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Electrical safety, defibrillation and diathermy

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Learning objectives

By reading this article, the reader should be able to:

- Understand the basics of electrical safety.
- Explain how earth faults occur and how they can be dangerous.
- Know how circuit breakers work and how they can make a supply safe.
- Discuss how defibrillators and diathermy work, and the key safety aspects with both of them.

Key points

- An understanding of electrical safety is vital to ensure no harm occurs when using electrical equipment.
- The earth is a key safety feature; earth faults can cause harm to users.
- Defibrillators produce high-voltage, high-current waveforms of short duration, which are normally biphasic, to reverse ventricular fibrillation.
- Diathermy machines produce high-voltage, but high-frequency waveforms that can provide cutting, or coagulation of tissues.

This article is the second of a series of three on electricity in this journal and links with the articles on electricity, magnetism and circuits, and on electronics and biological signal processing.[1,2]

If electricity is not used in the correct way, then morbidity and mortality from electrocution can occur. It is vital to understand electrical safety and the principles of defibrillation and diathermy. These are applications in which harm can come to patients if these electrical devices are used incorrectly; these applications demonstrate the principles and components discussed in the first article in this series.[1]

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Electrical safety features

The electricity supply

At a substation of the electricity supply, one connection of the transformer is firmly bonded to earth, which forms the start of the neutral lead of the supply. This earth connection forms a vital part of electrical safety. The connection on the other output of the transformer is called live. This is the active connection that can cause harm.

Class 1 equipment

The first safety feature recommends that the electrical device has its metal case, or exposed metal parts, earthed (Fig 1). This is class 1 equipment, which can be the monitors used in the operating theatre. The live lead is protected by fuses (or a circuit breaker, which is described later). Any fault which causes a low resistance pathway (such as a loose wire, moisture or a build-up of dust) to appear between live components in the circuit and the metal case, is dealt with by the protective earth pathway which takes the *fault* current to earth. In Fig 1, the fault is shown by a 'resistance' pathway to the case of 100 kΩ. If the leakage voltage source was assumed to be 100 V (it can be anything from a low voltage up to 230 V), then the fault current would be 1 mA. Normally this low resistance path to earth causes an increased live current through the fuse. The

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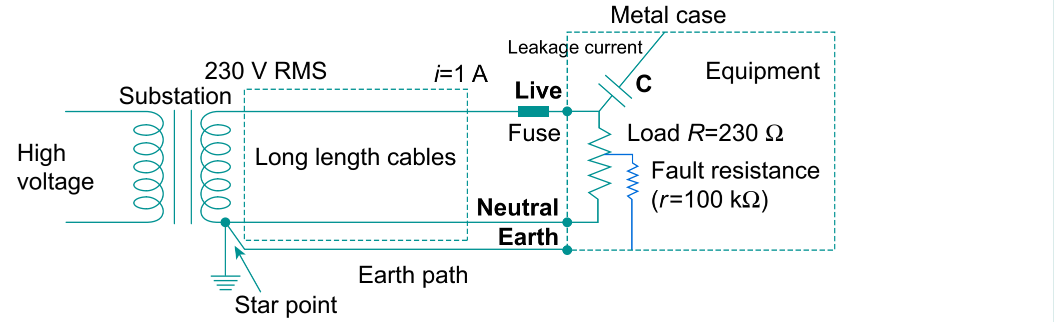

Fig 1 Diagram of the domestic mains supply, supplying class 1 equipment. The equipment has a load of 230 Ω, and so the normal current would be 1 A. The case of the equipment is earthed. The leakage current by capacitance is shown by C. See text for details. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

fuse would melt and *blow*, breaking the circuit, if the fault current was in the order of amps. However, in this example the fault current is too small to blow the fuse, so nothing would happen.

However, class 1 equipment should only be connected to the patient if there were a separate isolating transformer (Fig 2), and this is discussed later.

Class 2 equipment

Class 2 equipment has no protective earth. The power cable has only live and neutral (no earth lead), and the circuitry connected to the mains is then enclosed in a second insulated layer, with the case made of non-conductive plastic.

Class 3 equipment

Class 3 equipment is low voltage equipment, normally less than 25 V root mean square (RMS [supplied by a step-down transformer]) or less than 60 V direct current (DC [supplied by batteries]).

