Chapter 3 Biological measurement

3.1 Nerve conduction

Learning objectives:

- What is in a nerve fibre?
- How does a nerve fibre transmit an electrical impulse?
- What do we mean by action potential?

Nerve cells

Nerve cells transmit electrical impulses directly, or via other nerve cells, to the muscles or to/from the brain. These impulses may originate in sensory cells in the body or in the brain or in the case of the heart in a small region called the **sino-atrial (SA) node**. Nerve cells transmit electrical impulses to one another or to 'effector' cells in the muscles or brain via gaps called **synapses**. These gaps are of the order of nanometres in width and ensure the impulses pass in one direction only (from the end of the axon to the next cell).

Figure 1 shows the structure of a nerve cell which transmits electrical impulses to muscle fibres.

Dendrites are branches of the main part of the nerve cell. They receive electrical impulses from other nerve cells. The main part of the nerve cell contains its **nucleus**.

The **axon** of the nerve cell is the nerve fibre which transmits electrical impulses to effector cells in the muscle fibres to make the fibres contract. An axon from the spine to the foot may be several micrometres in width and more than a metre in length. The axon is insulated from the surrounding tissue by a sheath of **myelin** which has gaps at intervals of about a millimetre. The gaps, referred to as **nodes of Ranvier**, boost the speed of the nerve impulses, making each impulse jump from gap to gap.

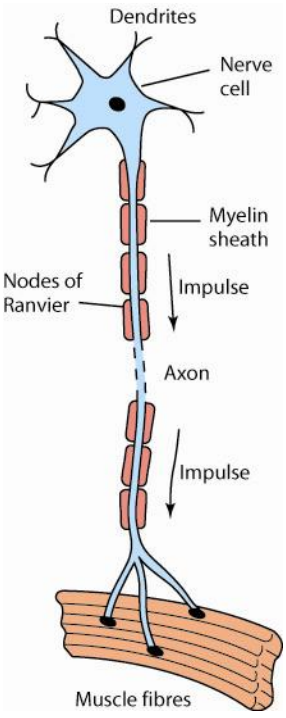

Figure 1 *A nerve cell*

Biopotentials

The **resting potential** of a nerve cell including the axon is about −70 mV relative to the exterior. There is a potential difference between the interior and exterior of the cell because the cell wall is a semi-permeable membrane. When the cell is in a resting state, the cell membrane keeps sodium ions outside the cell so the interior is negative relative to the exterior. The cell membrane is then said to be **polarised**.

When the cell receives an electrical impulse, the section of the cell membrane where the impulse is received becomes more permeable to sodium ions (Na^+) which then move through the cell membrane into the cell. The result is that the cell potential near that section of the membrane depolarises (i.e. its potential increases to zero) and reverse polarisation occurs until the cell

potential reaches +30 mV, as show in Figure 2. The potential of +30 mV reached due to reverse polarisation is referred to as the **action potential**.

At the action potential, the cell membrane now becomes permeable to potassium ions (K^+) which flow out through the cell wall, causing the cell to repolarise until the interior near that section of membrane is again at negative potential of −70 mV.

