5

ELECTRICAL ACTIVITY

5.1 NERVE IMPULSES: ACTION POTENTIAL

Nerve cells (neurons) have long thin extensions known as **nerve fibres (axons)** along which **nerve impulses** are propagated at speeds of up to 100 m s^{-1}.

An axon consists of a central core surrounded by a membrane through which small ions (in particular Na^+ and K^+) can pass under certain circumstances. When the axon is at rest (i.e. when it is not conducting an impulse) the fluid inside it (**axoplasm**) contains large, negatively charged, organic ions (most of which are proteins) and a high concentration of K^+ ions; the fluid immediately outside it (body tissue fluid) has a high concentration of Na^+ ions (Fig. 5.1). There is an excess of positive charge on the outside – the membrane is said to be **polarized,** and there is a PD across it of about 70 mV. (It is customary to regard the outside of the membrane as having a potential of zero, in which case the potential inside, the so-called **membrane potential,** is −70 mV.)

This ionic imbalance is the result of an equilibrium between diffusion and a process called the **sodium–potassium pump**. The 'pump' moves Na^+ ions out of the axon and K^+ ions into it. Diffusion returns some of the K^+ ions to the outside (where their concentration is lower), but is unable to return Na^+ ions to the inside because the membrane is relatively impermeable to (the larger) Na^+ ions.

When the nerve cell is stimulated, the membrane suddenly becomes permeable to Na^+ ions and they are able to move into the axon as a result of both diffusion and the influence of the negative charges inside it. This increases the positive charge inside the axon and so increases the membrane potential, first to zero (known as **depolarization**) and then to +30 mV (**reverse polarization**) – see Fig. 5.2. Almost immediately, the membrane becomes impermeable to Na^+ ions and so traps them inside the axon. K^+ ions continue to diffuse out and quickly restore the positive potential outside the membrane (**repolarization**). This sequence of events, which takes only about 2 ms, is known as an **action potential**. A much slower process (lasting about 50 ms) returns the axon to its initial state, with K^+ ions on the inside and Na^+ on the outside, so that it is ready to respond to the next stimulus.

