Surgical diathermy and electrical hazards: causes and prevention

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Abstract

The hospital environment is both unique and unusual in that electrical equipment is directly applied to the human body. From this application either capacitive or resistive coupling may lead to current flow and harm. Surgical diathermy, patient monitoring and imaging, although universal, are often misunderstood, and many clinicians are ignorant of their principles and hazards. Electrical equipment in hospital therefore has the potential to lead to serious injury or death. This article outlines the basic physics of electricity, in particular the principles behind diathermy, the hazards posed by it and by other devices and the various measures available to reduce the risk of these.

Keywords Coupling; diathermy; diathermy burns; diathermy pacemaker; diathermy safety; diathermy smoke; electrical equipment; electrical hazards; electrosurgery; microshock

Royal College of Anaesthetists CPD Matrix: 1A03, 2A06

Learning objectives

After reading this article, you should be able to:

- understand the basic concepts of electricity related to anaesthetic practice and those that govern the operation of the surgical diathermy unit
- understand the ways in which perioperative electrical injury may occur
- identify patient hazards associated with surgical diathermy
- understand the safety mechanisms in place to limit potential hazards and have a basic knowledge about how to prevent electrical injury in the theatre

Introduction

Electrical injury is caused by passage of electricity through the body. The main source is the domestic supply (Table 1).

The tissue damage is proportional to the:

- amount of electricity that flows (current)
- current path and density
- type of current (AC or DC)
- duration of exposure.

In the case of AC current, lower frequency causes more damage.

Basic principles of electricity

Electric current is the flow of electrons through a conductor past a given point per unit time, propelled by a driving force (voltage). Current is measured in amperes (A).

Ampere is a base SI unit. One ampere represents a flow of 6.24×10^{18} electrons (1 Coulomb of charge) past a specific point in 1 second.

- **Direct current (DC):** The current flows in one direction.
- **Alternating current (AC):** the flow of electrons reverses direction at regular intervals. In the UK the frequency of AC is 50 Hz.

- **Ohm's law:** current = voltage/resistance. This is usually applied to DC voltage (V) and direct current (I) across a resistence. AC flows not only through resistors, but also through capacitors. For this reason the term impedance is substituted for resistance. The unit for impedance is same as resistance (ohm) but is denoted by the letter Z.
- **Capacitor:** a capacitor consists of two parallel conductors separated by an insulator. Capacitors allow only AC and not DC to pass through them.
- **Capacitance:** capacitance (m) is the measure of the ability of a conductor or system to store charge.

- **Inductance:** when electrons flow in a wire, it results in inductance; the formation of a magnetic field around the wire. If the wire is repeatedly coiled around an iron core, very powerful magnetic fields can be induced.

Causes of electrical injury

Electrical injury occurs when the body forms part of an electrical circuit. This can occur in two main ways.

Resistive coupling

When the body comes into simultaneous contact with a source of electricity and earth (such as touching a live wire or socket by accident) then resistive coupling occurs. Sources of electricity can be due to machine malfunction or leakage currents. Leakage current occurs when a piece of equipment attached to the patient is at a higher potential than earth, or two different earth potentials are present in equipment to which the patient is attached (different earth potentials may exist in different parts of the same

Domestic power supply in some countries

Country	Voltage (V)	Frequency (Hz)
UK	230	50
USA	120	60
Australia	240	50
New Zealand	230	50

Table 1

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building). Even a small amount of current (termed 'microshock') can be dangerous when applied to the heart.

Microshock is a miniscule current, in the range 05—0.1 mA (50—100 mA) is potentially dangerous if applied to the heart via a central venous line when it can cause ventricular fibrillation (Figure 1).

Capacitive coupling

The patient's body can form a connection between an electrical source and earth by acting as one plate of a capacitor. For example, a 50-Hz operating theatre light separated from the patient by an air gap can act as one plate of a capacitor and the patient the other. As mentioned earlier, AC current can pass through a capacitor and induce current flow in the patient.