Leakage currents

Apart from inappropriate currents caused by faults, there are normally other ‘extra’ currents in the system caused by *stray capacitance*. Capacitance exists between all conductors, even if the insulation is intact and adequate, and this is the stray capacitance. The closer the conductors are together, the greater the stray capacitance. As the mains voltage is alternating current (AC), the stray capacitance between the mains wiring and earth results in ‘capacitive’ current to earth, because of the capacitive ‘resistance’. This occurs both in the supply system and in any equipment connected to it. This current is called leakage current and is illustrated in Fig 1. In designing equipment, manufacturers must keep leakage current within acceptable limits by careful choice of components.

The earthing is vital as it provides a safe low resistance path for any leakage current back to the (earthed) neutral

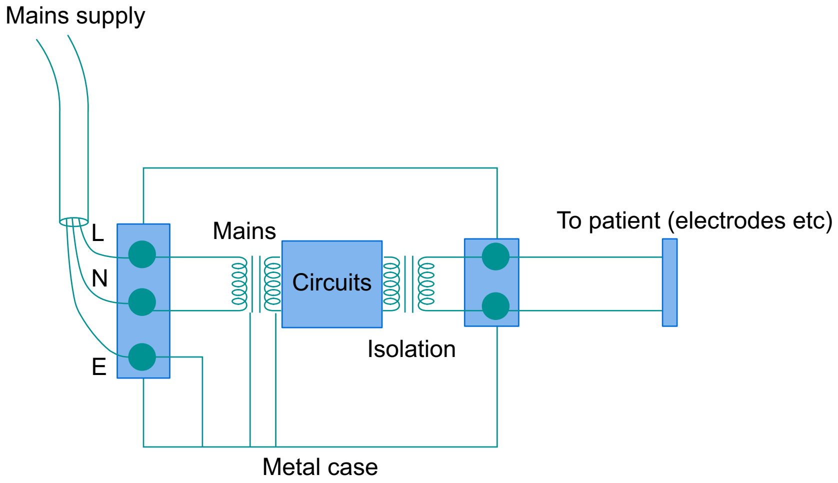

Fig 2 Diagram of a class 1 equipment which supplies a patient connected part via an isolation transformer. The mains transformer core and one side of the secondary is earthed for safety. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

point. Every class 1 device has some leakage current passing down the earth wire: this is called *earth leakage current*, for which there is a maximum allowed limit of 5 mA in normal (no fault) conditions, and 10 mA in single fault conditions.

Touch current presents a hazard to users and patients (Fig 3A). Touch current is leakage current that can find a path to earth through a user who touches the metal case of the equipment. Under normal conditions the touch current will be zero. If the case of the equipment is not earthed, owing to a problem or a fault (as in the diagram), then normal touch current will flow through the person. In this condition, where the earth has been disconnected, the upper safe limit is 500 μA.

Apart from the class 1–3 safety features, if equipment is to be connected to patients (e.g. ECG etc), it must be designated type B (body), BF (body floating) and CF (cardiac floating), each defined by allowable leakage currents as defined by the medical device standard, the International Electrotechnical Commission (IEC) 60601–1. B and BF designations have similar values (e.g. normal AC leakage current of 100 μA) but CF designations have currents set at 10% of these (10 μA). Only type CF is suitable for connection directly to the heart, or via any internal body site. The F symbol indicates a floating (non-earthed) system.

Earth faults

The earth connection can become disconnected because of damage to the mains cable, for example being continuously stepped on. The plug can be badly wired or the connection can be from the socket to an old corroded water pipe. Hospital maintenance or the equipment management service should always check the integrity of the earth connection. If an earth fault develops, normally no one would notice any difference initially. If a small leakage current develops, then the user would feel that the equipment has a *fuzzy* feel to it. If two or more faults develop, that is earth lead breakage and severe leakage fault currents (and the order this happens is not important), then this situation is highly dangerous to both the clinician and the patient. In this dual fault situation, if an anaesthetist touches the instrument case, for example, then a connection to earth can be made via the resistance of the person and the circuit will be completed. This is described in Fig 3A.