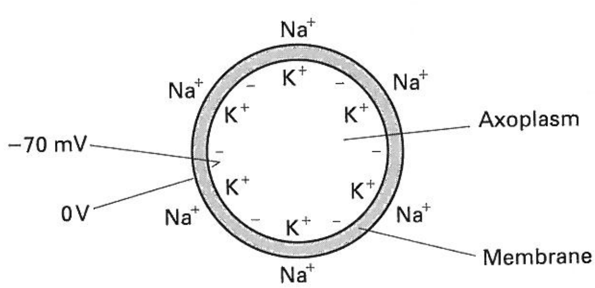


Fig. 5.1
Cross section of a resting (polarized) nerve fibre

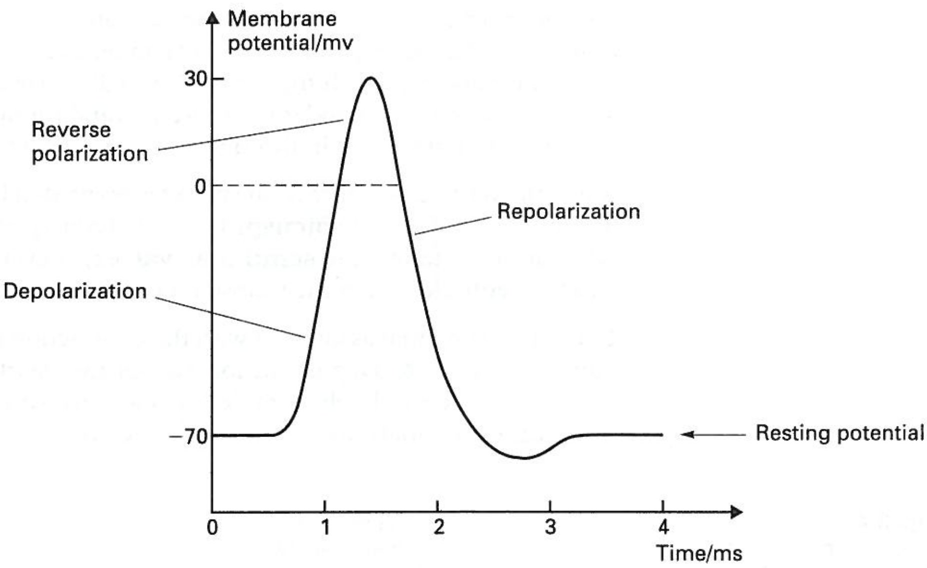


Fig. 5.2
Action potential of a nerve fibre

When part of the membrane becomes depolarized it triggers the (still polarized) part next to it to go through the same sequence of events as itself, (i.e. through the same action potential). This then triggers the next region, and so on so that the nerve impulse propagates along the fibre.

5.2 THE HEART

The heart (shown schematically in Fig. 5.3) is a double pump consisting of four chambers – the right and left **atria** (or **auricles**), and the right and left **ventricles**. The right-hand chambers take oxygen-depleted blood from the body and pass it to the lungs; the left-hand chambers take oxygen-rich blood from the lungs and pass it to the body.

The heart, like any muscle, contracts when subjected to an electrical stimulus. The stimuli which control the regular beating of the heart are produced by a specialized group of muscle cells located in the right atrium, and known as the **sinoatrial** (or **SA) node**. This generates a pulse, about 70 times a minute, which spreads out

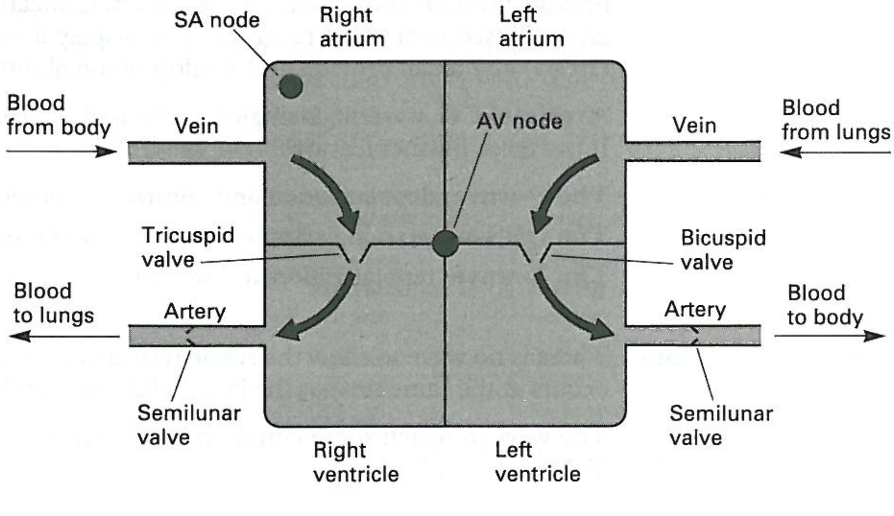


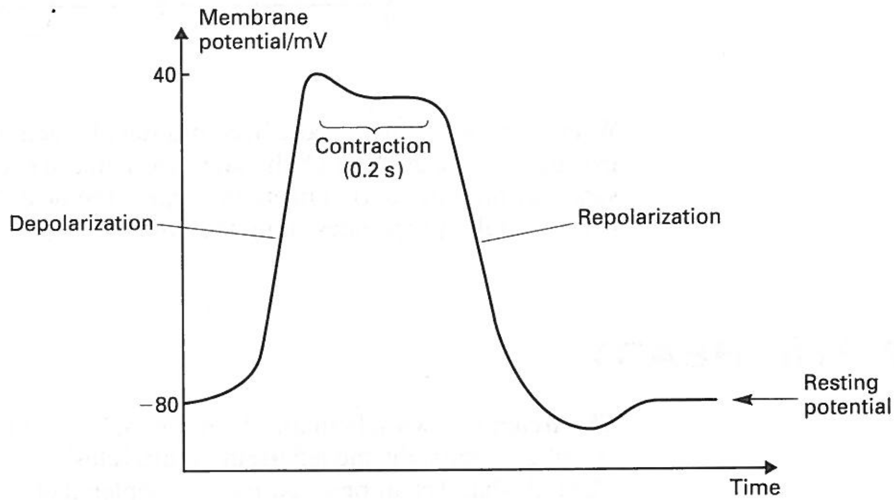
Fig. 5.3
The heart (schematic)

