Update in
Anaesthesia

Electricity and Magnetism

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Summary

This article outlines the areas of knowledge concerning electricity and magnetism that are essential for the practice of safe anaesthesia. The areas covered include basic concepts, amplification of biological potentials, sources of electrical interference, electrical hazards and their causes and prevention, diathermy and defibrillators.

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ELECTRICAL CHARGE

Charge is a fundamental property of matter. Atoms, the fundamental particles that make up matter are composed of protons (with a positive charge), neutrons (with no charge) and electrons (with a negative charge). Electrons are 'point particles' with no physical substructure and they have properties characteristic of both a particle and a waveform. They are bound into atoms by their tendency to be attracted towards positively charged protons. Materials that are electrical conductors have loosely bound electrons in their outer shells.

ELECTRICAL CURRENT

Like *charges* repel and tend to move from sites of high charge density, or potential, to those with lower potential. Moving or flowing charge constitutes an electrical current and, as an aid to understanding this concept, the flow of current is roughly analogous to flow of fluids (Figure 1). By convention current is described as flowing from the positive electrode to the negative electrode, although in reality electrons (negatively charged) move in opposite direction (Figure 2).

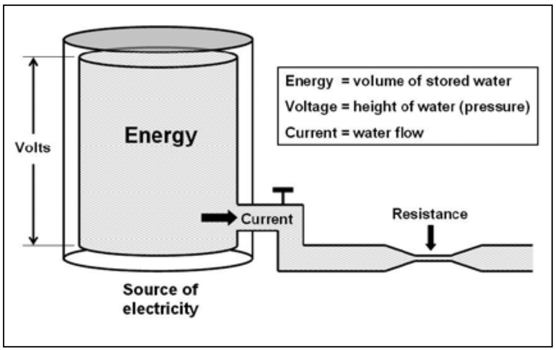

Figure 1. *Electricity explained as an analogy to fluid flow*

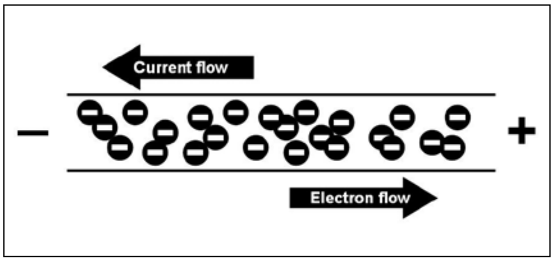

Figure 2. *Conventional electric current flow and electron flow*

DEFINITIONS AND UNITS

Ampere (A)
The unit of electrical current. *One of the seven fundamental SI units*.

Defined as the amount of current producing a force of 2×10^{-7} Newtons per meter ($N.m^{-1}$) between two infinitely long parallel conductors placed 1 meter apart in a vacuum.

Coulomb (C)
The unit of quantity of electrical charge.

Defined in terms of current flow per unit time or the quantity of charge carried past a point in one second by a current of 1A.

Volt (V)
The unit of electrical *potential*.

Defined as the difference of electrical potential between two points of a conductor carrying 1A current, when the power dissipated between the points is 1 watt (W).

Ohm (Ω)
The unit of resistance to flow of electrical current.

If a potential of 1V is applied across a conductor and the current flow is 1A, then the resistance is 1Ω.

STATIC ELECTRICITY

You may occasionally notice a click of energy when shaking someone's hand; this is due to build up of static charge by contact of our shoes on the carpet. The click is due to discharge of the static charge on contact with the other person. Static is a stationary collection of electrical charge that can be positive or negative. It is usually formed as a result of charge separation between dissimilar materials. Items are said to become charged, and a potential difference is created representing stored potential energy. This energy can be released or *discharged* as sparks, which has implications in theatre, particularly when using flammable agents such as ether.

CURRENT ELECTRICITY

Current describes moving electrical charge that flows around *circuits* and is described by Ohm's law:

$$\text{Current, I} = \frac{\text{Voltage, V}}{\text{Resistance, R}}$$

(or commonly rearranged as: $V = IR$)

