

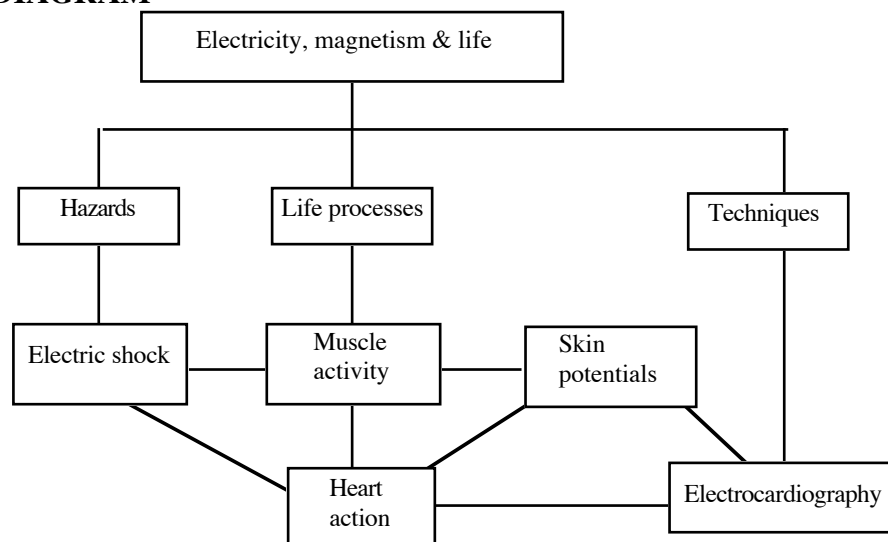
E8**APPLICATIONS****OBJECTIVES****Aims**

From this chapter you should gain a basic understanding of two important applications of electrical principles to the human body - the study of the function of the heart and electric shock. You should also develop an awareness of the principles of electrical safety and electrical wiring.

Minimum learning goals

When you have finished studying this chapter you should be able to do all of the following.

1. Explain, interpret and use the terms:
polarisation, depolarisation, electric shock, shocking current, active lead, neutral lead, earth, earthing, double insulation, microshock.
2. Describe the electrical behaviour of the heart and explain the general principles of electrocardiography.
3. Describe the physiological effects of alternating currents passing from limb to limb in the human body.
4. Describe emergency and first-aid steps for victims of electric shock.
5. Describe the multiply-earthed neutral (MEN) system of electric power distribution.
6. Describe examples of possible active-to-earth electric shock accidents, discuss the conditions under which such accidents might be fatal, and describe precautions for the prevention of such accidents.
7. Describe the Australian colour code and wiring conventions for three-pin power plugs and sockets.

PRE-LECTURE**CONCEPT DIAGRAM**

LECTURE

8-1 ELECTROCARDIOLOGY

Electrocardiology is a technique widely used in medicine and veterinary science for diagnosing the condition of the heart from its electrical activity. Since the body is a reasonably good conductor of electricity, currents generated by the heart produce potential differences on the skin. By attaching electrodes at a number of standardised points, these potentials, and hence the activity of the heart can be monitored. The purpose of this section of the lecture is to examine the physical principles underlying this vital clinical technique.

Individual heart-muscle cells

The heart is a special kind of muscle which, unlike the smooth and striated muscle found elsewhere in the body, can continuously contract and relax; this is the heartbeat. In practice, the heart's muscle cells are elongated. As we are concerned only with their electrical behaviour it is simpler, and adequate, to represent them as spherical. In the relaxed (i.e. non-contracted) state, a heart muscle cell is bounded by an electric double layer at the cell wall (figure 8.1). The cell is said to be **polarised**.

Electrodiffusive processes maintain a potential of -90 mV on the cell interior, relative to the surroundings. There is an electrostatic field in the cell membrane, between the layers of positive and negative charge. However (in accordance with Gauss's law) there is no electric field produced outside the cell. Consequently, between beats, when the whole heart is relaxed, it produces no external electric field. You may recall from chapter E4 that the membrane's sodium pump maintains a concentration of sodium ions outside the cell that is much greater than that inside.

