, resulting from a poor lifestyle. This reduces the blood supply to the heart muscle, causing severe pain in the chest and possibly death of part of the heart muscle or of the individual.

Capillaries

Capillaries are the smallest blood vessels, and they form the next stage of the blood vessel network after the arterioles (figure 6.8). The exchange of nutrients and waste between the blood and the body cells occurs in the capillaries. Heat from the cells is also absorbed by the blood in the capillaries. This exchange of materials and heat is easy because the thin walls of the capillaries are only one cell thick.

When you begin to exercise, the capillaries dilate (increase in diameter) to allow the increased blood flow required during exercise. Other capillaries feeding the working muscles also come into use by ‘gateways’ or precapillary sphincters, opening up and allowing more blood to the muscles. The cardiovascular system uses these sphincters to channel blood to various body sites depending on prevailing conditions (figure 6.9).

Capillaries are tiny blood vessels in the cardiovascular system between the ends of the arterioles and the venules. They are the site for the exchange of gases between the cells and the cardiovascular system.

Precapillary sphincters are one-way valves that control blood flow within capillaries.
A long-term exercise program may increase the number of capillaries supplying blood to muscles (including the heart). This allows an increased supply of oxygen and other nutrients to the muscles and a more rapid removal of wastes. The capillaries eventually carry these wastes to the venules, which then carry them into the veins.

**Veins**

When blood reaches the veins, it is no longer surging or pulsing under the influence of the heartbeat. Instead, the flow is steady and consistent. The walls of the veins are quite thin and not as elastic as the walls of the arteries.

Veins carry blood with lower oxygen content and a high carbon dioxide content because the muscles and cells have extracted oxygen to produce energy. The return of blood to the heart in the veins depends on the contraction of skeletal muscles. Veins running alongside muscles are squashed or squeezed when the muscles contract. One-way valves force blood in the veins upwards towards the heart (figure 6.10), against the force of gravity.

**Blood pooling** after exercise is a problem if you do not gradually cool down. Given the increased blood flow during exercise (from around 5 litres per minute to possibly over 30 litres per minute), a gradual return to rest conditions is paramount. During a cool-down, the muscle pump system continues to move the gradually diminishing excess blood flow around the body until it has reached resting level. Without this process, the combination of high blood flow and gravity creates an increase (or ‘pooling’) of blood in the legs.

**TABLE 6.1** Summary of structure and function of blood vessels

<table>
<thead>
<tr>
<th>Blood vessel</th>
<th>Structure</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artery</td>
<td>Large, thick, elastic wall</td>
<td>Carries blood away from the heart</td>
</tr>
<tr>
<td>Capillary</td>
<td>Small, thin wall</td>
<td>Site of exchange for nutrients and wastes between cells and cardiovascular system</td>
</tr>
<tr>
<td></td>
<td>Only one cell thick</td>
<td></td>
</tr>
<tr>
<td>Vein</td>
<td>Thin, large diameter</td>
<td>Carries blood back to heart</td>
</tr>
<tr>
<td></td>
<td>One-way valves</td>
<td></td>
</tr>
</tbody>
</table>
TEST your understanding

1. Download the diagram of the heart in your eBookPLUS. Label the structures of the heart. Indicate the direction of blood flow through the heart.

2. List the five functions of the cardiovascular system.

3. Outline the cardiac cycle. Explain the difference between systole and diastole.

4. Compare the differences between the three types of blood vessels — arteries, veins and capillaries.

5. Define heart rate. Discuss the factors that can affect heart rate.

APPLY your understanding

6. Define cardiac output. Calculate the cardiac output (Q) of an individual who has a heart rate of 75 bpm and a stroke volume of 70 mL/beat.

7. Define stroke volume. Calculate the stroke volume (SV) of an individual participating in moderate exercise who has a heart rate of 100 bpm and a cardiac output of 8 L/min.

8. Explain the importance of capillaries in physical activity.

9. Describe what the body does to lessen the problems caused by venous pooling.

10. Detail the path that blood flows through the heart, outlining all structures. Begin at the vena cava.

11. Learning activity: sheep’s heart dissection
   (a) In pairs or groups of three, dissect a sheep’s heart, locating chambers, valves, main entrance and exit blood vessels.
   (b) Write a report of the dissection that includes a labelled diagram you have drawn.