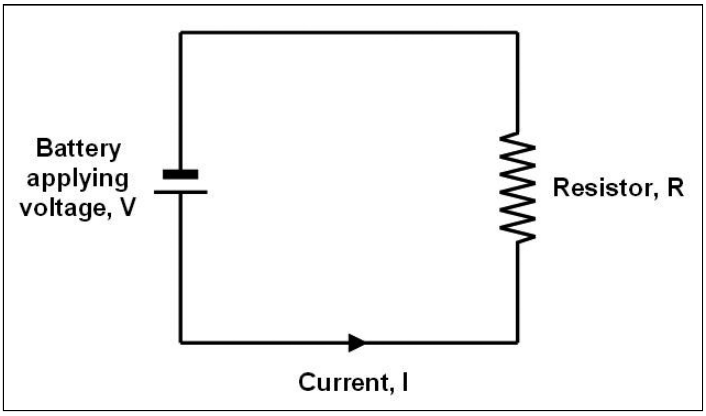

Figure 3. *Ohm's law*

Bridge circuits

Bridge circuits, for example the Wheatstone bridge, are used in equipment such as the transducer of an intra-arterial blood pressure system and are a simple application of Ohm's Law. Transducers change energy from one form to another – an arterial transducer responds to physical change (e.g. pressure causing stretch) by varying its resistance. A thermistor, which has a resistance that varies with temperature, is another example. A bridge circuit can be used to calculate the change in a physical quantity by measuring change in resistance of the transducer (Figure 4).

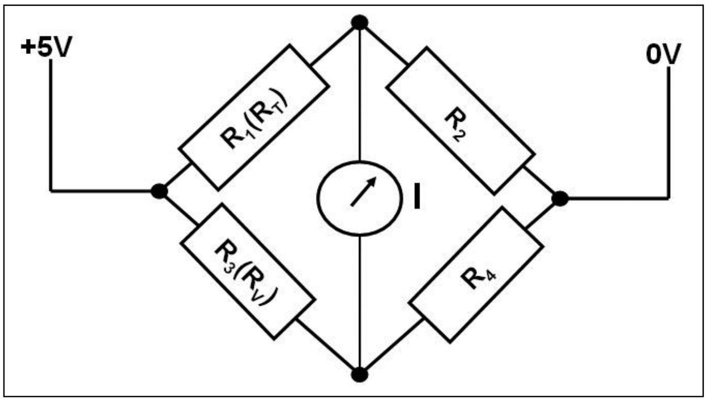

Figure 4. *The Wheatstone Bridge. When $R_1/R_2 = R_3/R_4$, no current flows through the meter (I) and the 'bridge' is said to be 'balanced'. The transducer (R_T) is connected in place of R_1 and a variable resistor (R_V) replaces as R_3. The transducer is zeroed by adjusting R_V until there is no current flow through I. A change in the transducer's resistance unbalances the circuit and causes a current to flow through the meter. The amount that the variable resistor must be changed to restore the bridge to balance (i.e. no flow at I), can be used to calculate the resistance change at the transducer and therefore the pressure change to which the transducer has been exposed*

Direct and alternating current

Direct current (DC) describes steady flow of current from a positive to negative pole. Almost all electronic equipment requires DC.

Alternating current (AC) is a sinusoidally oscillating flow of current produced as the potential between the poles reverses. Most electrical equipment runs on AC. United Kingdom mains is AC 240 volts, oscillating at (i.e. changing polarity at) a frequency of 50Hz (fifty times per second). The peak voltage is 340V. Because the voltage oscillates symmetrically around zero, the average or mean voltage is zero. The figure of 240V is actually the root-mean-square (RMS) of the component values and gives a more meaningful figure for the average voltage (squaring the values, averaging them, then taking the square root makes the negative values, positive).

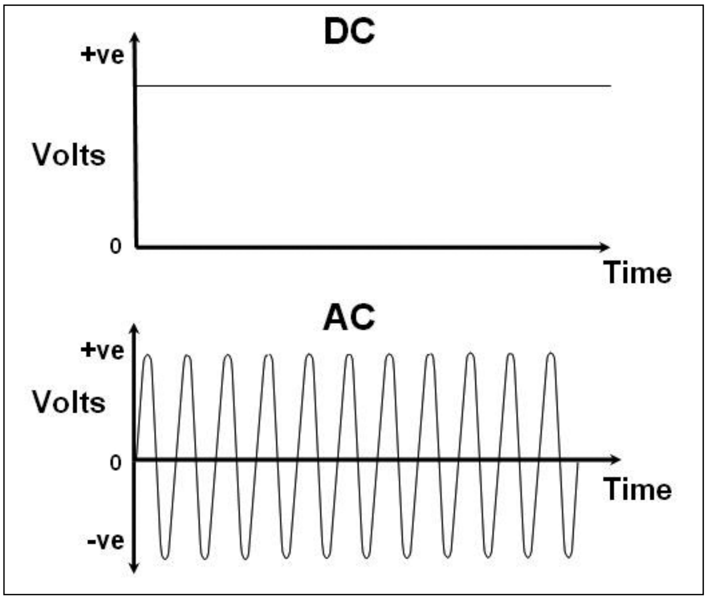

Figure 5. *Graphical description of direct and alternating currents*

MAGNETISM

Theory

Magnetic force is a fundamental natural force (like gravity) and, as such, is not easily explained. Magnetic poles are always paired and are usually described as *north* or *south*. Magnetic *fields* are classically described in terms of lines of flux, which show the direction of the magnet field at any particular point. Materials can be:

- *Ferromagnetic* – they are strongly attracted into a magnetic field, become magnetic while in the field and remain so after the field is removed,
- *Paramagnetic* – they are weakly attracted into a magnetic field,
- *Diamagnetic* – they are weakly repelled form a magnetic field.