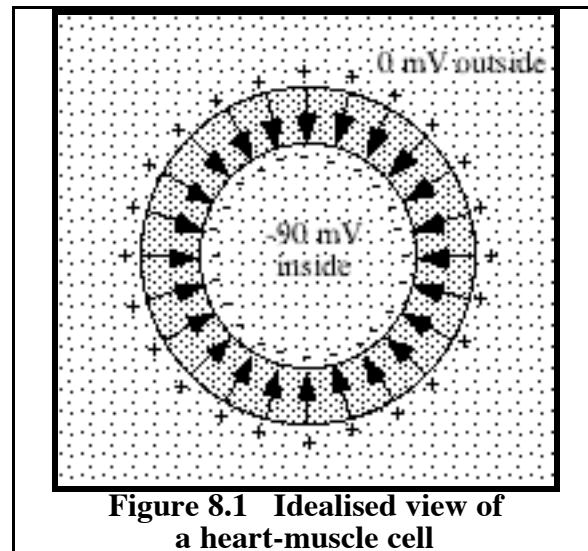


Figure 8.1 Idealised view of a heart-muscle cell

During the heartbeat, the cells are progressively depolarised (i.e. the charge layers disappear) in a coordinated way. The permeability of the cell membrane to sodium ions suddenly but briefly increases. Sodium ions rush into the cell, driven by both the concentration gradient and the electric field within the membrane. The inside of the cell becomes positive and the outside negative. There is movement of ions both inside and outside the cell as the charges are redistributed.

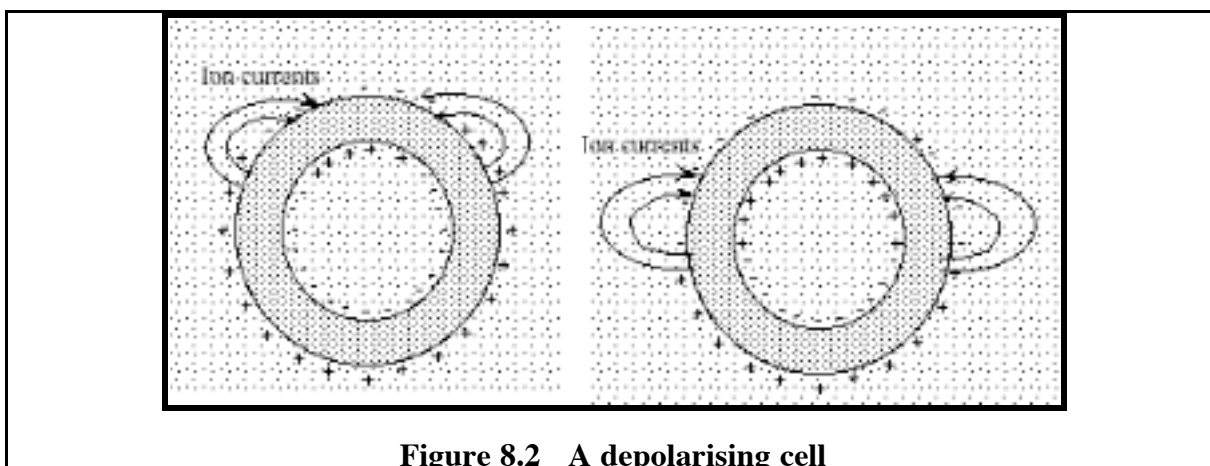


Figure 8.2 A depolarising cell

Associated with these ion currents there is an electric field and associated potential differences at places outside the cell, where previously there was no field. Figure 8.2 represents a cell which is partly depolarised, together with the transient ion currents. The combined effect of the simultaneous depolarisation of many cells produces the external electrical activity of the heart. Once a cell is fully depolarised, there is again no external electric field, and therefore once again the cell makes no contribution to the external electrical activity of the heart. Following the wave of depolarisation the sodium permeability returns to normal and the sodium-potassium pump restores each cell to its normal resting state.

Neighbouring cells in the heart wall depolarise in a coordinated manner, so that their external electric fields add up to produce a large scale electric field pattern, which changes as the depolarisation progresses.

The heartbeat

In their relaxed state, between beats, all the cells of the heart are polarised, and there is no external electric field. Muscle contraction, and the associated wave of cell depolarisation, starts at the sino-atrial node (top right of the heart in figure 8.3).

The region of contraction and depolarisation initially sweeps through the atria (the pumping chambers at the top of the heart); the combined effect of all the partially depolarised cells in this region generates an external electric field.

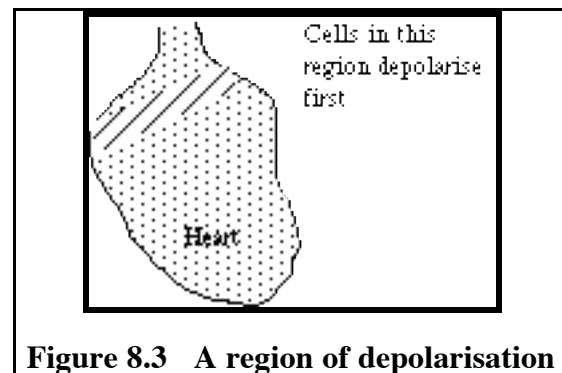


Figure 8.3 A region of depolarisation

The heart as a whole behaves like a dipole, negative above and positive below, with an upwardly directed electric field in the regions of the body around the heart (figure 8.4).