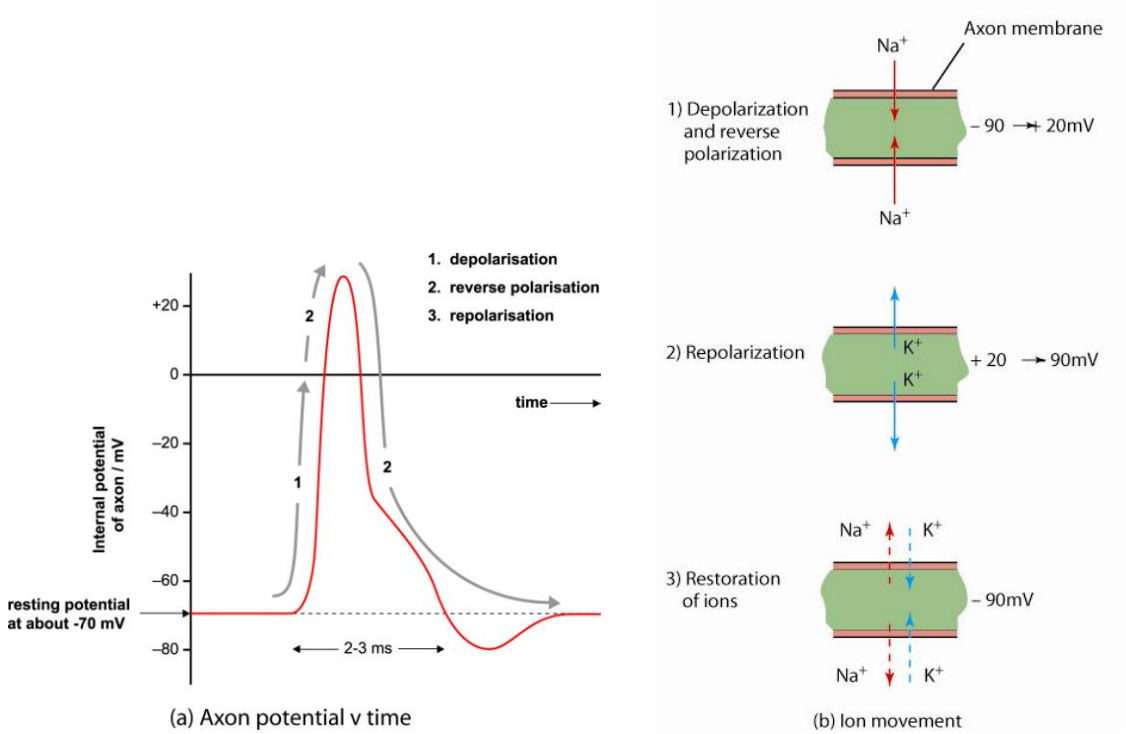

Figure 2 *The action potential of a nerve cell*

The whole process in which the potential changes from −70 mV to +30 mV and back to −70 mV takes no more than about 5 milliseconds and stimulates the adjacent parts of the membrane. The balance of sodium and potassium ions is gradually restored to the state at the resting potential in the next 50 milliseconds or so, preventing the stimulus from backfiring and ensuring that this section of the membrane can receive and transmit the next impulse. The electrical impulse moves away from where it was received and is transmitted across the main part of the cell, along the axon and on to the synapse at the end of the axon.

The speed of transmission of an electrical impulse along the axon is increased by the presence of the nodes of Ranvier in the myelin sheath surrounding the axon. This is because the switch from negative to positive potential at a node stimulates the membrane at the next node immediately. Transmission speeds range from less than 1 m s^{-1} to more than 100 m s^{-1} depending on the type of nerve.

Application

Ion channels

The membrane of a cell contains certain protein molecules which form channels in the cell membrane which sodium ions or potassium ions can pass through. Whether or not a sodium ion or a potassium ion can pass through a channel depends on the electrical potential difference between the interior and exterior of the membrane on the type of molecule.

Summary questions

$e = 1.6 \times 10^{-19}$ C

1 Explain why the potential at a point on a cell membrane changes from −70 mV to +30 mV when an electrical impulse is applied to the cell membrane.

2 When a certain type of cell membrane is stimulated electrically, sodium ions (Na^+) pass through it at a rate of 2.5×10^{16} ions per second per square metre. Calculate the current due to this flow of ions through a section of membrane of area 1.0×10^{-12} m^2.

3 **a** Sketch a graph to show how the potential of a cell membrane changes when an electrical impulse is applied to it. Indicate the resting potential and the action potential on your graph.

b Show on your graph the sequence of depolarisation, reverse polarisation and repolarisation.

4 **a** Explain the purpose of the myelin sheath surrounding the axon of a nerve cell.

b What are the nodes of Ranvier in the myelin sheath and what is their function?

3.2 ECG signals

Learning objectives:

- What makes the heart beat?
- What is an ECG trace?
- How can we measure an ECG trace and what does it tell us about the heart?

Basic structure of the heart

The human heart beats at a normal rate of about 70 times per minute without stopping, from birth to death. It pumps approximately five litres of blood round the body every minute, using energy at a rate of just a few watts.