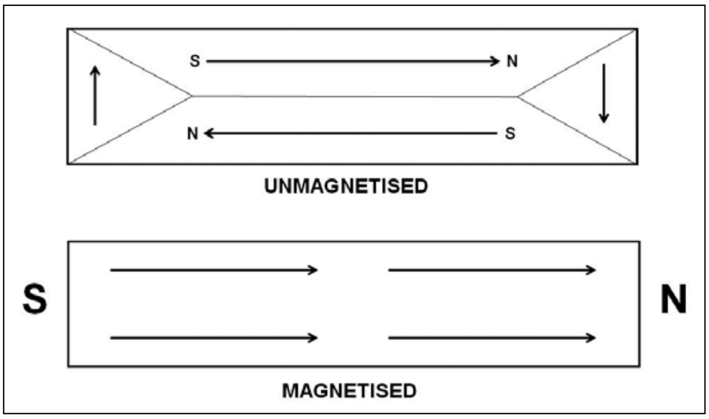

Figure 6. *Ferromagnetism is described in terms of 'domains' – areas within the substance that are uniformly magnetised, with polarity in the same direction*

Electromagnetism

Flow of electrical current and magnetism are inextricably linked. All moving charge (electrical current) produces a magnetic field. The *dynamo effect* means that if a conductor moves through a magnetic field, an electrical current will be *induced* in the conductor. Electromagnetism is governed by Flemings Rules - Figure 7.