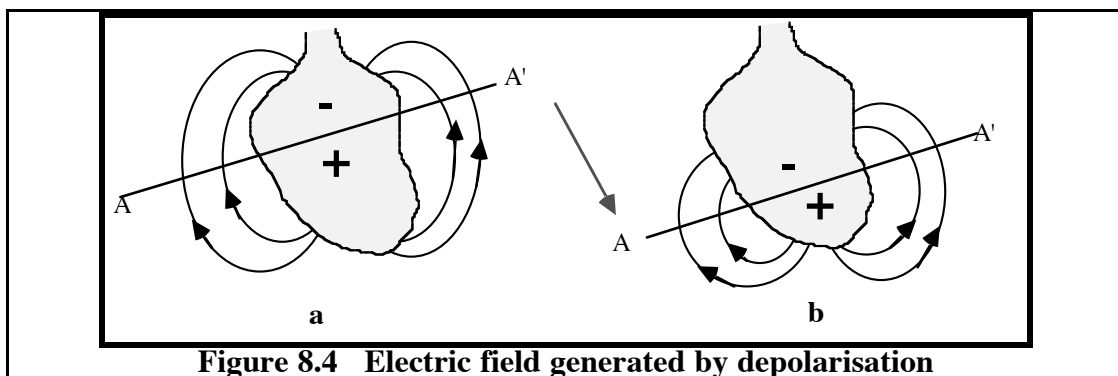


Figure 8.4 Electric field generated by depolarisation

Since the individual cells produce an external field *only* while they are in the process of depolarising, the instantaneous value of the external field is determined *only* by those cells in the depolarising region (the plane AA' in figure 8.4a). It is this feature which makes electrocardiograph (ECG) diagnosis so valuable.

The wave of depolarisation pauses briefly after passing through the atria, then continues to sweep downwards and to the left as the ventricles contract. At the stage shown in figure 8.4b, about 250 ms after the initiation of the beat, the main contraction of the ventricles is occurring. The electric field (and the ECG signal) reaches its greatest strength, and gives us information about the ventricular region of the heart. At other times during the beat, signals give information about other regions depending on the position of the plane of depolarising cells.

The heart as a battery in the chest

During the heartbeat, the heart as a whole behaves like an electric dipole which varies markedly throughout the cycle, but which always has the same polarity (the upper region of the heart is always negative). In understanding its external electrical effects, the heart can be thought of as a variable battery, located inside the chest with its negative electrode pointing up and to the right of the person (figure 8.5).

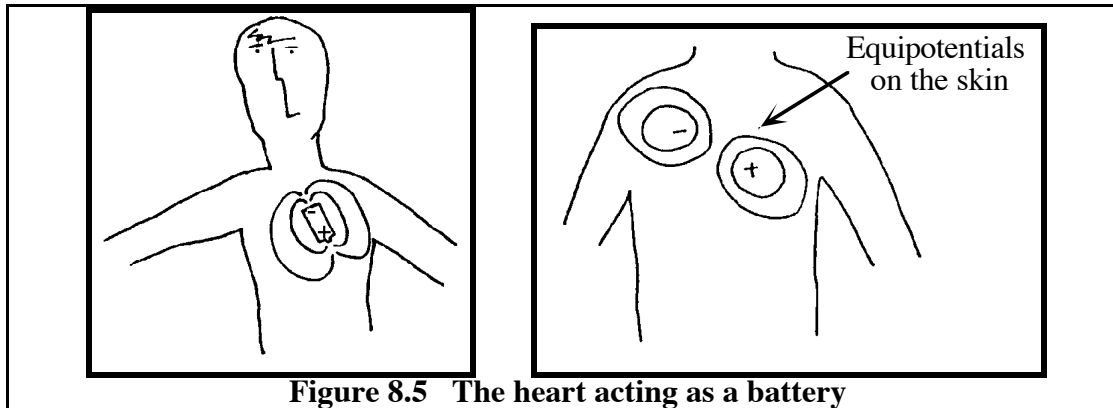


Figure 8.5 The heart acting as a battery

Currents generated by the heart (battery) exist in the resistive tissues of the body and give rise to potential differences over the surface of the skin. At the peak of the heart's electrical output, the potential distribution over the thorax looks like the right-hand part of figure 8.5. The lines are equipotentials drawn at intervals of about 0.25 mV. The potentials change during the pulse, as the strength and position of the heart's electric dipole change.

The electrocardiograph

By attaching electrodes to the skin at standard positions (up to 12) and recording the potentials during the pulse, the main features of the surface potential distribution, and hence of the electrical activity of the heart, can be determined. Since, as we saw above, any given cell produces an external electric field only while it is in the process of depolarising, each instant on an ECG trace corresponds to a particular region of the heart. Figure 8.6 shows the principle features of an ECG trace (where the ECG potential is measured between electrodes attached to the upper right and lower left regions of the chest) and the region of the heart corresponding to each feature.