In a magnetic resonance imaging suite, the powerful changing electromagnetic fields may induce currents in objects in contact with the patient. This can lead to interference affecting the electrocardiograph and pulse oximeter. More seriously they may cause local heating and skin burns too. There have been case reports of the finger on which the pulse oximeter was attached being lost due to severe burns.

Effects of electrocution

- 1 mA — tingling
- 5 mA — pain
- 15 mA — tonic muscle contraction ('no let go' current)
- 50 mA — tonic contraction of respiratory muscle and respiratory arrest
- 100 mA — ventricular fibrillation.

Methods to prevent electrical injury in theatre

These can be classified into general measures, equipment design and specific measures.

General measures

- Regular maintenance of electrical equipment.
- Making sure that the patient does not come in contact with earthed objects.
- The use of antistatic shoes.

Antistatic shoes have a protective effect by virtue of their high resistance. Strong resistance impedes the passage of electricity through the person to the earth and thus stops the formation of a completed electrical circuit. Antistatic shoes should have between 75 k (kilo) ohm and 10 M (mega) ohm resistance when new. This is low enough for safe dissipation of electrostatic charges which may be very high voltage, but high enough to stop passage of a dangerous current.

Static electricity is the build-up of charge on equipment that can lead to sparks, fire and even explosions. To counter these problems, operating theatre floors have conductive surfaces to drain away charge and trolleys are fitted with conducting wheels or contact straps. The electrical impedance (resistance) should be high enough to dissipate the static electricity but not low enough to allow enough current to flow to cause electric shock.

Equipment design

In the UK all medical equipment used in patient environment should meet the requirements of British Standard Safety 5724: Safety of Medical Equipment. This was revised in 1989 making it identical to the corresponding international standard (International Electro-technical Committee standard in IEC 601). The third edition of IEC60601-1 was introduced in December 2005

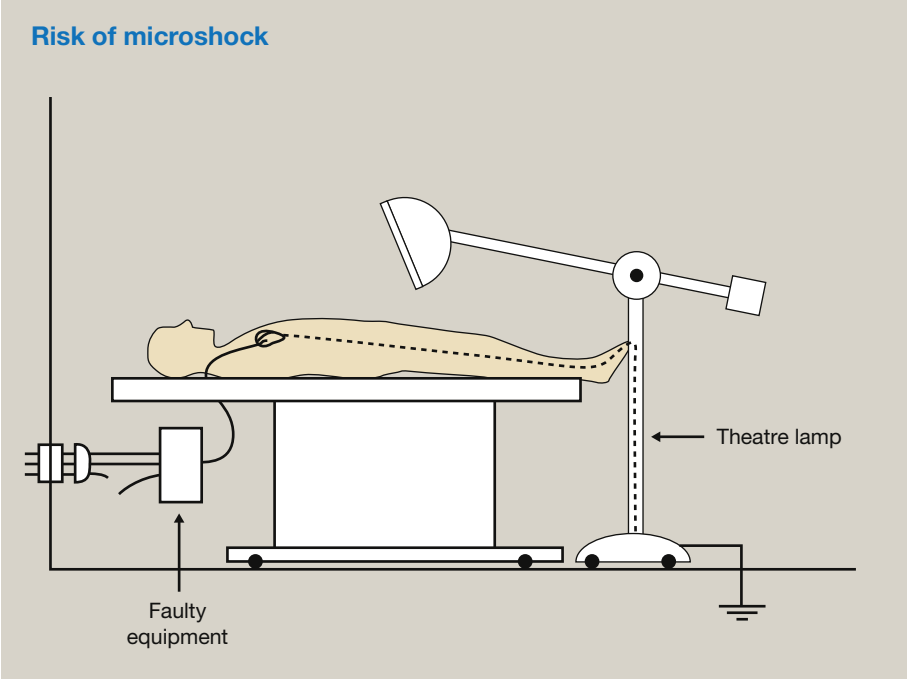

Figure 1

and has been renamed 'General Requirements for Basic Safety and Essential Performance' to reflect the fact that inadequate equipment performance may give rise to hazards. The new standard replaced the second edition but it is recognized that in practice there is likely to be a fairly long transitional period for compliance by manufacturers.