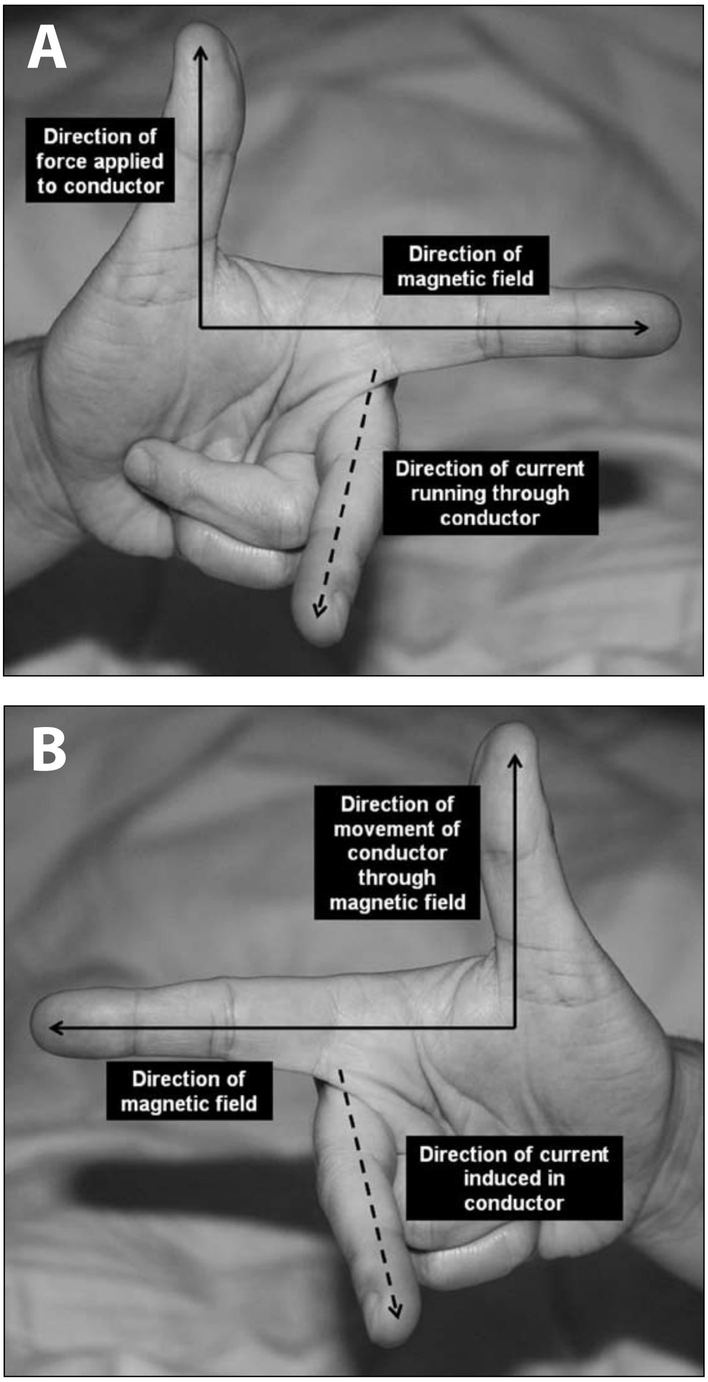

Figure 7. *Flemings left and right hand rules of electromagnetic induction. The left hand rule (A) predicts the direction of Movement of a conductor (thuMb), when a Current flows down it (in direction of seCond finger), in a magnetic Field in the direction of the First finger. The movement is driven by the induced electromotive force. The right hand rule (B) predicts the direction of current flow induced in a conductor moving through a magnetic field*

Current flowing in a coil of wire produces a magnetic field within the coil and this is called an electromagnet or a *solenoid*. The magnetic field density generated is directly proportional to current flow and the number of turns of wire in the coil and is strongest within the solenoid (Figure 8). If the current is oscillating then an oscillating magnetic field is generated. Under certain conditions this oscillating field generates propagated electromagnetic waves - this phenomenon forms the basis of radio transmission.

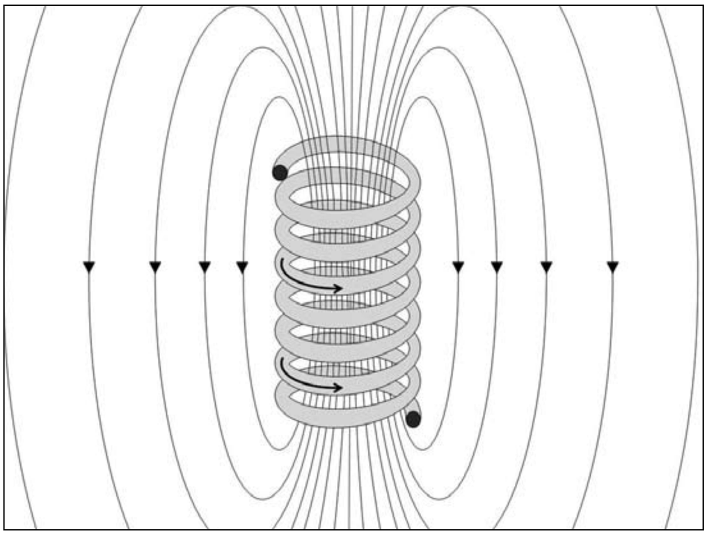

Figure 8. *The magnetic field generated within a solenoid, with a current applied as indicated by the arrows*

Applications of electromagnetism:

- Electric motors and dynamos,
- Transformers - step-up, step-down, isolating and signal transformers (see Figure 9),
- Solenoid valves - ventilators, gas mixers and safety interlocks,
- Magnetic 'springs' - e.g. the Bird ventilator,
- Paramagnetic oxygen analyzers,
- Magnetic resonance imaging (MRI).

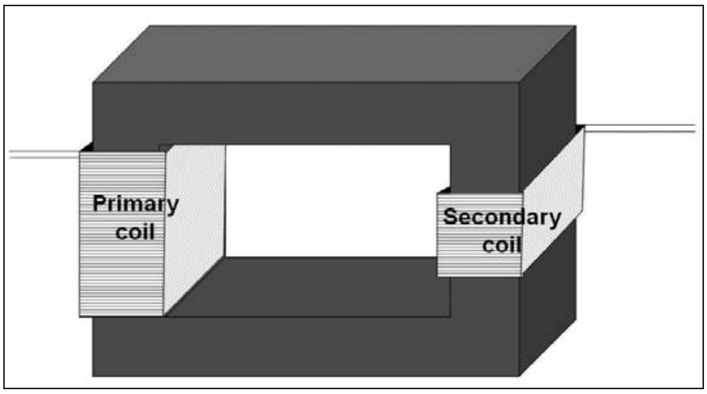

Figure 9. *A transformer is two coils of wire - the primary and secondary coils - wrapped around a piece of iron. It makes AC voltages larger or smaller. A transformer with more turns in the primary coil (as below) decreases the voltage and is a step-down transformer. The reverse arrangement produces a step-up transformer which increases the voltage (but proportionately decreases the current)*

CAPACITANCE, INDUCTANCE AND IMPEDANCE

Capacitance

Capacitance describes the ability of an object to store electrical charge and is measured in *farads*. Capacitors store electrical energy and generally consist of a pair of metal plates, separated by a non-conductor (the *dielectric*). They have a potential difference between them but cannot conduct direct current continuously, because of the presence of the non-conductor. When exposed to a direct current, the plates store charge (and current transiently flows) until the voltage between the plates equals that of the supply voltage; the capacitor is now charged.