There will be current flow through the person and the magnitude of it will be dependent on many factors: humidity, sweating, shoe insulation, etc. These factors will change the resistance to earth (person–earth resistance in Fig 3) and therefore the amount of current through the person. For example, if the anaesthetist is standing on an antistatic floor with one hand touching the faulty equipment and touching nothing else, then the resistance to earth is in excess of 20 kΩ, so that by Ohm's law the maximum current which can flow is 230/20 = 11.5 mA. Although this shock would be painful, it would not kill.

However, if the subject touches the metal equipment with one wet hand while touching an earth conductor such as a cold water tap with the other (or standing in a puddle of water with normal footwear), the resistance to earth would be much lower and possibly less than 2000 Ω. In this case, the subject would sustain a lethal electric current of 115 mA, causing ventricular fibrillation (VF). However, this is still a small current for the circuit, so it is likely that the circuit fuse will remain intact.

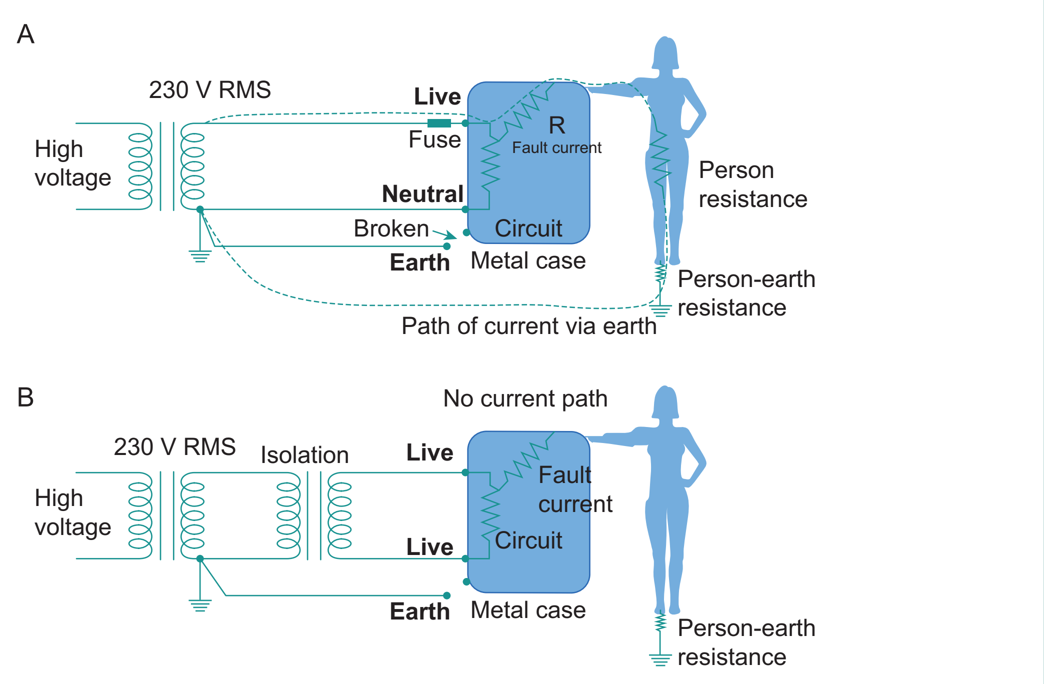

Fig 3 (A) A situation in which there is a dual fault. The connection from earth to the metal case is broken and there is a fault resistance to the case caused by an internal fault. There will be current going to the earth through the person. The magnitude of the current will be dependent on the person resistance and the person-earth resistance. R is the fault resistance. (B) A situation in which there is an isolation transformer present. In this case, the dual fault situation described in (A) does not give a complete current path owing to the transformer, and no current flows through the person. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice.*)

Microshock

When the current through the body is delivered by external means as discussed above (e.g. subject touching live wires), this can cause injury and sometimes death if the current is greater than 50 mA. However, if the current has been delivered by internal sources (such as when using internal pacemaker wires, cardiac catheters with incorporated electrodes, a catheter filled with saline) then the current needed to produce VF, is much less, typically 50 μA, as more of the current will go directly through the myocardium. This is called *microshock*. Microshock can occur because of a fault condition, where the potential of the internal device becomes greater than 0 V. This means that if the patient has a pathway to earth, an internal current of greater than 50 μA could occur, which would be very dangerous. The frequency is important as well and low frequencies such as 50 Hz are the most dangerous. High voltages at high frequencies in the MHz range are used in diathermy, and although these cause burns, they do not cause VF.