12. Practical activity: heart rate and exercise
   (a) Before you begin the physical activities, sit down quietly and manually measure your resting heart rate.
   (b) Perform each of the following activities, taking your pulse for 10 seconds immediately after you complete each activity. Rest until heart rate has returned to resting heart rate between each activity.
      – Walking for 2 minutes
      – Jogging for 2 minutes
      – Situps for 30 seconds
      – Stepups on a bench for 2 minutes
      – Seated toe-touches for 30 seconds
      – Running for 3 minutes as fast as possible
   (c) Record and graph your results. Multiply by six to determine your heart rate.
   (d) Identify which activity caused the highest heart rate. Suggest reasons for this.
   (e) Discuss the relationship between your heart rate and the intensity of the activity. Provide examples.
6.2 Cardiovascular system: blood and blood circulation

**KEY CONCEPT** Blood circulates around the body to deliver oxygen and nutrients to cells while removing waste products. Blood travels around two major circuits: the systemic circuit (the body), and the pulmonary circuit (the lungs).

**Blood**

Blood is the only body tissue that is a liquid. Blood cells make up 45 per cent of the blood volume, while plasma makes up the other 55 per cent. Blood transports materials required for energy production, including oxygen and glucose, and byproducts of energy production such as carbon dioxide and lactate, around the body. Blood also plays a very important role in the thermoregulation of the body. Each individual has approximately 4–5 litres of blood in their body, and it takes around one minute to circulate around the body at rest. Exercise improves the quality and quantity of the body’s blood supply. The three types of blood cell are described below.

**Red blood cells**

- Make up 99 per cent of all blood cells
- Transport oxygen to, and carbon dioxide from, the cells and muscles
- Contain haemoglobin (the substance that carries oxygen through the bloodstream)
- Are continuously produced in the bone marrow in the cavities of bones (see chapter 2, page 16)
- Are continually removed by the liver and spleen when worn out
- Have a lifespan of about four months

**White blood cells**

- Exist in the body in a ratio of 1 to every 700 red blood cells
- Come in a variety of shapes and sizes
- Are generally larger than red blood cells
- Can pass through capillary walls into the body cells to fight disease-causing organisms by absorbing and digesting them
- Have a lifespan of a few days

**Platelets**

- Cause blood to clot when a blood vessel is damaged
- Are smaller than red blood cells
- Are produced in the bone marrow

**Plasma**

Plasma is a clear yellowish fluid of which over 90 per cent is water. It carries the blood cells, continually passing through the capillary walls and into the cells. Plasma provides the cells with proteins, salts, glucose, fats, antibodies and some oxygen. It also removes waste products. In emergencies, plasma is the first substance fed into the injured body to replace any lost fluids. Any blood transfusions are normally given later.

**TABLE 6.2** Summary of the role and function of blood components

<table>
<thead>
<tr>
<th>Blood component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red blood cell</td>
<td>Transports oxygen around the body</td>
</tr>
<tr>
<td>White blood cell</td>
<td>Protects against disease</td>
</tr>
<tr>
<td>Platelet</td>
<td>Causes blood to clot</td>
</tr>
<tr>
<td>Plasma</td>
<td>Carries blood cells around body</td>
</tr>
</tbody>
</table>

**Figure 6.11** The components of blood
**Blood circulation**

Circulation of blood throughout the body is divided into two closed circuits:

- **Systemic circulation**, when oxygenated (oxygen-rich) blood is transported from the heart via the left ventricle and aorta and circulated into the arteries around the body (except for the lungs), and deoxygenated (oxygen-poor) blood returns to the heart via the vena cava and into the right atrium.

- **Pulmonary circulation**, when deoxygenated blood is transported away from the heart and circulated to the lungs via the right ventricle and pulmonary artery, and oxygenated blood returns to the heart via the pulmonary vein and into the left atrium.

The following sequence shows how blood is circulated through the body (figure 6.12):

1. The right atrium receives blood (low in oxygen and high in carbon dioxide) from the body via the vena cava.
2. The right ventricle receives blood from the right atrium via the tricuspid valve and pumps this blood to the lungs via the pulmonary artery.
3. Blood gives up carbon dioxide and takes up oxygen while in the lungs.
4. Oxygenated blood returns via the pulmonary vein to the left atrium.
5. Blood enters the left ventricle via the bicuspid valve and is pumped through the aorta into the arterial system.
6. Blood flows to all extremities of the body through the arterioles.
7. Blood enters capillaries, where oxygen and nutrients are fed to the cells, and carbon dioxide, water and other wastes are removed from the cells.
8. Capillaries carry blood to the venules, then to the veins.
9. Veins return oxygen-poor blood to the right atrium.