Capacitors can conduct AC current since the plates alternately charge and discharge as the direction of current flow changes (Figure 10).

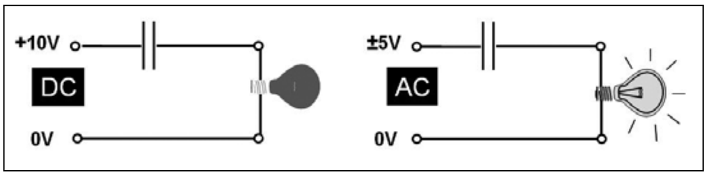

Figure 10. *Capacitors prevent the flow of direct current (after an initial current flow which charges the capacitor to the applied voltage). Alternating current is conducted to an extent that depends on the capacitance of the capacitor and the frequency of the AC current*

The energy stored by the capacitor is calculated by, $E = ½C \times V^2$.

Capacitance exists between many objects in theatre which act as pairs of plates (e.g. between the ECG leads, the patient, a theatre light and the table), with the air acting as the insulator between them. This *capacitive coupling* can cause electrostatic interference; an example is the interference from diathermy as a result of capacitive coupling between an insulated diathermy lead, overlying an ECG lead. Allowing current flow between the terminals of a charged capacitor discharges it and releases the stored energy.

Inductance

Inductance arises in circuits with alternating or oscillating currents. As the current reverses, the associated magnetic field (see above) in a coil or loop of wire waxes and wanes. The fluctuating magnetic field *induces* a current in the same wire in the opposite direction to original current, which is in opposition to the original change (*Lenz's Law*).

Inductance is proportional to rate of change of current (i.e. the AC frequency) and the number of turns in the coil. Hence the resistance to current flow (the impedance – see below) is *frequency dependent*.

Impedance

This is a fundamental concept in AC circuits and signal processing, describing the opposition to the passage of current. Impedance is analogous to resistance in DC circuits and, like resistance, is measured in *ohms*. Impedance is given the symbol, Z.

The magnitude of impedance depends upon a complex relationship between the signal frequency and the capacitance, inductance and resistance of circuit. It is the *frequency dependence* of impedance that makes it possible to build circuits which present high impedance to one range of frequencies and low impedance to others - this is the basis of *electronic filters*.

Electronic filters

Filters act to create a low impedance path to transmit signals in a desired frequency range (e.g. the ECG signal) while attenuating all other frequencies. They are described by their transmission characteristics:

- *High pass* - transmit frequencies *above* a cut-off frequency,
- *Low pass* - transmit frequencies *below* a cut-off frequency,
- *Band pass* - transmit frequencies within a middle range (a band).

CLINCAL ROLE OF CAPACITORS AND INDUCTORS

Defibrillators

Defibrillation is the application of a preset electrical current across the myocardium to cause synchronous depolarization of the cardiac muscle, with the aim of converting a dysrhythmia into normal sinus rhythm.

The most important component of a defibrillator is a capacitor (Figure 11), which stores a large amount of energy in the form of electrical charge, then releases it over a short period of time. For successful defibrillation, the current delivered must be maintained for several milliseconds. The current and charge delivered by a discharging capacitor decay rapidly and exponentially. Inductors therefore have a role in prolonging the duration of current flow.

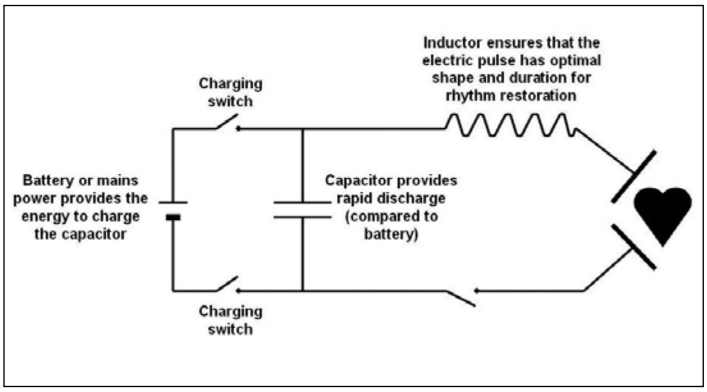

Figure 11. *Schematic diagram of a defibrillator. The charging voltage is approximately 5000V and the total current delivered is up to 35A. The stored energy of the capacitor is* $½CxV^2$

Monophasic and biphasic defibrillators (Figure 12)

In many countries biphasic defibrillators have replaced monophasic dibrillators. They require lower energy levels to achieve defibrillation and the risk of damage to the cardiac muscle is therefore less. Smaller capacitors are required and batteries have longer life.