Equipment is classified according to the means of protection.

- **Class 1:** any conducting part of the equipment which may contact the patient is connected to earth by an earth wire (the third pin of the plug connecting the equipment to the mains socket). It incorporates a fuse in the mains plug that melts to break the circuit when a live supply comes in contact with the accessible part, and it also has fuses in the live and neutral conductors for additional protection.
- **Class 2:** this is equipment protected by double or reinforced insulation. The power cable has only live and neutral conductors and incorporates only one fuse.
- **Class 3**: battery-powered equipment with 'safety extra-low voltage' (SELV). SELV is defined as voltage not exceeding 25 V AC or 60 V DC. Even with this low voltage, the chance of microshock still exists.
- **Type B equipment:** this can be class 1, 2 and 3 equipment designed to have low leakage currents.
- **Type BF equipment:** similar to type B, but the part applied to the patient is isolated from all other parts of the equipment.
- **Type CF equipment:** this is equipment considered safe to be directly connected to the heart which allows almost no leakage current.

Types B, BF, and CF also may be designed with defibrillator protection (Figure 2).

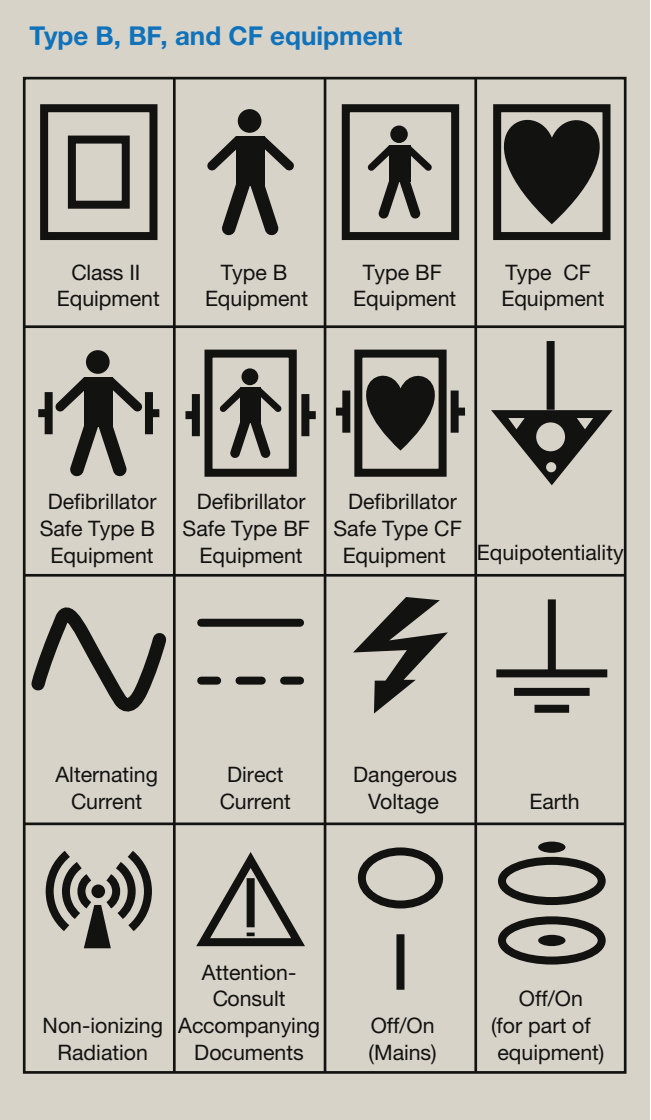

Figure 2

Specific measures

Maintenance of equipotentiality: Different equipment is connected to each other to bring them all to the same earth potential. If equipment in close proximity has a different potential, then current can flow from the equipment with higher voltage to that with a lower voltage if a person is in contact with the equipment completes the circuit. Thus there is no risk of potentially hazardous earth differentials.

Isolated or floating circuits: Patients are not connected directly to earth via plates and/or electrodes so current cannot reach the patient if contact with a live supply occurs. This is achieved by the use of an isolating transformer (Figure 3).