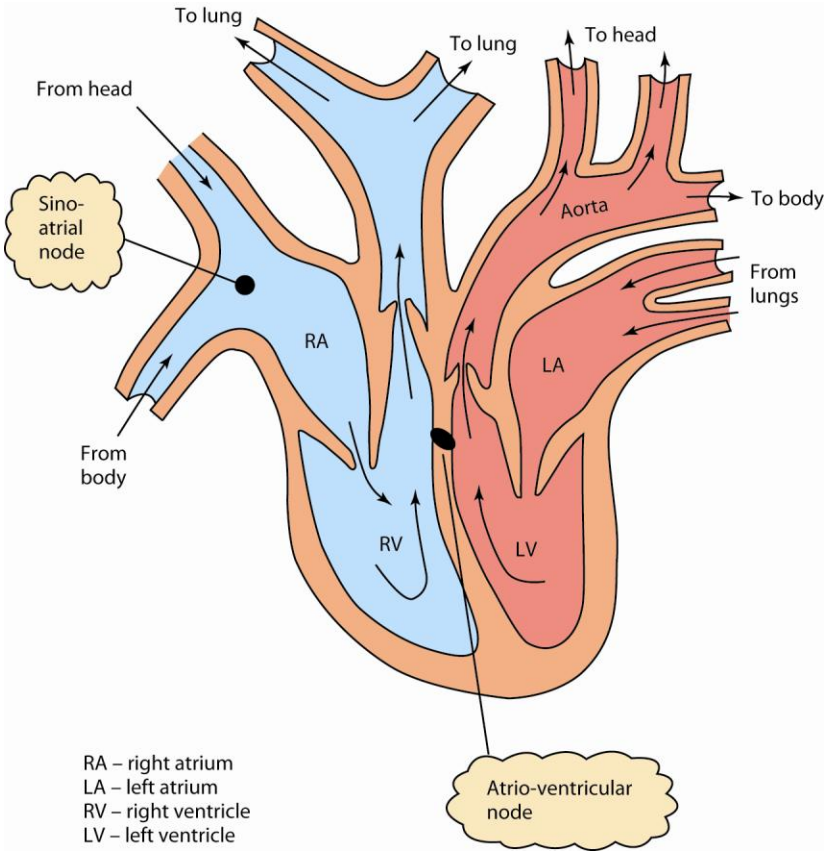

Figure 1 *Inside the heart*

Figure 1 shows a cross-section of the human heart. In effect, the heart is a double pump. It drives blood from the right ventricle to the lungs then back from the lungs into the left atrium then into the left ventricle then out to the rest of the body and then back the right atrium.

Each time the heart beats, its electrical potential changes by more than 100 mV as the muscles of the heart contract and relax in a sequence that forces blood from the two atrial chambers of the heart into the corresponding ventricles and then out to the arteries. This sequence is due to nerve cells that conduct electrical signals generated at the sino-atrial (SA) node in the right atrium. These nerve cells extend from the SA node across the surface of the heart, making the muscles of

the atrial chambers contract and stimulating the **atrio-ventricular (AV) node**. This relays the electrical signals to further nerve cells which make the ventricles contract. Valves ensure the blood passes one way only through the heart from each atrial chamber, as shown in Figure 1.

Figure 2 shows how the potential of the heart changes each time the heart beats. An electrical impulse from the SA node depolarises then repolarises the nerves of the atria, making the atria muscles contract then relax. The impulse reaches the AV node which, after a delay, then stimulates the nerves of the ventricles, making the muscles of the ventricles relax.

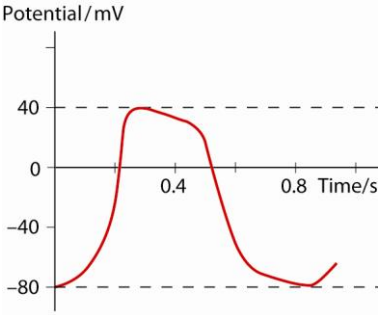

Figure 2 *The variation of heart potential during a heart beat*

Electrocardiograms

The change of electrical potential of the heart is conducted through body fluids and tissue to the skin, causing changes of potential of the order of 1 mV which can be detected by electrodes connected to an amplifier. An electrocardiograph (ECG) is designed to measure and record the potential difference between two points on the surface of the body. An ECG trace provides important information about the condition of the heart.