Circuit breakers

For general protection of equipment, there is a fuse situated in the live line. This will break when a fault situation occurs where the extra fault current melts the fuse. But fault situations can occur with small leakage currents in mA, and a more sensitive circuit breaker is needed. A *residual current device* (RCD) is much more sensitive and can break a circuit before a person perceives any discomfort. This relies on the principle that normally the current in the live and neutral leads are equal. In a fault situation, there is an imbalance of current between these two leads, and this causes an electrically operated switch (a comparator) to break the circuit. A typical circuit is shown in Fig 4.

One problem with using RCDs is that they rely on disconnecting the total mains supply to provide safety. In some clinical situations this is unacceptable. Consider a situation where a mains lead that has become wet is plugged in at an ICU bedspace. This results in excessive leakage current and the supply is disconnected to protect the users. In doing so it might also disconnect the supply to monitors and ventilators. A solution to this, but only used in strictly controlled situations (such as the ICU and operating theatres), are earth-free supplies.

Earth-free supplies

The conventional live–neutral–earth system has several advantages especially for domestic use as only one lead is at mains potential. This has advantages, for example only one fuse is needed, but as discussed above an earth-free mains supply for operating theatres is possible. A 1:1 isolating transformer is added to the normal system so that no voltage change occurs. The primary winding is connected to the live and neutral, and the secondary is not connected to earth and is therefore earth-free. This feeds one or more of the power outlets. The earth can be connected to the case as before. In the situation when either of the two live leads become connected to the case and the earth connection to the case is not present or high resistance, then the current cannot pass through the patient to the earth situation (Fig 3B).

Defibrillators

Defibrillators are devices that are used to apply a large electric shock to the heart

The voltage, current and shape of the waveform needed to defibrillate the heart is critical. The instantaneous power needed is typically 125 kW (50 A needed across the thorax of resistance 50 Ω, and power is I^2R), and this cannot be provided directly from the domestic mains supply, as the maximum power from a normal mains socket is about 15 kW. Defibrillators utilise the charge stored in a capacitor, typically 80 μF, which can provide stored energy of 250 J (Energy is 0.5CV,[2] where V = 2500 and C = 80 μF.). However, just discharging a capacitor through the resistance of the thorax would result in a decaying exponential, from an initial high peak current with a very long tail. These high peak currents cause damage to the heart and the long tail can allow fibrillation to recur.[3,4] These circuits are normally powered by domestic mains, but they can be battery powered. In this case, the battery powers a high-frequency oscillator, which drives a step-up

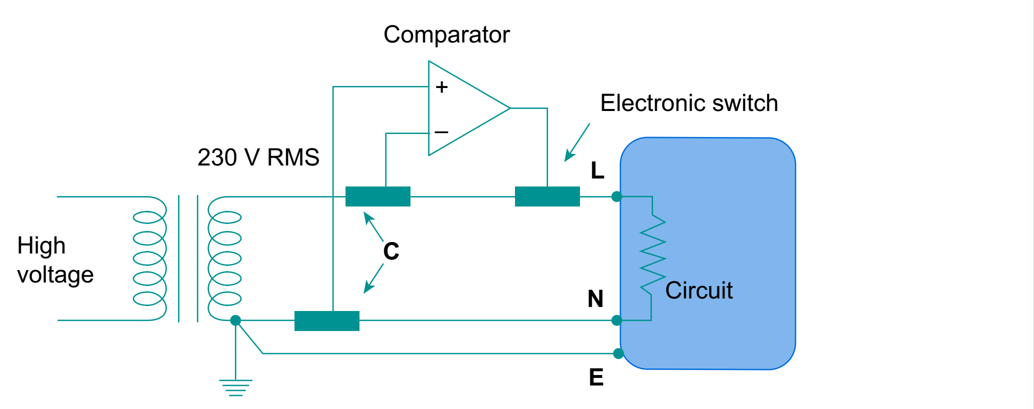

Fig 4 An example of a sensitive circuit breaker. C in the diagram represents circuit components which give a voltage output proportional to the current flowing through them. These outputs, one from the live line, the other from the neutral line, are supplied to a comparator circuit. This circuit compares the two inputs and gives an output if there are different by a desired amount. This output will operate an electronic switch and break the circuit. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice.*)

transformer, which is needed to convert the battery voltage to the required much higher voltage. This is shown in Fig 5B.