**Systemic circulation** describes the arteries and veins that feed blood from the heart to the whole body and back to the heart again for reoxygenation.

**Pulmonary circulation** describes the arteries and veins that feed blood from the heart to and from the lungs where blood is oxygenated.

**eLesson**
Circulation of blood throughout the body
Searchlight ID: eles-0452
### Features of the cardiovascular system

#### Blood pressure

Blood pressure is an indicator of the body’s health. It shows:
- how hard the heart has to work to push the blood through the arteries, capillaries and veins
- the health of the arteries and capillaries.

Blood pressure has two measurements: an upper reading called the **systolic blood pressure**, and a lower reading called the **diastolic blood pressure**.

- **Systolic blood pressure** is a measure of the pressure that the blood exerts against the artery walls during the contractile (emptying) stage of the heart’s pumping.
- **Diastolic blood pressure** is a measure of the same pressure against the artery walls, but during the relaxation (filling) phase of the heart’s pumping action. A typical blood pressure reading is 120/80 mm Hg. (The measurement ‘mm Hg’ means millimetres of mercury, referring to the mercury-based device that measures blood pressure — a sphygmomanometer.) Figure 6.13 illustrates how to use a sphygmomanometer to measure blood pressure.

Many factors affect systolic blood pressure. As a general rule, it should not be more than 140 mm Hg while at rest. Values above 140 mm Hg signify hypertension or high blood pressure. This is of concern as the heart has to work harder to pump blood around the body due to the increased pressure in the vessel walls. People with hypertension are at greater risk of developing cardiovascular diseases (see chapter 8). A guideline for predicting healthy systolic blood pressure is 100 plus your age, with a recommended maximum of 140–50 (table 6.3). However, with a healthy and active lifestyle, older people could sustain a systolic blood pressure of around 120 mm Hg. Regular exercise usually helps keep systolic blood pressure below the averages for 40–60 year olds.
TABLE 6.3 Average arterial blood pressures from birth to 60 years (mm Hg)

<table>
<thead>
<tr>
<th>Age</th>
<th>Systolic</th>
<th>Diastolic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborn</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>1 month</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>2 years</td>
<td>85</td>
<td>60</td>
</tr>
<tr>
<td>4 years</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>10 years</td>
<td>105</td>
<td>70</td>
</tr>
<tr>
<td>15 years</td>
<td>110</td>
<td>70</td>
</tr>
<tr>
<td>20 years</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>30 years</td>
<td>130</td>
<td>85</td>
</tr>
<tr>
<td>40 years</td>
<td>140</td>
<td>90</td>
</tr>
<tr>
<td>50 years</td>
<td>145</td>
<td>90</td>
</tr>
<tr>
<td>60 years</td>
<td>150</td>
<td>90</td>
</tr>
</tbody>
</table>

**TEST your understanding**

1. Name the four components of blood and describe the function of each.
2. Define haemoglobin. Outline its importance in physical activity.
3. Identify the two closed circulatory systems of the body and describe their function.
4. Create a flowchart of the circulation of blood throughout the body, beginning at the right atrium.
5. Define blood pressure. Identify and discuss the two reading measurements.

**APPLY your understanding**

6. Imagine you are a red blood cell. Describe your path around the body, making sure to include anything that you may do along the way.
7. **Practical activity: blood pressure readings**
   (a) In pairs or groups of three, with one sphygmomanometer or digital blood-pressure reader per group, measure each other’s heart rate and systolic and diastolic blood pressure when:
      - lying down
      - standing
      - sitting
      - riding an exercise bike.
   (b) Explain the differences in your blood pressure readings under the four conditions.
   (c) Compare and explain the similarities between the heart rate and blood pressure readings.
   (d) Did these results match what should have happened?
6.3 Role of the cardiovascular system in thermoregulation

**KEY CONCEPT** The cardiovascular system plays an important role in balancing heat gain or heat loss through the redirection of blood flow to dissipate or conserve heat for optimal functioning of the body.

**Thermoregulation** is the maintenance of core body temperature with a narrow range.

**Homeostasis** is a constant internal environment for optimal functioning of the body and its systems.

**Vasodilation** is a process whereby blood vessels increase their diameter causing an increase in blood flow.

**Vasoconstriction** is a process whereby blood vessels narrow or constrict causing a decrease in blood flow.

**Thermoregulation** relates to the maintenance of body temperature and the heat exchange that occurs between the body and the environment. Core temperature has a narrow range (36.5–37.5 °C) and any alterations can have an impact on the functioning of the individual.