AMPLIFIERS

Principles

An amplifier increases the *power* of an electrical signal – the output signal is *proportional to input but of greater magnitude*. The ratio between output and input is the amplification factor or gain, with the power gain expressed in decibels (dB). Voltage gain is the ratio of input signal voltage to output voltage.

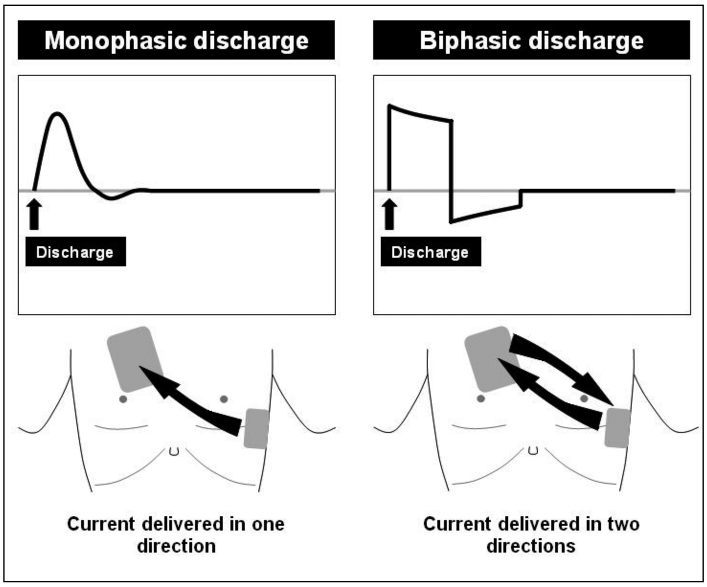

Figure 12. *Biphasic defibrillators – the current waveform is electronically regulated*

An ideal amplifier should have the following properties:

- *a good signal to noise ratio* (expressed in dB),
- a *linear frequency response* over its working frequency range (Figure 13),
- an output signal which does not drift with time or temperature (Figure 14)- achieved with careful design, re-zeroing and thermal compensation,
- minimal *hysteresis* within the system (Figure 15),
- an adequate *dynamic response* over its working frequency range. Gain should be constant for all frequencies in the signal and any phase change or delay should be the same for all frequencies in the signal, i.e. optimal damping (see *Biological signals article*).