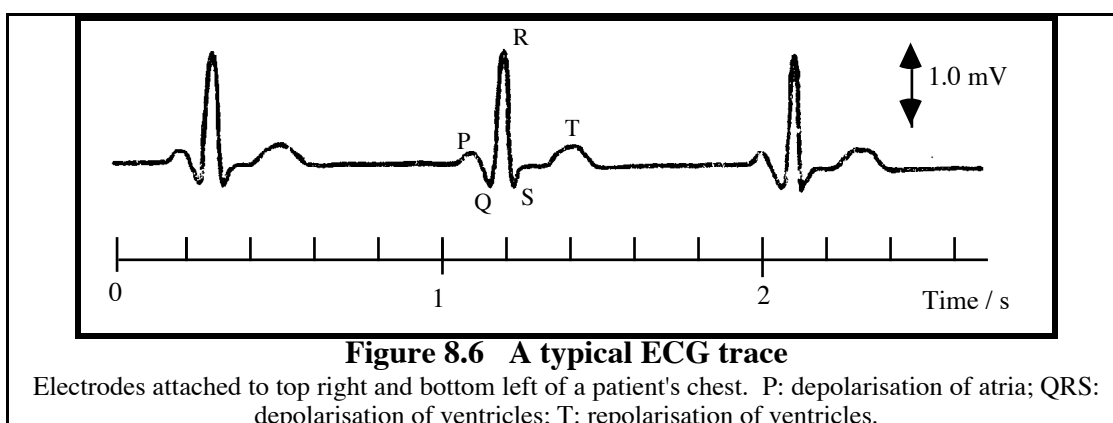


Figure 8.6 A typical ECG trace

Electrodes attached to top right and bottom left of a patient's chest. P: depolarisation of atria; QRS: depolarisation of ventricles; T: repolarisation of ventricles.

More about cardiology

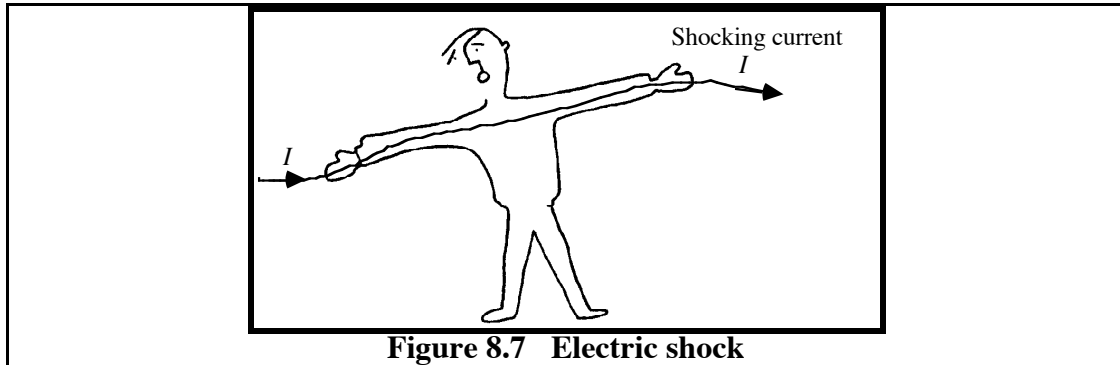
In the lecture we discuss the usual clinical electrocardiograph using external electrodes and a chart recorder. In intensive care, internal cardiac electrodes are often used to obtain more direct and detailed information. In research, but not generally clinically, the ECG recordings may be processed to give a three-dimensional display of the dipole moment of the heart (this is the so-called vector cardiograph). With minor variations of technique and interpretation, electrocardiography is also used in veterinary practice.

8-2 ELECTRIC SHOCK

Fatal electric shock occurs when a sufficiently large electric current flows through the body. The danger arises because a fraction of such a current flows through the heart and may disrupt the cardiac cycle. In the most common domestic and industrial electric shock accident, the contact with live conductors of the electricity mains causes current to flow through the body, typically from arm to arm or from arm to leg. In this section of the lecture we discuss the effects of such electric currents, how they can arise in accidental situations and the principles of electrical safety.

The physiological effects of electric current

Suppose the body is accidentally connected to a circuit and a current (I) flows from hand to hand (similar results would ensue for the same current from hand to feet, head to bottom, etc.).



The effects of such a current are shown in table 8.1. The effects do not suddenly occur at definite values of current. Variation occurs with age, sex and health of the victim and with the path taken by the current in the body. There are also differences between the effects of alternating and direct currents.