Core temperature increases in response to exercise due to increased blood flow around the body, muscle use and energy production, as well as the environmental conditions that an individual may exercise in, such as heat and humidity.

The body has a number of mechanisms to address changes in body temperature such as heat loss, heat gain or the need for heat balance. The cardiovascular system plays an important role in thermoregulation and maintaining **homeostasis** of the body; that is, maintaining a constant internal environment for the optimal functioning of the body and its systems.

Optimal functioning of the body occurs when body temperature is approximately 37 °C. Body temperature is monitored by the brain, specifically the hypothalamus, and the mechanisms to control it include:

- sweating
- shivering
- controlling blood flow to the skin and around the body.

It is in this last mechanism that the cardiovascular system plays the greatest role.

When the body is too hot and there is need for heat loss, the cardiovascular system will automatically direct more blood flow through the vessels to the skin surface in an attempt to cool the body via increased sweating and heat loss to the external environment. The blood vessels expand or dilate to allow this increased blood flow and this process is known as **vasodilation**.

When the body is too cold and there is need for heat retention, the cardiovascular system will restrict blood flow to the skin and redirect it to the internal organs, decreasing heat loss. The blood vessels reduce in size or contract and this process is known as **vasoconstriction**.

**Figure 6.14** Thermoregulation is important in different environmental conditions to keep the body at its optimal functioning.
Thermoregulation is essential to maintain optimal body temperature. During exercise, both vasodilation and vasoconstriction can reduce blood flow to working muscles, either through redirection of blood to the skin for heat loss or internal organs to maintain heat, and ultimately impact on the energy production of the athlete. This often results in the athlete being unable to perform at their desired level, or at all, in order to maintain the homeostasis of the body.

Hyperthermia and exercise in the heat

During exercise, energy expended during muscular contraction results in heat production, which in turn brings about an increase in both muscle and core body temperature. Although an increased temperature of the skeletal muscles enhances the ability of the muscles to contract, performance becomes markedly impaired when the body's core temperature rises significantly. A rise in core temperature greater than 37.5–38.3 degrees is referred to as hyperthermia.

When the body's core temperature begins to rise, the body's thermoregulation mechanisms, such as sweat production, operate to ensure that any increase remains within a safe range. This is essential since core temperature rises of more than about three degrees Celsius can result in the impairment of bodily and mental functions, and the development of heat stroke, which can be fatal.

Exercising in the heat imposes additional stress on the body's thermoregulation mechanisms, and the cardiovascular system must work harder to maintain homeostasis to stop core temperature rising towards critical levels.

The cardiovascular system assists in the removal of body heat via redirection of blood flow and increased sweating rates. There is an increase in blood flow to the skin (vasodilation) in an attempt to increase the rate of the body cooling through the evaporation of sweat from the surface of the skin.

The redirection of blood flow and increased sweating can lead to impaired performance, as less blood flows to the working muscles than would normally in cooler conditions. Fluid loss through sweating causes a decrease in blood plasma volumes, so it is important that the athlete drinks plenty of water to help counteract this.

**FIGURE 6.15** Cooling the body while exercising in the heat is important to limit the effects of hyperthermia.
**Hypothermia and exercise in the cold**

**Hypothermia** is a thermal risk associated with exercising in cold environmental conditions. It occurs when the body’s core temperature falls below 35 degrees Celsius. The body will respond to heat loss via shivering and the redirection of blood flow in order to generate heat and maintain core temperature.

The cardiovascular system attempts to reduce this heat loss by redirecting blood flow away from the extremities and towards the major organs in order to sustain their function. The vasoconstriction of the blood vessels close to the skin assists in reducing the heat lost to the external environment.

Once again, performance in physical activity will be impaired as blood flow to working muscles will also be reduced in an attempt to maintain homeostasis.

![Thermoregulation mechanisms to control body temperature](image)

**Figure 6.17** Thermoregulation mechanisms to control body temperature

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**TEST your understanding**

1. Explain the relationship between thermoregulation and homeostasis.
2. Discuss the role of vasodilation and vasoconstriction in thermoregulation.
3. Outline the differences between hyperthermia and hypothermia.

**APPLY your understanding**

4. Participating in physical activity on a hot day can stress the body. Discuss the role of the cardiovascular system in the removal of heat from the body.
KEY CONCEPT Under exercise conditions, certain changes occur to the cardiovascular system to allow the body to meet the new demands placed on it. These responses last only for the duration of the training or exercise session and a short time afterwards (recovery).