Monophasic waveforms

A waveform that has been used successfully in external devices is the critically damped sine wave current waveform as shown in Fig 6. The current from one electrode to the other is all in one direction. This waveform shape has been achieved by the addition of an inductor to the circuit, as shown in Fig 5A.

Biphasic waveforms

This waveform has now been superseded by biphasic waveforms, which is where the current changes direction partway through the cycle. Biphasic waveforms have been shown to be more efficient, have a higher first shock success and require less energy.[5] All new external defibrillators in the UK now use biphasic waveforms, but some monophasic devices are still in use. Biphasic systems were initially produced by altering the components in the resistor-inductor-capacitor circuit of Fig 5 to produce an underdamped biphasic waveform as in Fig 7. Current systems tend to use the truncated exponential biphasic waveform shown in Fig 8. This waveform is generated by the discharge of a capacitor, but the process is now controlled by electronic switches. In this system, the charged capacitor is discharged through the patient with a normal exponential decay. After typically 4 ms, the connection to the patient is broken and the capacitor connections are reversed by the equivalent of a dual pole electronic switch, as shown in Fig 9, and the patient reconnected.

Diathermy

If a voltage is applied across a body, via suitable electrodes, the body becomes part of a circuit and a current will flow, the magnitude depending on the resistance of the tissue. This current can cause heating (even burns) or other electrophysiological effects, depending on its frequency. As the frequency increases, the heating increases but the other harmful effects on tissues decrease, and at frequencies above 100 kHz (i.e. radio frequencies), the effect is entirely heating with no electrophysiological harm, that is neuromuscular effects and electrolysis. This is the basis of diathermy. The average current through the body is the same throughout but the current per unit area, the current density, can vary. If the material in which current passes is of smaller cross section, then the current density will be higher and the heating effect greater. The resistance of the material is inversely proportional to its size and cross-sectional area, so as the material becomes smaller, its resistance gets larger. The heating power is the product of the current squared and the resistance. In diathermy, one (or both) of the electrodes are small, and so localised heating will occur there. The total heating power is around 200 W.

In monopolar diathermy the inactive electrode in the circuit is much larger and situated elsewhere on the body (Fig

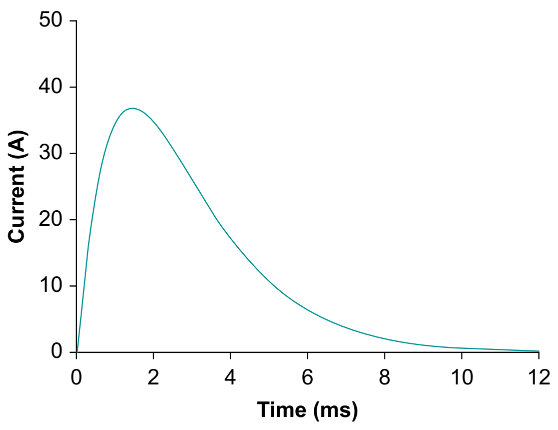

Fig 6 Critically damped waveform commonly used in the output circuits of monophasic defibrillators. The values shown are typical ones. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