Shocking current	Effect
Less than 1 mA	No observable effect.
~1 mA to ~10 mA	Tingling sensation.
~10 mA	'Let go' current. Muscular paralysis.
~10 mA to ~100 mA	Laboured breathing.
~100 mA	Breathing stops. Ventricular fibrillation.
~1 A to ~10 A	Thermal damage to tissue.

Table 8.1 Somatic effects of electric current

Notes

- For currents less than 100 mA effects are usually reversible when the current is interrupted.
- Typically a 50 A, 10 ms pulse is used to defibrillate the heart

If a current of less than about 1 mA is passed through the body, there is generally no sensation and apparently no significant physiological effect. As the current is increased to a few milliamperes, a tingling sensation is felt, becoming more and more uncomfortable as the current is increased.

At about 10 mA muscles contract and are held contracted; in particular the fingers clamp on to a conductor, and it is impossible to open the hand. The term *let go current* means the highest current

at which one can still let go. It is important to note that a current just above the let go current value is usually harmless. When the current is broken, the victim is shaken but alive.

As the current rises above 10 mA, breathing becomes laboured and may cease. The victim may still recover spontaneously if the current is promptly stopped.

A current of about 100 mA sustained for a second or so is all that is needed to switch the heart over from its normal pumping rhythm to a useless random twitching action known as **ventricular fibrillation**. The heart action does not recover spontaneously when the current is broken.

Currents much greater than 100 mA can also cause internal and skin burns. Paradoxically, brief currents of > 1 A may be less dangerous than lower currents, as instead of putting the heart into ventricular fibrillation, they are sufficient to clamp the whole heart muscle simultaneously, and when the current is turned off, the normal heart beat may resume of its own accord. Indeed, currents of about 1 A are used clinically to defibrillate the heart.

First aid for electric shock victims

Anyone working with electrical equipment should be familiar with the technique of cardio-pulmonary resuscitation (CPR). Courses available to the public are run from time to time by hospitals and first aid organisations. Briefly, if someone is struck by electric shock:

- 1) interrupt the current;
- 2) if breathing has stopped, apply mouth-to-mouth breathing;
- 3) if there is no pulse, apply full CPR;
- 4) get an ambulance quickly.

It is vital to realise that if the heart has gone into ventricular fibrillation it will not restart spontaneously. The victim will not survive unless CPR is started promptly and continued until expert medical treatment, including defibrillation, is applied.

Live or active mains leads

In this and the following paragraphs we consider how the body can sustain a dangerous shock by accidentally becoming part of a mains power circuit. To do this, it is first necessary to understand the principles of mains power wiring. A domestic or industrial (single phase) supply can be represented in simplified form as in figure 8.8.

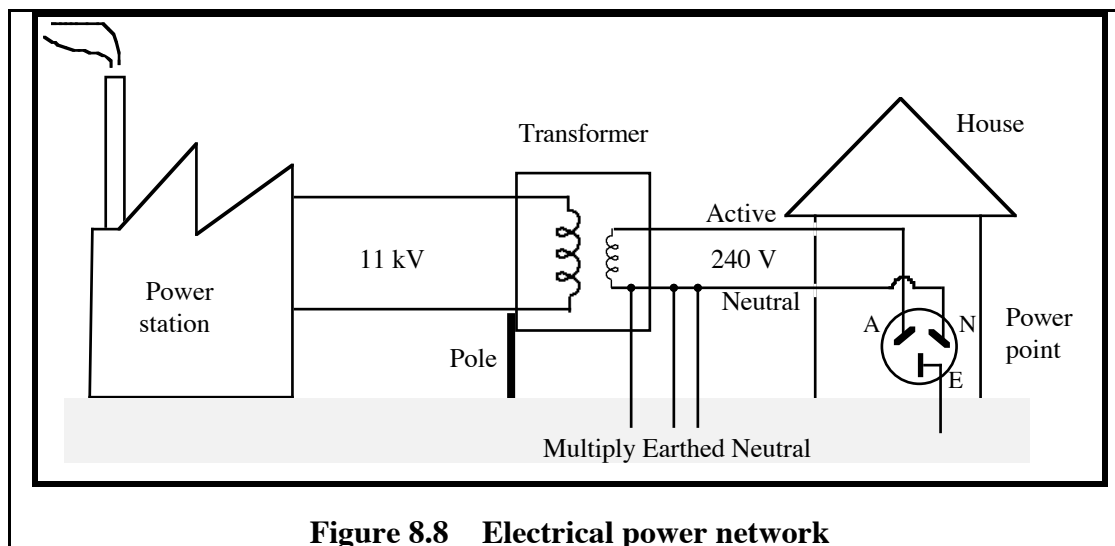


Figure 8.8 Electrical power network

Power from the generator is transmitted at high voltage (typically 11 kV AC) to various substations and local transformers where it is stepped down to 240 V for general use. You can see the local transformers on poles in the street. At the transformer, one lead, known as the **neutral** (N) is connected to earth via a thick cable with one end buried in the ground. The other wire from the transformer, the **active** lead (A) is thus at an average potential of 240 V relative to the ground, i.e. to our surroundings. Active and neutral conductors are connected, albeit via a complex distribution