over both atria causing them to contract and force blood into their respective ventricles. The pulse passes to the **atrioventricular** (or **AV**) **node**, where it is delayed for about 0.1 s. It then spreads rapidly across the ventricles causing them to contract and force blood into the arteries and round the body. Finally, the heart relaxes and draws blood in through the veins so that the cycle can start again.

When the ventricles contract, the blood is prevented from returning to the atria by two one-way valves (the **bicuspid** and the **tricuspid**). A second pair of one-way valves in the arteries (the **semilunar valves**) prevents blood being sucked back into the ventricles when they subsequently relax.

The action potential associated with the contraction and relaxation of the heart is shown in Fig. 5.4. Depolarization causes the heart to contract; repolarization causes it to relax. Each complete cycle corresponds to one heartbeat. The membrane potentials, like those of nerve cells, are created by ionic imbalance.

Fig. 5.4
The action potential of the heart muscle



5.3 THE ELECTROCARDIOGRAM (ECG)

The PD which exists between polarized and depolarized heart cells can be detected at the surface of the body. The signals are much attenuated by their passage through body tissue and require amplification before being displayed on an oscilloscope or chart recorder. The display is called an **electrocardiogram** (**ECG**) and it can provide useful information about the condition of the heart.

A typical ECG, covering a single heartbeat of a normal heart, is shown in Fig. 5.5. It has three distinct features.

The P-wave: depolarization and contraction of the atria.

The QRS-wave: depolarization and contraction of the ventricles.

The T-wave: repolarization and relaxation of the ventricles.

Note There is no wave to show the repolarization of the atria because this occurs at the same time as the large QRS-wave and is masked by it.

The ways in which some common heart conditions affect the trace are listed in Table 5.1.

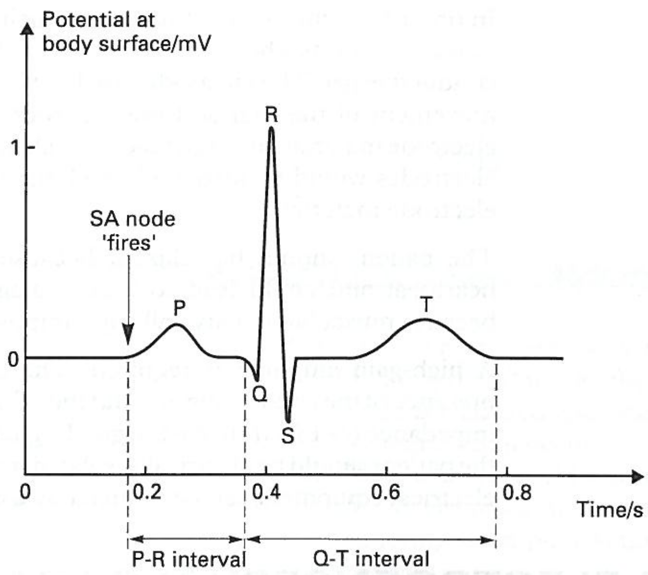


Fig. 5.5
ECG of a normal heart

Table 5.1
Some common heart disorders

Feature	*Possible cause*
Jagged trace	Ventricular fibrillation – rapid twitching of ventricles with very little actual pumping
Decreased QRS height	Reduced ventricular contraction
Decreased T height	Heart muscle lacks oxygen
Increased T height	Excess potassium in body
Increased Q–T interval	Heart attack
Increased P–R interval	Scarring of atria and/or AV node