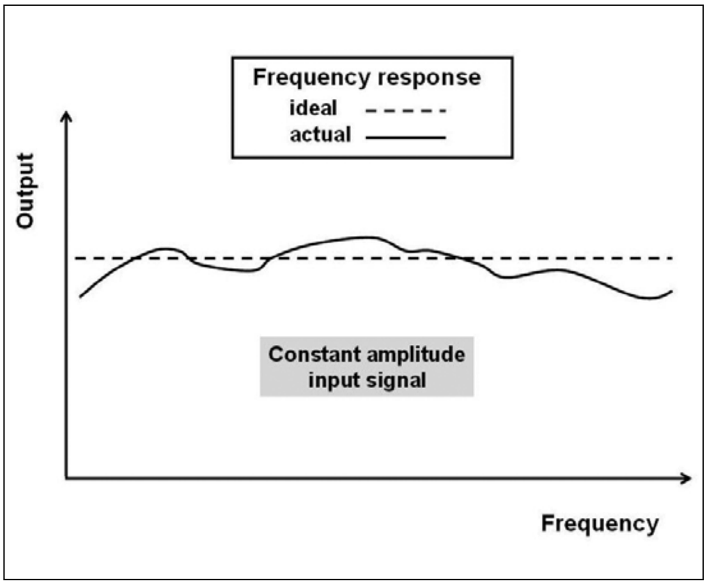

Figure 13. *A non-linear frequency response is shown*

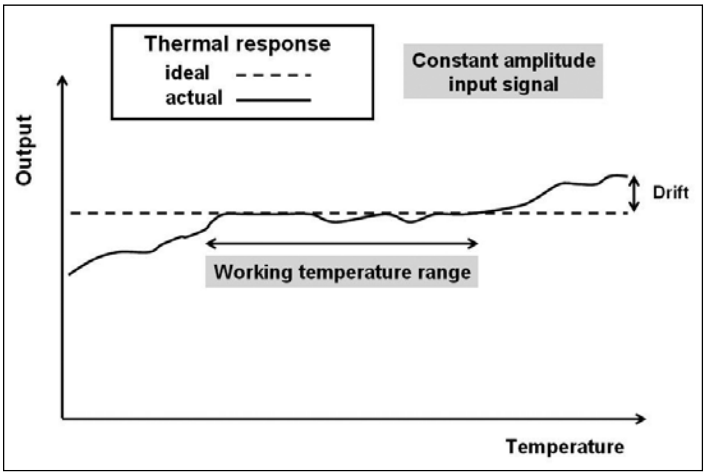

Figure 14. *Example of an amplifier with thermal drift*

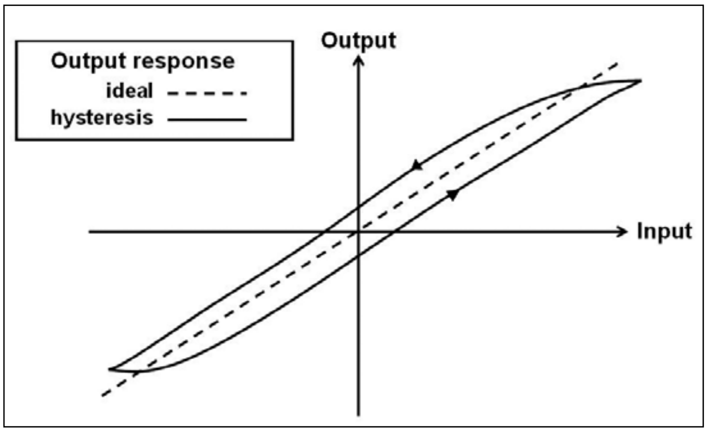

Figure 15. *Hysteresis – for a certain input the output is different, depending on whether the input is increasing or decreasing*

Differential amplifiers

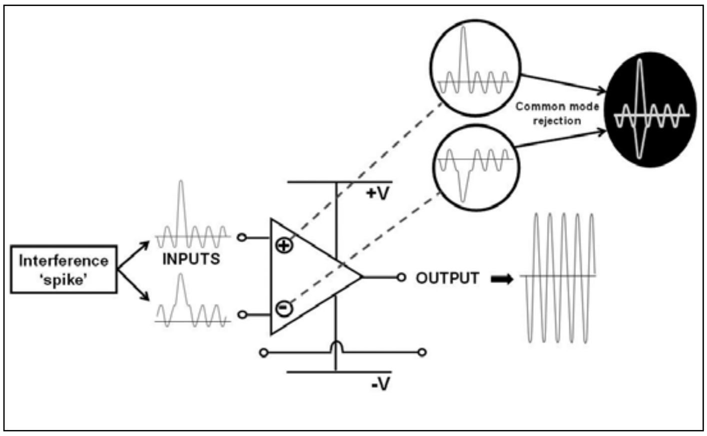

Figure 16. *A differential amplifier uses a 'common mode rejection' to exclude interference common to two separate inputs, thereby improving the 'signal to noise ratio' of the remaining signal*

Amplifiers in clinical practice

- Amplification of biological signals is usually performed in several stages. Maximum transfer of signal power occurs when output and input impedances are equal (*impedance matching*).

- Negative feedback is used to stabilize amplifiers and prevent oscillations.
- The frequency response can be modified to enhance amplification of a relevant frequency band (*active filter*).
- Differential input amplifiers are generally used in biomedical equipment and they provide considerable improvement in *signal to noise ratio*.

SOURCES OF INTERFERENCE

Noise

This is interference superimposed on the required signal. It may be extraneous or introduced within monitoring equipment. Any interference reduces the *signal to noise ratio* and degrades the quality of the information available.

Interference sources include:

- Electrostatic induction - electrical potentials induced in the patient by adjacent electrical fields,
- Electromagnetic induction,
- Electrode contact potentials (Ag-AgCl),
- Movement artifacts - skin potentials and induction,
- 50Hz mains and switching spikes,
- Radiofrequency energy - broadcast (mobile phones) and diathermy - high frequency and high power.

EFFECTS OF ELECTRICITY ON THE BODY

Electrocution means to kill by electricity. The effects of electricity passing through the body depend upon current density and the path taken. High current densities deliver large amounts of energy and cause burns. Low current densities can still be dangerous because of their effects on excitable tissues, notably the heart. The response to different current levels varies between individuals.