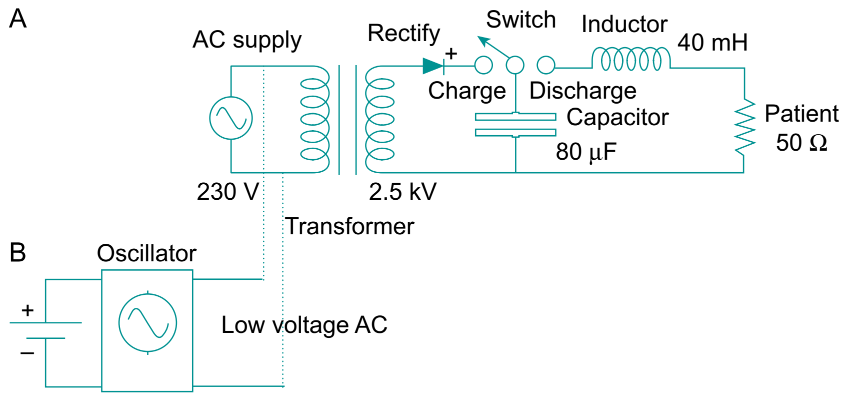

Fig 5 A typical monophasic defibrillator circuit. (A) The mains version. The mains voltage is transformed up to a very high voltage (e.g. 5000 V). This voltage is rectified by a diode, which only passes the positive part of the alternating cycle to the capacitor. When the switch is in the charge position, the capacitor is charged up to the supplied voltage. When the switch is passed over to discharge, it is discharged through the inductor and patient. (B) The battery version. This part replaces the 230 V AC supply shown in (A), but the transformer has a much higher step up ratio. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

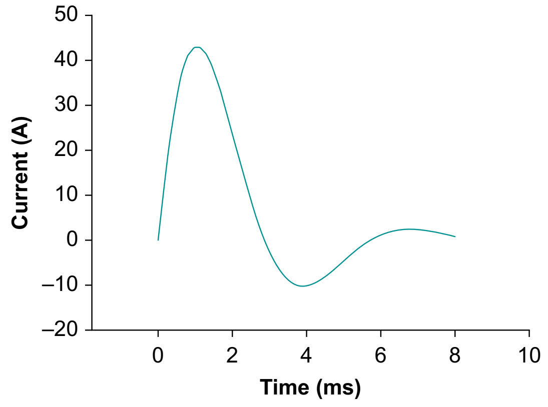

Fig 7 Underdamped biphasic waveform. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

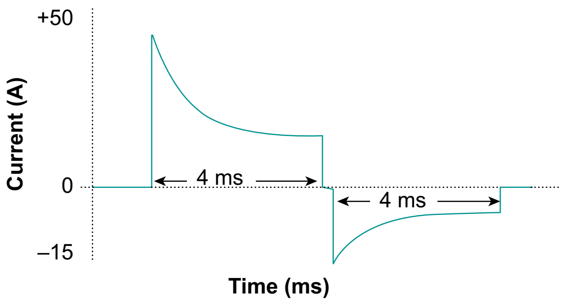

Fig 8 Diagram showing a biphasic waveform, the truncated exponential. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

10). This is the *passive* electrode, and because of its large surface area, the current density is low, and minimal heating occurs.

Diathermy can be used for cutting tissue, or for coagulation, different waveforms are used for each. Normally a continuous waveform, for example 500 kHz and 250 V, is used for cutting, and a non-continuous waveform with similar frequency is used for coagulation. In this case the waveform voltage is 8 kV for 6% of the total waveform time, and zero for the rest.

Diathermy electrodes

The electrode systems used in surgical diathermy can be monopolar or bipolar. Each has different characteristics and uses.

Monopolar electrodes

The monopolar system is shown in Fig 10. The power available in this mode is high, and produces efficient cutting. The active electrode is available in an assortment of instrument tips depending on the cutting and coagulation application. However, as the patient forms a major part of the electrical circuit, every precaution for safety must be taken. If there is an electrical conductor in the body, such as a metal prosthesis, or a pacemaker, some or most of the current could pass through it and heat it up. In areas of high current density this could cause tissue damage.

Bipolar electrodes

In the bipolar arrangement both electrodes are small, forming each end of the diathermy forceps, in which high current densities are produced. The intense heating effects are the same at each electrode, and the body does not form part of the circuit. The bipolar surgical diathermy has a localised, precise effect on the tissue and suits delicate surgery such as ophthalmic surgery. The technique has good coagulation effect but less cutting ability because of the low power available. It is preferred when the patient has a pacemaker, as stray current is less likely to interfere with its function.