The cardiovascular system and physical activity

When you begin to exercise, a number of changes occur within the cardiovascular system to meet the requirements of the body. These immediate, short-term responses are commonly called acute responses to exercise. They revolve around the greater demand for and more efficient delivery of oxygen and fuels to the working muscles to create energy and remove waste products.

Increased heart rate (HR)
- During exercise, HR quickly increases above resting levels to assist with the greater requirements of the muscles for oxygen to create energy and the associated removal of wastes.
- Generally, HR increases linearly with exercise intensity (figures 6.18 and 6.19). That is, as exercise intensity increases, so too does HR.
- Average resting HR is approximately 72 bpm, reaching up to and beyond 200 bpm during maximal exercise.
- HR will return to resting levels once physical activity is ceased.
- An approximate calculation of your maximum HR is 220 minus your age. For example, maximum HR for an 18-year-old is:
  \[ 220 - \text{age} = \text{maximum HR} \]
  \[ 220 - 18 = 202 \text{ advisable maximum HR} \]

![Figure 6.18 Heart rate responses before, during and after exercise for a trained athlete and an untrained athlete](image)

Increased stroke volume (SV)
- The amount of blood pumped from the heart into the arterial system with each contraction of the left ventricle (stroke volume) increases to allow more oxygen to be delivered to the working muscles to create energy.
- Like heart rate, stroke volume increases with exercise intensity, but only to a certain point. The shorter filling time of the ventricles when the heart is beating...
The human body in motion rapidly means the stroke volume will plateau at approximately 40–60 per cent of an individual's maximal exercise capacity and remain unchanged until exhaustion (figure 6.19).

- Stroke volume for the average adult female and male at rest may be about 60 mL/beat and 80 mL/beat, respectively. These values can increase to 110–130 mL/beat during maximal exercise. For a trained athlete, these values will be higher.

<table>
<thead>
<tr>
<th>Exercise intensity</th>
<th>Stroke volume (millilitres per beat)</th>
<th>Heart rate (beats per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Moderate</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Maximum</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Figure 6.19 Heart rate and stroke volume responses to exercise**

**Increased cardiac output ($Q$)**

- The amount of blood pumped from the heart into the arterial system over 1 minute (cardiac output, $Q$) increases due to the increase in both heart rate and stroke volume to deliver more blood and oxygen to the working muscles ($Q = HR \times SV$). This is shown in table 6.4.
- Like heart rate and stroke volume, cardiac output increases proportionally with exercise intensity.
- At rest, cardiac output for the average adult male is approximately 5–6 litres per minute (L/min). It may rise to about 20 L/min for an untrained male during maximal exercise. Figures for females are slightly lower for a number of physiological reasons, about 15 L/min for an untrained female during exercise.

**Integrated cardiac response to exercise**

As previously discussed, cardiac output is directly affected by the responses of heart rate and stroke volume to the increased demand for oxygen and fuel to working muscles for energy production.

$$Q = HR \times SV$$

The contribution of all three varies as an individual transitions from rest to exercise of increasing intensities.

At rest, the average heart rate is 70 beats per minute and stroke volume is approximately 70 millilitres per beat. This gives a cardiac output ($Q = HR \times SV$) of roughly 5 litres per minute.

$$70 \text{ bpm} \times 70 \text{ mL/beat} = 4.9 \text{ L/min}$$

As the individual transitions from rest to exercise, both heart rate and stroke volume will increase to increase the cardiac output of the heart and meet the new energy demands required by the body. Depending on the intensity required, the contributions will vary.
During submaximal exercise, such as moderate-paced jogging, heart rate will increase until it meets the demands of the body, plateauing when it reaches **steady state**. Steady state occurs during submaximal activity where the oxygen demands of the body are being met by the supply of the cardiorespiratory system. Heart rate may increase to approximately 140 bpm, with stroke volume peaking at about 120 mL/beat, giving a cardiac output of approximately 16–17 litres per minute.

\[ 140 \text{ bpm} \times 120 \text{ mL/beat} = 16.8 \text{ L/min} \]

As exercise intensity continues to increase beyond steady state, such as fast-paced running, heart rate will also increase linearly until it reaches maximum heart rate of values near 200 beats per minute. This in turn will increase the cardiac output of an individual.