network, to the A and N points of the user's outlet sockets. The user's **earth** (E) point is connected as directly as possible to the ground close to the house. Since the neutral wires in the power lines carry large currents and since they have finite resistance (ideally the resistance would be zero) they cannot be at exactly the same potential at all places along the wire. So, as shown in figure 8.8, the neutral is usually connected to ground at several other points between the transformer and the houses (this is the so-called MEN or multiply-earthed neutral wiring system) in order to keep the neutral lead at a potential near ground (zero). This ensures that only the active lead is at a high potential which is less dangerous than having two high voltage wires. Note, however, that the neutral lead cannot be exactly at earth potential at all places.

Active-to-ground shocks

In normal use, current goes to the electrical equipment (e.g. toaster) via the active wire and back to the transformer via the neutral. The current reverses every 10 ms (for 50 Hz AC supply). However, because the neutral is earthed, the current can return via the earth rather than the neutral. For example, an unwary breakfaster, touching the live end of the toaster element with a knife can get a shock.

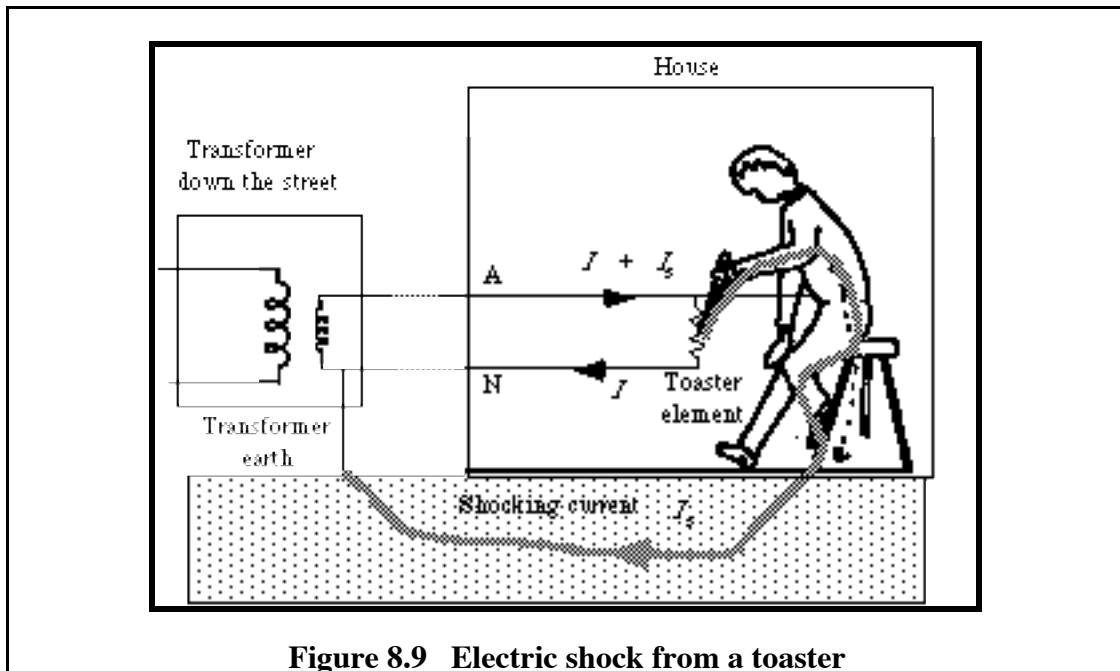


Figure 8.9 Electric shock from a toaster

In addition to the normal current, I , through the toaster there is an additional shocking current I_s through the active lead, through the knife, hand, arm, body, chair, floor and back to the neutral via the earth (see diagram above). How dangerous such a shock is depends on the current, which in turn depends on the resistance in the path of the shocking current, i.e. the resistance provided by the person, floor, chair, etc.