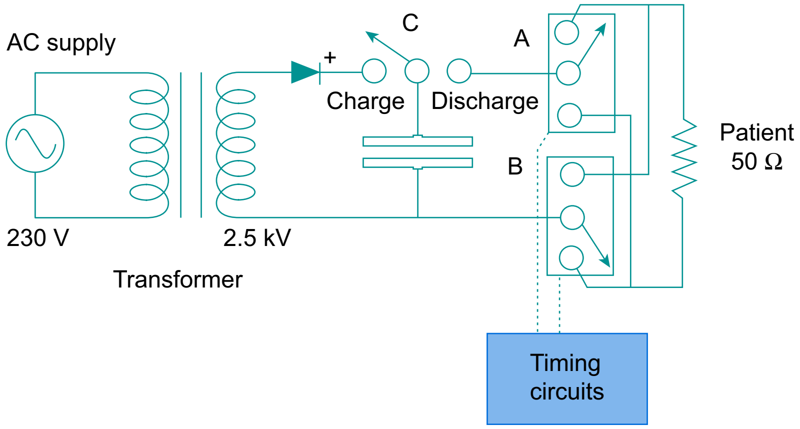

Fig 9 A typical truncated exponential biphasic defibrillator circuit. The capacitor is charged up as described in the monophasic system. When switch C is passed over to discharge, it is discharged through the patient. After a certain time, the timing circuits switch over the electronic switches A and B, so the polarity is reversed. (Reproduced with permission from Magee and Tooley, *The Physics, Clinical Measurement and Equipment of Anaesthetic Practice*.)

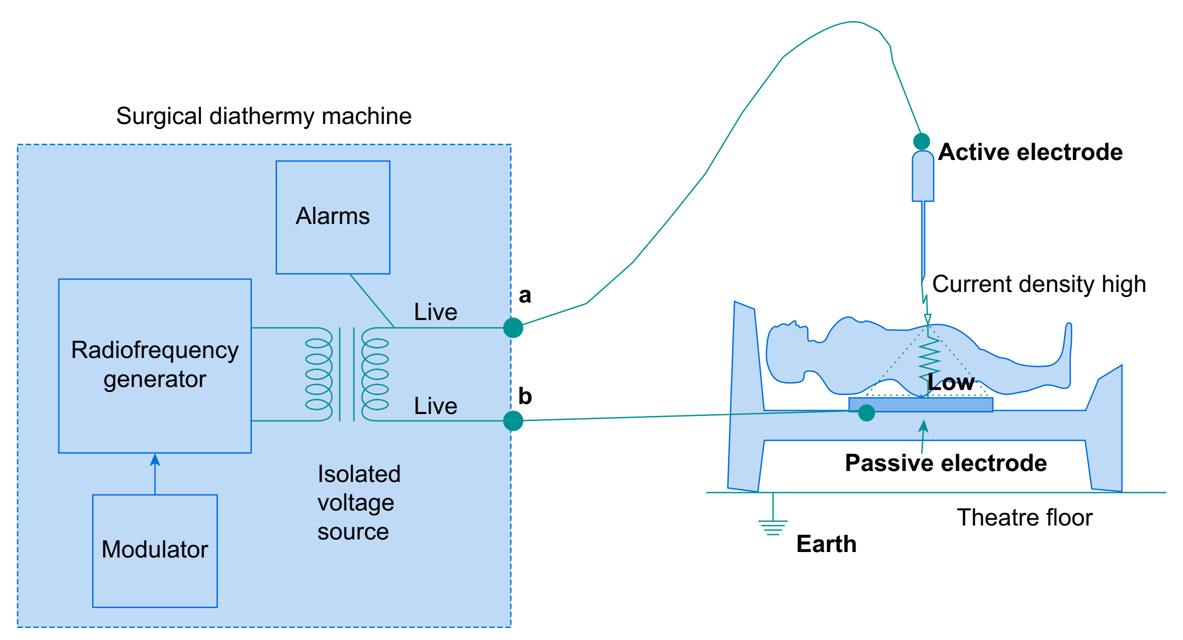

Fig 10 Set-up for an isolated monopolar surgical diathermy system, showing the electrodes. **a** and **b** denote active and passive, respectively (Figure adapted from Tooley.[6]).