The pd between any two points on the body's surface is due to:

- the conductivity of the body fluids
- the position of the points on the body
- the action potential of the heart.

The electrodes are normally connected to two limbs with a third limb earthed.

A recording of the variation of such a pd with time is called an **electrocardiogram** or ECG trace. Figure 3 shows a typical ECG trace for a healthy person.

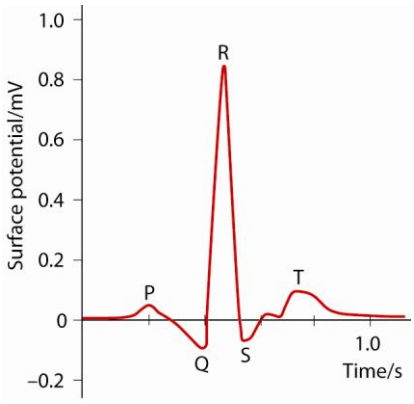

Figure 3 *An ECG trace of a healthy person*

The main features of the ECG trace shown in Figure 3 can be summarised as follows.

- The peak pd is about 1 millivolt and lasts about 0.1 s.
- The main features of the trace are labelled as **P**, **Q**, **R**, **S** and **T** according to convention.
- The wave at **P** is due to the atria depolarising and contracting.
- **QRS** is due to depolarisation and contraction of the ventricles; this masks the repolarisation and relaxation of the atria.
- The wave at **T** is caused by repolarisation and relaxation of the ventricles.

To measure and display an ECG waveform, the pd between two chosen points on the body surface must be amplified from about 1 mV to about 1 V to enable it to be displayed on an oscilloscope, a chart recorder or a computer VDU screen. Figure 4 represents the amplifier with leads from the patient to the amplifier's input terminals and a suitable instrument connected to the amplifier's output terminals.