Calculation of the shocking current

In the example above, the average potential between active and earth is 240 V. The resistance in the path of the current through the breakfaster is made up as follows:

$$R \text{ (total)} = R \text{ (mains supply)} + R \text{ (knife)} + R \text{ (hand-to-knife; contact)} + R \text{ (body)} \\ + R \text{ (body-to-floor)} + R \text{ (earth return path)}.$$

Of all of these, the resistance of the earth, the knife and the mains supply are less than a few ohms and can be neglected. The body resistance (arm, trunk, leg) is about 300Ω . The body contact resistances to the knife and to the floor will depend critically on the circumstances. Thus

$$I_{\text{shock}} = \frac{V}{R_{\text{body}} + R_{\text{contact}}}$$

A metal knife in a dry hand could lead to a contact resistance of about $5\text{ k}\Omega$. On a dry wooden floor, the body-to-floor resistance could exceed $100\text{ k}\Omega$, giving a total resistance of around $100\text{ k}\Omega$ so

$$\begin{aligned} I_{\text{shock}} &\approx \frac{240\text{ V}}{100\text{ k}\Omega} \\ &\approx 2\text{ mA} \text{ i.e. a few mA} \end{aligned}$$

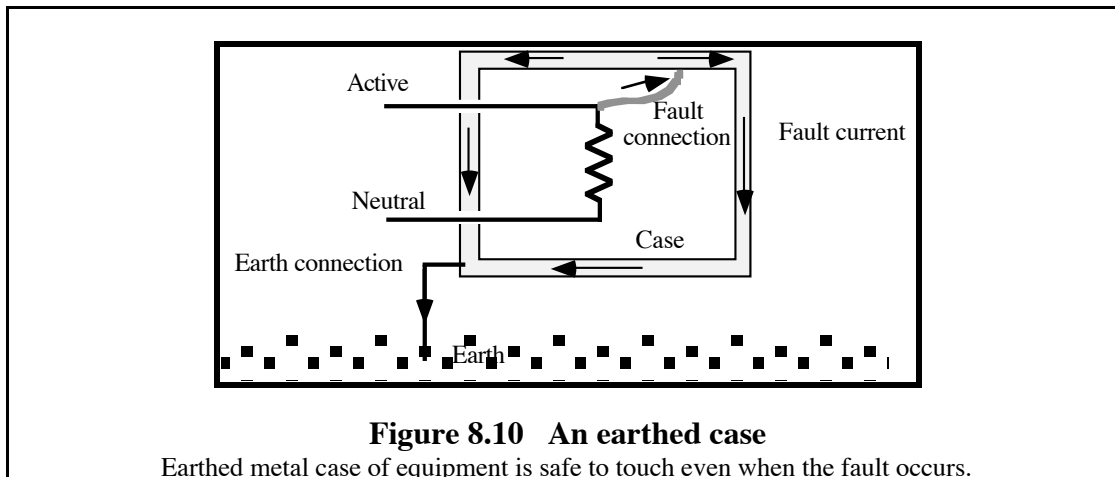
Our breakfaster would feel tingling, but would probably be unharmed.

However, in circumstances where the skin resistance is low (damp palms, wet feet on concrete etc.) the body contact resistance can easily fall below a few thousand ohms, and contact with a 240 volt active lead can give a fatal shock ($> 100\text{ mA}$).

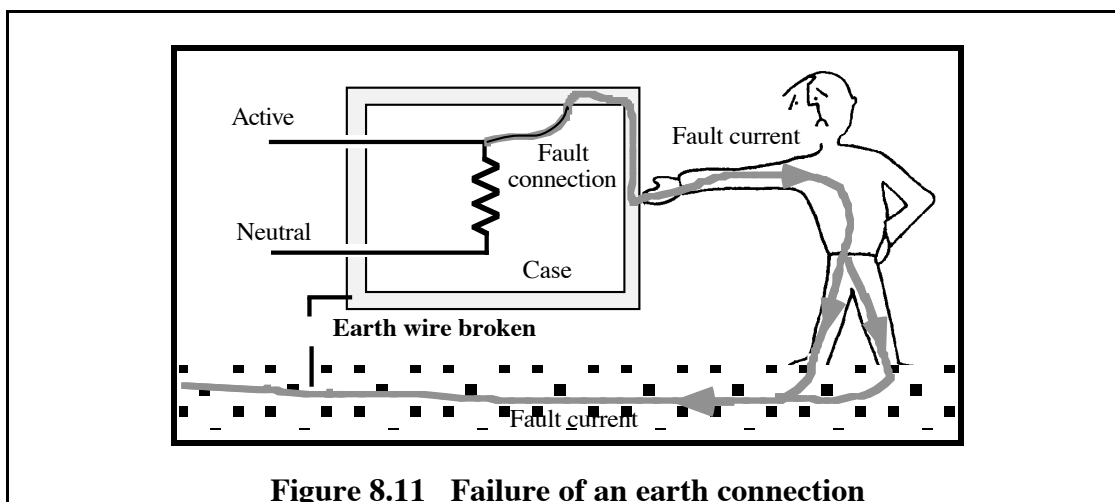
Earthed electrical equipment

Much electrical equipment (particularly in industry and in laboratories) is protected by connecting the outer metallic case to earth. In addition all active and neutral wiring is insulated. This scheme provides a two stage protection mechanism against electric shock. Figure 8.10 is a schematic of such a piece of apparatus.