5.4 OBTAINING THE ECG

The exact shape of the waveform depends on where the electrodes are placed. There are twelve standard arrangements, none of which involves the right leg because it is too far from the heart. In the so-called bipolar connections, any two of the other three limbs may be used (Table 5.2). Unipolar limb connections use three electrodes, two of which are held at zero potential and are connected to two different limbs. By attaching the third electrode to the remaining limb, it is possible to record the difference in potential between one limb and the average of the other two. The unipolar chest arrangement compares the potential at any one of six sites on the chest close to the heart with the average potential of the three limbs.

Table 5.2
Standard electrode arrangements

Arrangement	*First electrode*	*Neutral electrode(s)*	*Name*
Bipolar	Right arm	Left arm	Lead I
	Right arm	Left leg	Lead II
	Left arm	Left leg	Lead III
Unipolar limb	Right arm	Left arm, Left leg	aVR
	Left arm	Right arm, Left leg	aVL
	Left leg	Right arm, Left arm	aVF
Unipolar chest	One of 6 chest sites	Both arms, Left leg	V_1 to V_6

In order to reduce contact resistance, hairs and dead cells are removed from the skin at the points where the electrodes are attached, and the skin is smeared with a conductive gel. The electrodes are held in place with adhesive tape – any relative movement of the skin and the electrodes would produce a 'noisy' signal. The electrode material must not react with chemicals produced by the skin. If it did, the electrodes would polarize and block the signal. Silver is commonly used as the electrode material.

The patient should be relaxed, because any anxiety will be reflected in the heartbeat and could lead to a false diagnosis. Movement should be avoided because muscular activity will superimpose unwanted signals on the trace.

A high-gain amplifier is required. The contact resistance is high, despite the presence of the conducting gel, and therefore the amplifier should have a high input impedance ($>1\ \text{M}\Omega$) to ensure good signal transfer. For safety, the connections to the patient should be electrically isolated from the mains supply. Noise from nearby electrical equipment can be reduced by using a differential amplifier.

5.5 THE ELECTROENCEPHALOGRAM (EEG)

The action potentials of nerve cells in the brain give rise to electrical signals that can be detected at the surface of the skull – **brain waves**. They can be monitored by placing electrodes on the skull. The signals have only small amplitude ($\sim 50\ \mu\text{V}$) but after suitable amplification they can be displayed on an oscilloscope or chart recorder. The trace obtained is called an **electroencephalogram (EEG)**.

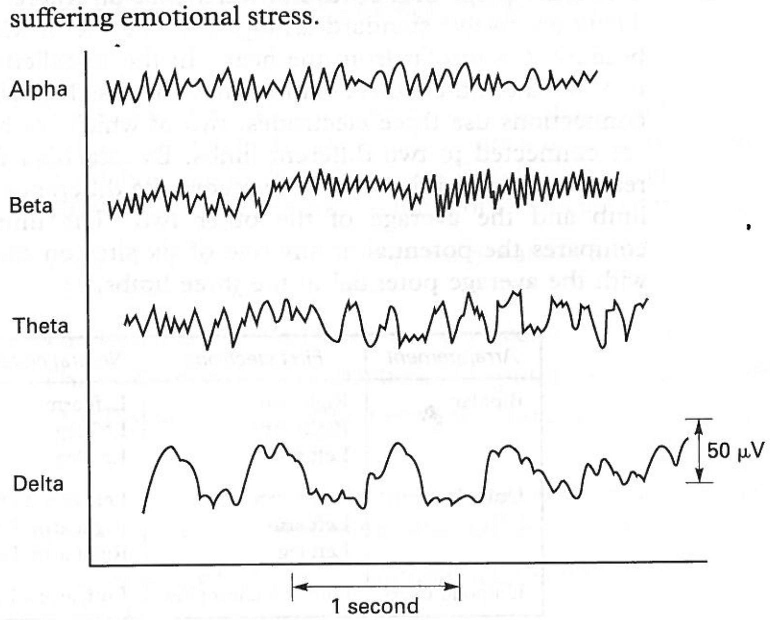
The waveform is not repetitive like that produced by the heart, and exhibits many variations in both frequency and amplitude. The brain of a normal person produces four distinct types of wave (Fig. 5.6).