At high to maximal intensities, any increase in cardiac output is due to this increase in heart rate, not stroke volume. Stroke volume tends to plateau when exercise intensity reaches around 40–60 per cent of the individual’s maximal exercise capacity.

\[ 200 \text{ bpm} \times 120 \text{ mL/beat} = 24 \text{ L/min} \]

**TABLE 6.4** Heart rate and stroke volume responses to various exercise intensities

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Heart rate (beats per minute)</th>
<th>Stroke volume (millilitres per beat)</th>
<th>Cardiac output (litres/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>70</td>
<td>70</td>
<td>4.9</td>
</tr>
<tr>
<td>Submaximal</td>
<td>140</td>
<td>120</td>
<td>16.8</td>
</tr>
<tr>
<td>Maximal</td>
<td>200</td>
<td>120</td>
<td>24</td>
</tr>
</tbody>
</table>

**Increased systolic blood pressure (BP)**
- Average BP at rest is \( \frac{120}{80} \) mm Hg.
- During exercise, the systolic reading usually rises. This is due to increases in heart rate, stroke volume and cardiac output, and the fact that blood is being pumped more forcefully into the arteries.
- Under maximal intensity, systolic BP can reach around 200 mm Hg.
- The diastolic reading remains largely unchanged.

**Increased blood flow and blood vessel diameter**
- Speed of blood flow increases due to the increases in heart rate, stroke volume and cardiac output.
- Blood vessels will increase their diameter to accommodate the increase in blood flow (vasodilation). As depicted in figure 6.10 on page 132, one-way valves in veins work to accommodate the increased blood flow’s return to the heart.

**Blood flow redistribution**
- During exercise, blood flow is redistributed to the working muscles and away from those areas of the body that are less needed for the activity, such as the gut and kidneys (figure 6.20).
- At rest, blood flow to the muscles is approximately 15 to 20 per cent, or 1.5 L/min.
- As the intensity of physical activity and the demand for oxygen increase, blood flow to the muscles increases to 80 to 90 per cent, or about 10 L/min. This is achieved by the capillaries supplying the working muscles expanding in diameter (vasodilation) and blood flow to the organs is reduced by the narrowing (vasoconstriction) of the capillaries that supply them with blood.
- Removal of heat is also a reason for the redistribution of blood flow from the internal organs to the extremities (skin) shown in figure 6.20.
**Decayed blood volume**

During exercise, blood volumes decrease due to the decrease in blood plasma levels. This is caused by the loss of fluid through the thermoregulatory processes of sweat and evaporation, as well as the removal of metabolic by-products associated with energy production. The size of the decrease depends on the intensity and duration of the exercise, the hydration level of the individual and environment conditions, such as temperature and humidity.

**Increased arteriovenous oxygen difference (a-VO\(_2\) diff.)**

- The **arteriovenous oxygen difference (a-VO\(_2\) diff.)** is a comparison of the amount of oxygen in the arteries with the amount of oxygen in the veins.
- It is measured in millilitres per 100 millilitres of blood.
- At rest, the arteries have an oxygen concentration of about 20 mL/100 mL of blood and veins about 13 mL/100 mL, a difference of 7 mL/100 mL.
- During exercise, the working muscles demand more oxygen for energy production, so the arterial blood will have more oxygen extracted by the working muscles than when they are at rest.
- The arterial blood entering the working muscle area during exercise will still have an oxygen concentration of 20 mL/100 mL, but the venous blood leaving the working muscles will have been drained of more oxygen and may have an oxygen concentration of about 5 mL/100 mL.
- Under exercise conditions, the a-VO\(_2\) diff. could therefore be 15 mL/100 mL (figure 6.21).

---

**Oxygen concentration in blood (mL/100 mL)**

<table>
<thead>
<tr>
<th></th>
<th>At rest</th>
<th>During exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>In arteries</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>In veins</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>a-VO(_2) diff.</td>
<td>7</td>
<td>15</td>
</tr>
</tbody>
</table>

**Figure 6.21** The arteriovenous oxygen difference during exercise
TEST your understanding

1 Define acute response to exercise.
2 Complete the table below by indicating whether the physiological parameter has increased, decreased or remained unchanged as a result of participating in exercise. Include the measurement values for rest and exercise.