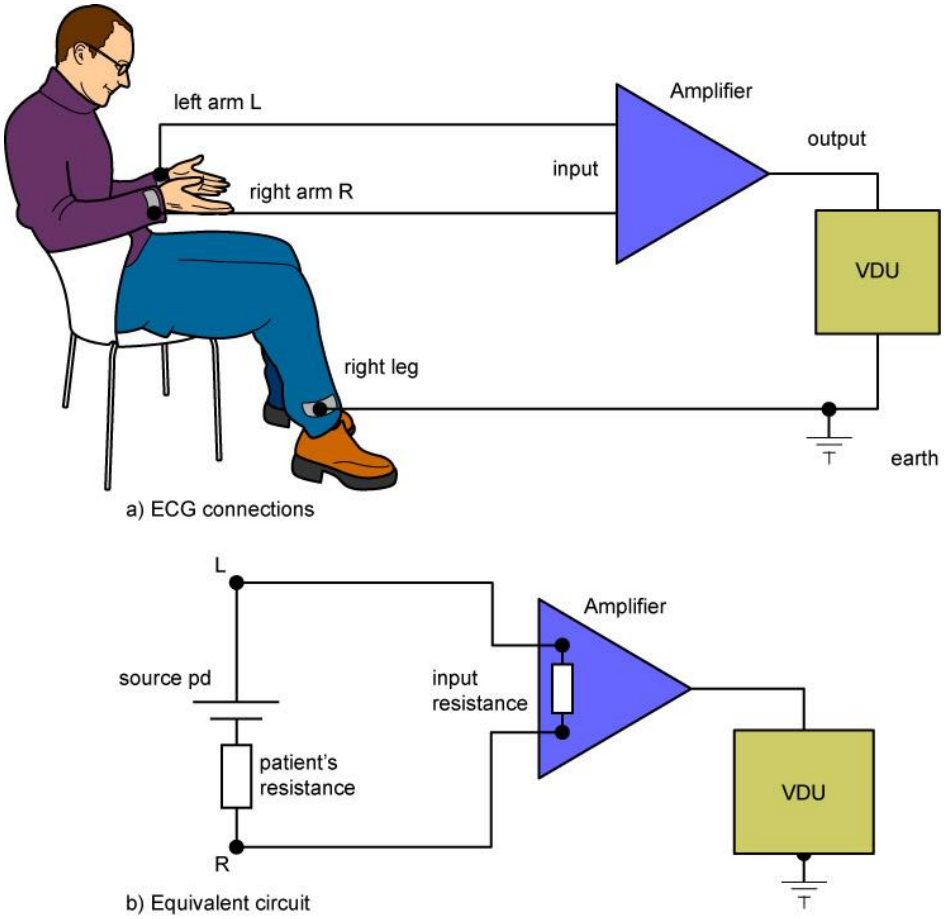

Figure 4 *Making an ECG trace*

The amplifier must have the following characteristics.

- Its **voltage gain** (i.e. the amplifier output pd ÷ the input pd to the amplifier) must be of the order of 1000 over a frequency range up to about 20 Hz. Beyond this frequency, unwanted signals due to muscle activity or from the mains supply must be filtered out.
- Its **frequency response** should be even across the frequency range otherwise the output voltage from the amplifier will be distorted.

- A **high input impedance** (i.e. opposition due to effects such as resistance, capacitance and back emf) is essential otherwise a significant fraction of the input pd will be lost due to body resistance and contact resistance where the electrodes are on the skin. Contact resistance is lowered as much as possible by using a conducting paste between the electrode surface and the skin. However, the remaining resistance due to body fluids can be as much as 1000 Ω. The input resistance of the amplifier and the patient's electrical resistance form a potential divider so the 'source' pd is split between the two resistances. If the input resistance is not much higher than the patient's resistance, the input pd to the amplifier will be significantly less than the source pd.
- The amplifier must have a high **signal-to-noise** ratio otherwise the output signal is masked by random electrical signals (i.e. noise) generated in the amplifier itself. The output pd of the amplifier is either displayed on an oscilloscope, a chart recorder or a computer screen.

Link

See *AS Physics A* Topic 5.5 for the potential divider.

Summary questions

1 a State the function of each of the following parts of the heart.

i The SA node

ii The AV node

b A human heart is supplied with energy at an average rate of 2.0 W. Estimate the energy supplied to it in one day.

2 a Draw a labelled diagram of an ECG trace obtained from a person with a healthy heart, showing how the pd varies with time during one heart beat.

b Label the main features P Q R S and T on your trace and describe how they relate to the changes in the heart that take place during one heart beat.

3 a Explain why it is essential for an ECG amplifier to have a high input impedance.

b An ECG amplifier is connected to a patient as shown in Figure 5.

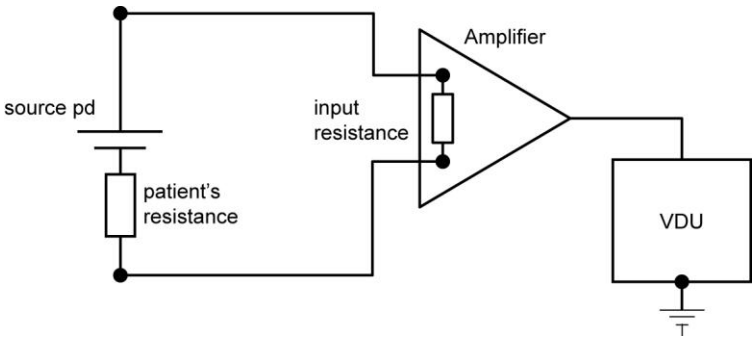

Figure 5

The amplifier has an effective input resistance of 70 kΩ. The total resistance of the patient in the ECG circuit is 20 kΩ and the pd across the input terminals of the amplifier has a maximum value of 0.70 mV.

Calculate:

i the maximum pd generated by the patient's heart at the electrodes connected to the patient

ii the maximum input pd if the patient's resistance was reduced to 1 kΩ.

4 State three essential characteristics of an ECG amplifier other than high input impedance, giving a reason why each characteristic is essential.