Safety of diathermy

Diathermy machines have outputs that are isolated from earth (Fig 10), to minimise leakage currents to earth. To complete an electrical circuit for the maximum diathermy current to flow, the circuit must be completed from **a** (in Fig 10) to the active electrode, via the patient resistance, to the passive electrode, back to output **b** (in Fig 10). In theory, if the passive electrode were to become disconnected, no current would flow. If an earthed object (such as a drip stand) were to

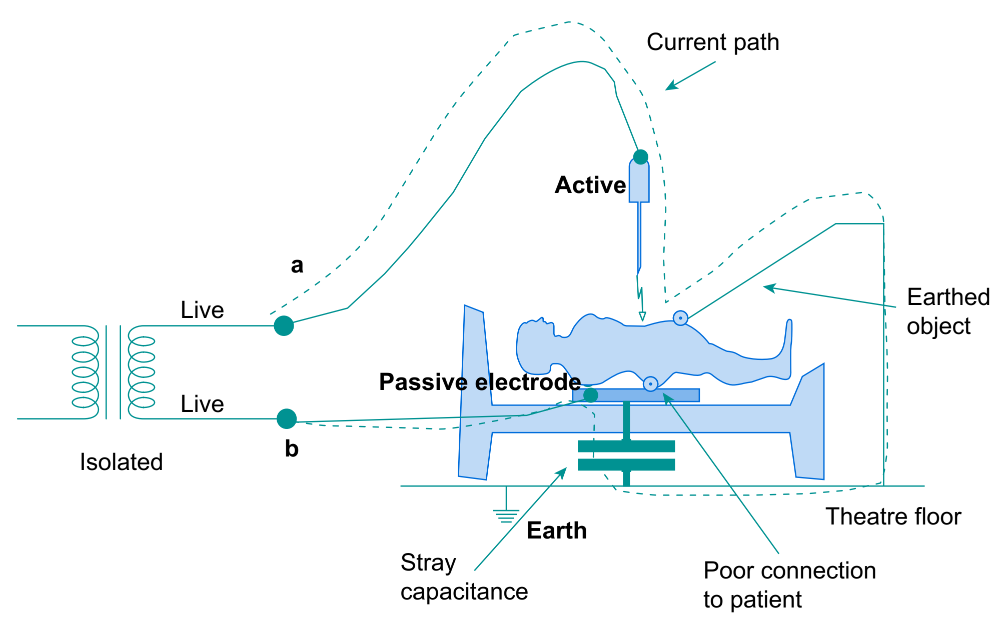

Fig 11 Diathermy circuit demonstrating stray capacitance. **a** and **b** are outputs from the diathermy machine, and the patient has a poor contact with the passive electrode. An earthed object, such as a drip stand, is touching the patient. Stray capacitance is shown between the passive electrode and the theatre floor. (Figure adapted from Tooley.[6]).

touch the patient, then this should have no effect, as it is not part of the return current path. However, there is also the problem of stray capacitance.

Stray capacitance

Capacitors can be considered as frequency-dependent resistances, where the resistance (or more correctly termed the reactance) decreases as the frequency increases. Capacitors only conduct AC, and the current flow is proportional to the frequency. Electrical capacitance can occur, for example between the passive electrode and the ground of the operating theatre (which can be indirectly connected to earth). This ‘capacitor’ will have a low capacitance value but pass very small currents at domestic mains frequencies. However, it will present a much lower reactance at the higher diathermy frequencies and so allow stray circuits to occur, which may result in burns. For example, if there is a poor connection between the passive electrode and the patient, and an earthed object is in contact with the patient (Fig 11), then an alternate current path could be formed for the return current. The current in this case flows from a (Fig 10) to the active electrode, into the patient, then some of current leaves by the earthed object and flows to earth. To complete the circuit back to connection b, the current passes from earth to the passive electrode via the stray capacitance. Burns can arise at the connection between the sharp object and the patient, but can also arise at parts of higher current density where only certain parts of the passive electrode are touching the patient such as an improperly applied diathermy plate. Burns can be minimised by ensuring that the passive electrode is securely attached with the maximum surface area to the patient so that the correct circuit is the best route for the current to flow. No other objects may touch the patient when the diathermy is on. Alarms can be installed to warn users that of high stray leakage currents. The stray currents are higher with increasing frequency, so a compromise frequency around 500 kHz to minimise this effect is used.

Declaration of interest

The author declares that he has no conflicts of interest.

MCQs

The associated MCQs (to support CME/CPD activity) will be accessible at www.bjaed.org/cme/home by subscribers to *BJA Education*.

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Further Reading

For more in-depth information on this topic, please refer to chapters 6, 20 and 21 from Magee P, Tooley M. *The physics, clinical measurement and equipment of anaesthetic Practice*. second edition. OUP; 2011, ISBN 978-0-19-959515-0