Circuit breakers: Known as current-operated earth leakage circuit breakers (COELCB) or 'earth trip' or 'residual current circuit breakers', these are devices where the supply live and neutral wires are coiled with the same number of windings around the core of a transformer. A third winding connects these to the coil of a relay that operates the circuit breaker. If the current in the live and neutral conductors are the same then the magnetic fluxes (see induction) cancel each other out. If they are different (due to current leakage) the magnetic flux will induce a current in the third winding that causes the relay to break the circuit.

Diathermy

Diathermy (from the Greek words 'through heat') refers to the tissue-heating effect that occurs when the body forms part of a circuit, through which a high-frequency current passes. William T Bovie is often credited with the invention of the diathermy unit, but the German physician Nagelschmidt first coined the word.

Mechanism

The passage of current through the body is via electrolytic solutions in the tissues and bloodstream. The source voltage is created by the diathermy generator, which converts mains 50 Hz current into a high-frequency current of 0.2–3 MHz. At these radiofrequencies there is minimal risk of muscle or nerve stimulation. Instead, electrical energy is converted to heat as the electrons overcome the impedance of the body. The heat generated is governed by Joule's law:

$$Q(\text{heat in Joules}) = I^2(\text{current density}) \times R(\text{resistance}) \times t(\text{time})$$

Current density is the current per unit cross-sectional area. If the current is concentrated at a single point such as the active

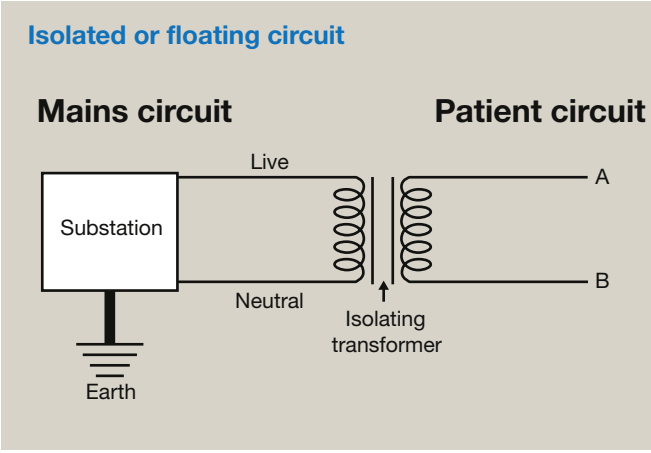

Figure 3

electrode (surgical tool), the effect will be greater than if spread out over a large area (the dispersive electrode plate). Tissue temperature at the active electrode tip is about 1000°C, but 1 cm away from the tip it only reaches about 38°C. For a given voltage the current is the same, but if the area through which the current flow falls, resistance increases and more heat is produced (Table 2).

Diathermy circuits (Figure 4)

Historically, diathermy used mains voltage referenced to earth and the dispersive electrode was earthed. If this pad became loose, was incorrectly applied, or the current found an alternative path to earth (e.g. via a limb in contact with the table), burns would result.

Modern diathermy generators use an isolated circuit with output voltages referenced to the generator itself. This requires current to flow back to the generator to complete a circuit. If this circuit is broken (e.g. if the dispersive electrode is not connected), current will not flow.

The metal casing of the diathermy machine is earthed in case of insulation failure.

Diathermy modes

There are two types of diathermy circuits: monopolar and bipolar.

Monopolar is used more frequently due to its greater versatility. In this mode, current flows from the diathermy device through the surgical active electrode, through the body, and back to the diathermy device via the dispersive electrode. The current density is greatest at the active electrode and heating occurs here.

In bipolar mode the surgical tool is a pair of forceps where one blade represents the active electrode and the other the return electrode. The current flows at high current densities from one tip to the other via the bite of tissue between, rather than through the body; this eliminates the need for a dispersive pad. Modern devices are capable of sealing vessels up to 7 mm in diameter by a combination of mechanical pressure and diathermy. Microprocessors use tissue response generators to adjust current and voltage based on the sensed tissue impedance, so vessels can be reliably sealed to withstand three times normal systolic pressure.