<table>
<thead>
<tr>
<th>Physiological parameter</th>
<th>Acute response</th>
<th>Measurement at rest</th>
<th>Measurement during submaximal exercise</th>
<th>Measurement during maximal exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood flow and redistribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arteriovenous difference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

APPLY your understanding

3 Explain the relationship between the following factors and how they are affected by physical activity:
   - heart rate
   - stroke volume
   - cardiac output.
4 Outline the changes in blood flow that occur as a result of participating in physical activity.
5 Discuss the changes in the arteriovenous oxygen difference between rest and exercise. Explain why this occurs.
6 Practical activity: acute responses of the cardiovascular system to exercise
   Participate in two different activities for approximately 20 minutes each (e.g. basketball and aerobics class).
   For each activity, follow this procedure:
   Step 1 Record your resting heart rate prior to beginning the activity (manually or via a heart rate monitor).
   Step 2 Record your heart rate at the following intervals in each activity: 5 minutes, 10 minutes, 15 minutes, the end of the activity.
   Step 3 At the completion of the activity, sit quietly and record your heart rate at the following intervals after completion: 1 minute, 3 minutes, 5 minutes.
   Step 4 Record and graph your results. Answer the following questions:
      (a) At which stage did your heart rate rise the most? Suggest reasons for this.
      (b) At which stage did your heart rate rise the least? Suggest reasons for this.
      (c) Explain why heart rate increases as exercise begins.
      (d) Describe the relationship between heart rate and intensity of activity.
      (e) Outline other acute responses of the cardiovascular system that would have occurred during this activity.
KEY SKILLS

- Use and apply correct anatomical terminology to identify the structures and function of the cardiovascular and respiratory systems
- Describe the role and function of the blood components
- Examine the role of the cardiovascular system in thermoregulation
- Analyse the relationship between stroke volume, heart rate and cardiac output at rest and during submaximal and maximal exercise
- Perform, measure and report on changes to the cardiovascular and respiratory systems at rest compared with exercise

UNDERSTANDING THE KEY SKILLS

To address these key skills, it is important to remember the following:

- correct anatomical names for the structures of the cardiorespiratory system
- understand the functions of all structures in the cardiovascular system including the heart, blood vessels and components of blood
- understand the concepts of thermoregulation, homeostasis, hyperthermia and hypothermia and the role of the cardiovascular system in maintaining these
- heart rate, stroke volume and cardiac output are interrelated and their contribution to exercise is dependent of the intensity of exercise.

PRACTICE QUESTION

(adapted from ACHPER Unit 1 Exam 2011, question 2)

The graph below shows the blood flow to the major organs and skeletal muscles during submaximal exercise.

HOW THE MARKS ARE AWARDED

a. **1 mark** — correct definition of cardiac output
b. **1 mark** — identifying A as the line that represents blood flow to working muscles
   - **1 mark** for linking Line A to the information on the graph, increase in time and increase in blood flow required by muscles during exercise
   - **1 mark** each for naming and describing the physiological adaptations of vasoconstriction and vasodilation and how they contribute to the redistribution of blood flow.

Sample response

a. **Cardiac output** is the amount of blood pumped around the body per minute (L/min).

b. **Line A.** As exercise time increases, there is an increased need for blood carrying oxygen at the muscles.

c. **Vasoconstriction**, decrease in blood vessel diameter therefore decreased blood flow to the major organs, and **vasodilation**, increase in blood vessel diameter therefore increased blood flow to the skeletal muscles.
PRACTISE THE KEY SKILLS
1. Explain the role of the following physiological parameters in ensuring oxygen delivery to working muscles during exercise or physical activity.
   a. Heart rate
   b. Stroke volume
2. Describe the function of each of the four components of blood.
3. Explain how the cardiovascular system assists in thermoregulation.

KEY SKILLS EXAM PRACTICE
(ACHPER Trial Exam 2015, question 7)
1. a. Describe systemic circulation, beginning at the left atrium. Include references to structures of the heart and blood vessels. 6 marks
   b. Other than valves, outline another mechanism that assists in the return of venous blood back to the heart. 2 marks