If the active insulation breaks down, the fault current flows back to the source of power via the outer case and local ground (not through the neutral as usual).



Danger arises if the earth connection is not sound. The apparatus will continue to work, and it may not be noticed for years that the earth is broken. Now, however, if the insulation of the active wire fails, the case can become connected to the active lead. The equipment is in a condition which is **READY TO ELECTROCUTE** (figure 8.11).



The metal casing, which was a safety feature when it was earthed, has become a means of delivering a fault current through the victim, along the path shown in figure 8.11.

The degree of danger depends on the skin contact resistance, as explained in the example above. One particularly dangerous situation arises when someone is connecting two pieces of equipment together, one of which is correctly earthed, and the other has a broken earth connection and an insulation fault. The fault current can then flow from one hand to the other (and a dry floor is of no help).

Wiring convention

The usual Australian power point is referred to technically as a **general purpose outlet** (or GPO). The diagram shows the wiring conventions for the active, neutral and earth conductors, as seen looking at the outlet.

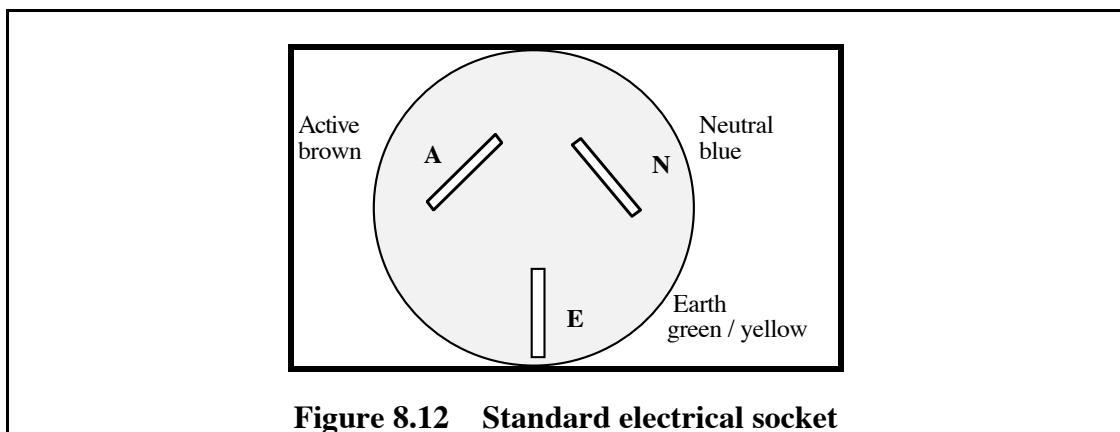



Figure 8.12 Standard electrical socket

The wiring and testing of plug connections should be done by licensed electricians, or other technically qualified personnel.

Double insulation

Many small power tools and domestic appliances are double insulated. This means that instead of having an earthed conducting case, they have a plastic case and all external metal parts are separated from the mains by **two separate electrically insulating barriers** or a single insulator of equivalent insulating properties. In electric hand drills for example, part of the internal drive shaft is plastic.

Such equipment is marked with a double square symbol: .

Microshock

In cardiac intensive care, patients may have catheters and electrodes inserted into or near the heart. Such patients are vulnerable to **microshock** produced by current accidentally carried directly to the heart by the inserted lines. Research at the Prince Henry Hospital in Sydney during the 1970s established that the minimum current passed directly into the heart which would induce ventricular fibrillation was only about $60 \mu\text{A}$. Since a typical resistance of the saline column in a cardiac catheter is about 500Ω , it follows from that a potential as low as 30 mV on the catheter is potentially fatal.

Such small potentials are easily produced in any number of ways - contact potentials, earth leakage currents, induced EMF's, electrostatic effects, etc. Before the dangers were fully appreciated there is little doubt that many cardiac patients who died of heart failure were indeed victims of microshock.

The practices now adopted to avoid microshock in cardiac treatment areas are among the most rigorous protections against stray currents and potentials in the application of electricity. A very strict code of practice includes:

- high resistance electrodes and catheters where possible;

- a physically massive common earth conductor, known as the equipotential earth to which all equipment associated with the patient is connected (this even includes the bedside lamp);
- isolating transformers so that neither current carrying conductor is directly connected to the earth;
- automatic cut-outs which rapidly switch off the supply if a fault current is detected.

(For full details on this topic, consult Australian Standard No. AS2500.)

Signs used in patient treatment areas

Two grades of protection are used, each identified by standard signs as shown in figures 8.13 and 8.14.