Surgical effects

The surgeon has the ability to alter the power setting, the waveform, the diathermy tool and how it is applied (Figure 5).

Cutting: The cutting effect is achieved by using a pure continuous sine wave of low voltage. This rapidly produces high temperatures that vaporize tissue fluid causing cells to explode forming a gap in the tissues. The electrode need not be in contact with tissue, as an arc is formed producing a clean cut. With the coagulation setting on high power, cutting also occurs, but this produces a larger zone of greater thermal damage.

Electrical concepts

Term	Description	SI units
Charge (Q)	Measure of the fundamental property of matter that determines its electromagnetic interaction 1 Coulomb=6.2415 × 10^{18} electrons	Coulombs
Current (I)	Measure of the flow of charge per unit time	Amperes
Voltage (V)	Measure of the electrical force that determines flow of current Ohm's law $V = I \times R$	Volts
Resistance (R)	Measure of the opposition to the flow of current	Ohms
Impedance (Z)	Opposition to flow of current in an AC circuit Specific tissue impedance 2000–3000 Ohms	Ohms
Current density	Measure of the flow of current per unit area	Amperes/m^2
Power (P)	Rate at which Energy is transferred $P = V \times I = I^2 \times R$	Watt
Energy (E)	A measure of the capacity to do work = Power × Time	Joules

Table 2

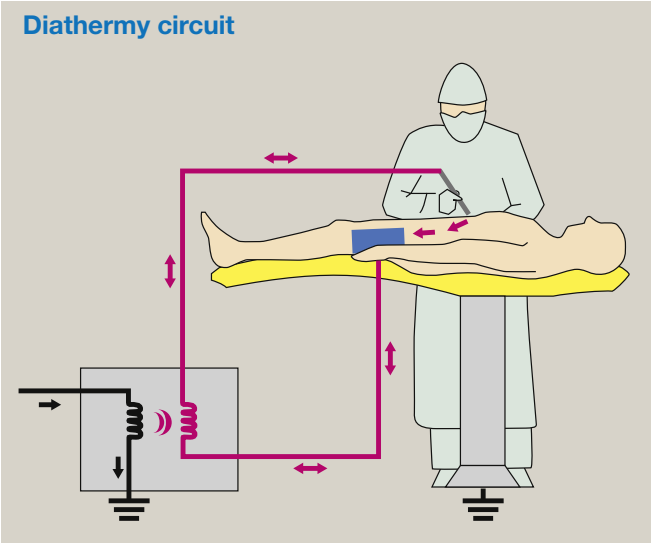

Figure 4 A circuit is formed as current flows from the generator, to the active electrode, through the body, back through the passive dispersive electrode to the generator.

Coagulation: The coagulation effect is achieved by using an intermittent sine wave with a short 'on' time and a longer 'off' time; a low duty cycle.

Duty cycle = On time/Period (On time/Off time)

Coagulation: uses a higher voltage to achieve the same power because it is applied intermittently. This intermittent delivery reduces the rate of heat rise and produces a coagulation effect.

Fulguration: This occurs if coagulation voltage is high enough to arc causing a zone of thermal damage around the vaporized tissue.

Desiccation: This is achieved by keeping the probe in contact with the tissue but using heat insufficient for cutting. This dries out the tissue and a coagulum is formed.