CHAPTER REVIEW

CHAPTER SUMMARY

Cardiovascular system
- The cardiovascular system has five main functions:
  - to circulate blood
  - to transport water, oxygen and nutrients
  - to transport wastes
  - to help maintain body temperature
  - to help fight disease.
- The heart is an involuntary muscle that pumps blood throughout the cardiovascular system. It has four chambers, two atria and two ventricles, a septum that divides the heart into two pumps, and valves at the entrances of structures to allow only a one-way flow of blood.
- The heart works via contraction and relaxation of the atria and ventricles. This is known as the cardiac cycle.
- The three types of blood vessels are arteries, capillaries and veins.
  - Arteries carry blood away from the heart.
  - Capillaries are the site of exchange of gases between the cells and the cardiovascular system.
  - Veins return blood to the heart.
- Blood is made up of blood cells and plasma. There are also three types of blood cell:
  - red blood cells
  - white blood cells
  - platelets.
- Blood circulation occurs via two main circuits:
  - the systemic circuit (the body)
  - the pulmonary circuit (the lungs).
- Blood pressure has two measurements:
  - systolic
  - diastolic.
- Thermoregulation is the maintenance of body temperature and heat exchange that occurs between the body and the environment.
- The cardiovascular system assists thermoregulation through the redirection of blood flow via the expanding of blood vessels (vasodilation) to increase heat loss or the reduction in size of blood vessels (vasoconstriction) to reduce heat loss.
- If thermoregulation is impaired, the individual risks developing:
  - hyperthermia where heat gain is greater than heat loss and the body’s core temperature rises above 37.5 degrees Celsius
  - hypothermia where heat loss is greater than the heat that can be produced and core temperature falls below 35 degrees Celsius.
- There is a direct relationship between heart rate, stroke volume and cardiac output in response to increased demands to produce energy during exercise across a range of varying intensities.
- The cardiovascular system adapts to the onset of exercise via increases in heart rate, stroke volume, cardiac output, systolic blood pressure, arteriovenous difference (a-VO₂ diff.), blood flow and redistribution of blood flow.

CHAPTER 6 • Structure and functions of the cardiovascular system 147
MULTIPLE CHOICE QUESTIONS

1. The heart is divided into four chambers called atria and ventricles. Atria are the (A) upper chambers that eject the blood from the heart. (B) upper chambers that receive the blood into the heart. (C) lower chambers that eject the blood from the heart. (D) lower chambers that receive the blood into the heart.

2. One-way valves allow blood flow to travel from the (A) aorta to the ventricles. (B) atria to the aorta. (C) atria to the ventricles. (D) aorta to the atria.

3. Arteries carry blood (A) away from the heart. (B) to the heart. (C) away from the capillaries. (D) to the veins.

4. Deoxygenated blood travels via which structure of the heart to the lungs to be oxygenated? (A) Vena cava (B) Pulmonary vein (C) Aorta (D) Pulmonary artery

5. The function of the red blood cells is to (A) fight infection. (B) clot the blood. (C) carrying oxygen to the working muscles. (D) carry the blood cells around the body.

6. The main role of the cardiovascular system in thermoregulation is (A) increasing the volume of blood. (B) warming the muscles. (C) reducing heart rate. (D) redirection of blood flow.

7. Exercising in the heat requires the body to work harder to keep the core temperature within a safe zone. Individuals are at risk of developing which condition when heat production exceeds heat loss? (A) Hypothermia (B) Hyperthermia (C) Homeostasis (D) Hypothalamus

8. Blood vessels increase in diameter to accommodate increased blood flow during exercise. This is known as (A) vasodilation. (B) vasoconstriction. (C) vasovagal. (D) valsalva.

9. To facilitate the removal of heat, the body redistributes blood flow (A) from the heart to the lungs. (B) from the vital organs to the skin. (C) from the skin to the muscles. (D) from the vital organs to the head.

10. At high intensities, any increase in cardiac output is due to the linear increase in (A) heart rate. (B) stroke volume. (C) heart rate and stroke volume. (D) blood pressure.
EXAM QUESTIONS

Question 1  (ACHPER Trial Exam 2013, question 4a)
When comparing arteries to veins, the following differences can be observed.
Use the table to fill in the relevant statements. The first one has been completed for you.

<table>
<thead>
<tr>
<th>Arteries:</th>
<th>Parameter</th>
<th>Veins:</th>
</tr>
</thead>
<tbody>
<tr>
<td>is oxygenated</td>
<td>Blood (is oxygenated/is de-oxygenated)</td>
<td>is de-oxygenated</td>
</tr>
<tr>
<td></td>
<td>Transports blood (away from heart/towards the heart)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valves (have them/don’t have them)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wall thickness (are thicker/are thinner)</td>
<td></td>
</tr>
</tbody>
</table>

3 marks

Question 2  (ACHPER Trial exam 2013, question 3)
During an ironman event, an athlete’s body temperature will increase significantly.
Explain how the cardiovascular system assists in maintaining body temperature during exercise, such as an ironman competition.

2 marks

Question 3
Outline the relationship between heart rate, stroke volume and cardiac output, and explain how they respond to increases in exercise intensity from submaximal to maximal exercise.

2 marks

Question 4  (ACHPER Trial Exam 2014, question 1e)
Explain the relationship between the cardiovascular and respiratory systems in response to exercise.

3 marks