Alpha waves (8–13 Hz) are produced when the mind is relaxed and the eyes are closed.

Beta waves (14–100 Hz) occur during mental activity.

Delta waves (0.5–3.5 Hz) occur during deep sleep.

Theta waves (4–7 Hz) are usually found in children. They also occur in adults suffering emotional stress.



EEGs have been used:

(i) In the diagnosis of brain disorders such as epilepsy.
(ii) In research on the nature of sleep.
(iii) To monitor the effects of anaesthesia during surgery.
(iv) To provide evidence of brain death.

QUESTIONS ON CHAPTER 5

1. Surface electrodes are attached to the right and left arms of a healthy young patient. The potential difference between the two electrodes is recorded continuously using an electrocardiograph.

(a) Sketch a graph of the observed potential difference as a function of time over one complete heart cycle.

(b) Label the axes and indicate the typical signal amplitude and time of one complete cycle.

(c) Why are the electrode surfaces which contact the skin covered with a gel containing a strong electrolyte before being attached to the patient?

(d) Explain why a differential amplifier is used in processing the signals from the two electrodes. [N, '93]

2. **(a)** Sketch a graph of the action potential as a function of time for a typical nerve axon, giving approximate scales on the axes. Air breaks down so that a current flows when the electric field strength is $2.5 \times 10^6\,\text{V m}^{-1}$. If a typical axon has a membrane thickness of 10 nm state, giving your reasoning, whether air or the membrane is the better insulator.

4.3×10^{-8} mol of sodium ions enter the core of an axon per square metre of membrane area during an action potential lasting one millisecond. Calculate the average electric current density associated with this ionic flow and the average electric current if the action potential involves a membrane area of $5.0 \times 10^{-12}\,\text{m}^2$.

Charge of an electron $= -1.6 \times 10^{-19}$ C
The Avogadro constant $= 6.0 \times 10^{23}\,\text{mol}^{-1}$

(b) Electrodes are placed on the surface of the body to record the cardiac waveform in a healthy person.

(i) Sketch a graph of potential difference between the electrodes as a function of time during a single beat of the heart, giving approximate scales on the axes.

(ii) Mark on the time axis the approximate points when the sino-atrial node is triggered and when ventricular stimulation occurs.

(iii) What change would you expect to find in the electrocardiogram of a patient suffering from poor ventricular contraction?

(iv) Why should the person under examination be as quiet and relaxed as possible? [N, '87]

3. **(a)** Sketch the waveform produced by an electrocardiograph from electrodes attached to the surface of the chest of a healthy human subject. Label the axes with appropriate values and mark the events in your waveform associated with the following features: ventricular depolarization, ventricular repolarization, atrial repolarization.

Explain

(i) the meaning of depolarization and repolarization,

(ii) the roles played by the atria and the ventricles.

(b) Two electrodes used to pick up the electrical signal from the chest are each of contact resistance R. They are connected to an amplifier between whose input terminals there is a resistance of $1.0\,\text{M}\Omega$. Calculate the value of R such that the voltage transferred to the amplifier input terminals is 75% of that appearing between the contact points on the skin.

Name **one** other desirable property of the amplifier apart from large voltage amplification and high input resistance.

(c) Explain the method used to ensure good electrical contact between the electrode and the skin.

Why must the subject be relaxed in order to obtain a good electrocardiograph recording? [N, '90]