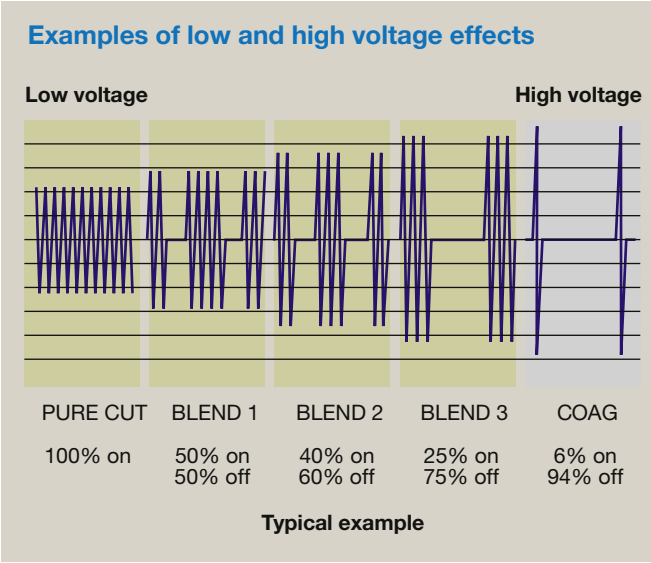

Figure 5

Blend: It is also possible to use a blended waveform. A separate waveform with higher duty cycles giving more cut and less coagulation.

Diathermy hazards

Burns and fires: Fires can occur when pools of flammable, alcohol-based skin preparations are ignited. Thermoelectric burns occur where the current density rises inadvertently, such as where tissue in a pedicle burns when the current is concentrated as it flows between the two electrodes. Burns can occur at the dispersive electrode if it is applied incorrectly or not of sufficient size, so the site should be well perfused, be distant to any metal implants that may become heated, and be free from hair. Burns have also been reported from insulation failure at the active electrode or accidental contact between the active electrode and another conductor.

There is one case report of ignition of a diathermy handset during use of transnasal humidified rapid insufflatory exchange (THRIVE). Avoiding airway fires mandates the use of the lowest effective voltage, avoiding cutting mode when using diathermy in the airway or using bipolar diathermy. Arranging drapes to minimize the pooling of oxygen or shrouding the diathermy instrument tip with carbon dioxide should also be considered.

Safety systems: Dispersive electrode contact monitoring pads have a dual foil design that allows measurement of skin impedance to ensure adequate skin contact. An audible alarm alerts staff to electrode failure. The isolated circuit reduces the risk of burns from contact with earthed objects, as the current must return to the generator to complete the circuit; however, burns can still occur due to capacitive coupling.

Capacitive coupling: A capacitor is simply two conductors (one of which may be the active electrode) separated by an insulator such as air. High-frequency currents flow through a capacitor since an electrostatic field is created between the two conductors, and when the insulating capacity is exceeded, a current is induced in the other conductor. If this current is high enough it can cause a burn at sites of patient contact. This is a hazard during laparoscopic surgery between the active electrode and a metal trochar.

Electromagnetic interference (EMI): Diathermy can interfere with both electroencephalography and electrocardiography monitoring electrodes. Of greater consequence is the interaction between EMI and cardiac pacemakers or implantable defibrillators. Bipolar is safer than monopolar, but can still cause EMI. The effects are unpredictable and include inappropriate pacing, damage to the device, inappropriate defibrillation, and myocardial heat damage. Modern pacemakers have a titanium shell and interference monitor to protect them from EMI. The use of a magnet to reset pacemakers to asynchronous continuous pacing is not predictable. Current advice suggests limiting the use of diathermy to short low-power bursts and avoiding monopolar where possible. Placement of the dispersive electrode away from the device increases safety. Where appropriate the device should be checked and reprogrammed to monitoring mode prior to surgery.[1]

Diathermy surgical smoke: Diathermy smoke consists of 95% steam and 5% cellular debris, this debris has a mean diameter of 0.07 μm and contains a variety of toxic mutagenic chemicals including hydrogen cyanide and benzene. Viruses and viable cancer cells can also be transmitted in surgical smoke and diathermy machines now contain a surgical smoke evacuator with a 0.1-μm filter attached to the diathermy pencil less than 2 cm from the site of smoke production.[2]

Similar devices

Ultrasonic surgical tools are not diathermy devices. They operate by containing elements that vibrate at 55.5 kHz. No electrical energy flows. The cutting and coagulation effect occurs at lower temperatures than diathermy, by a combination of mechanical and heat energy that denatures proteins. ◆

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Acknowledgements

The author acknowledges the contributions to this merged article of Drs Hasher Palluthu Kadavil and Daniel E. Boyd who collaborated on the earlier versions of *Electrical Hazards* and *Surgical Diathermy* respectively.