Table 1. *Macroshock - the effects of a hand to hand AC current at 50Hz for 1 second*

Current	Effect
(< 1mA	No sensation - microshock)
1mA	Tingle
5mA	Pain
15mA	No-let-go threshold - tetanic contraction
50mA	Respiratory arrest - respiratory muscles in tetany
75mA	Arrhythmias, ventricular ectopics and myocardial 'pump failure'
100mA	VF cardiac arrest
> 5A	Asystole

There are two main risks:

1. **Macroshock.** The current flow is greater than 1mA and is sensed by the individual.
2. **Microshock.** The current is 100mcA to 1mA, is too small to be sensed but can be hazardous if a part of the equipment is applied to the heart (e.g. central venous lines).

Microshock

The intracardiac VF threshold is 60-100mcA with a small surface area electrode. Below the sensory threshold, the shock cannot be felt and this is termed microshock. Intact dry skin is the most important safeguard against shocks. Lowering the skin resistance with contact electrodes or saline substantially increases the current for any given applied voltage.

DIATHERMY

Definition

The generation of heat in body tissues by passage of a high-frequency electric current between two electrodes, placed in or on the body. When applied specifically to surgery the high-frequency current, at the tip of a diathermy knife, produces sufficient heat to cut tissues, or to coagulate and kill cells, with a minimum of bleeding.

Principles

A voltage source from an electrosurgical generator is applied across the tissue causing an electrical current to flow. This forms a simple electrical circuit, with the tissue acting as a resistor. Current flowing through the resistance of the tissue causes the generation of heat within the tissue itself, and the heat causes the tissue damage. The resistance of the tissue converts the electrical energy of the voltage source into heat (thermal energy), which causes the tissue temperature to rise:

Heat produced = Electrical energy expended

Excitable tissues are very sensitive to low frequency alternating current and stimulation ceases above about 100kHz, therefore diathermy uses a range between 200kHz to 5MHz. In this frequency range electrosurgical energy causes minimal neuromuscular stimulation and no risk of electrocution.

Diathermy circuits are either *bipolar* or *monopolar*, and different effects on tissues are achieved by varying the electrical waveform and/or the power level.

Bipolar diathermy

The active and return electrode functions are both accomplished *at the surgical site*, with the current path confined to tissue grasped between the tips of the forceps. Current does not spread through the patient's body.

Monopolar diathermy

The active electrode is in the wound and the patient return electrode is attached somewhere else on the body. The current flows through the patient to the patient return electrode and then back to the generator. Monopolar diathermy is versatile and clinically effective.

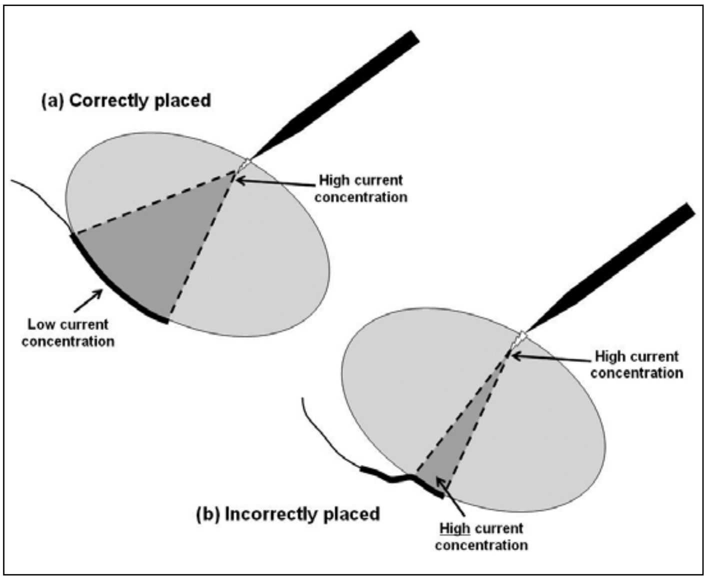

Figure 17. *If the return electrode of monopolar diathermy is poorly placed (b) there is increased current density and a risk of burns. Modern generators monitor the adequacy of contact by measuring the impedance between the pad and patient. There is an inverse relationship between impedance and contact area and, if it detects a dangerously high level of impedance at the patient/pad interface, the system deactivates the generator before injury can occur*

Modern generators have *isolated circuits*, which eliminate many hazards inherent in earthed systems. If the return electrode circuit to the patient is broken, an isolated generator will deactivate the system because the current cannot return to its source. The function of the patient return electrode is to remove current from the patient safely. It carries the same current as active electrode but the effect of the current is less because of its size and relative conductivity; the *current density is lower*. The more concentrated the energy, the greater the thermodynamic effect.

The extent of the burn is governed by the relationship:

$$\text{Burn} = \frac{\text{current x time}}{\text{area}}$$

Other risks of diathermy:

- A potential source of ignition risking fires or explosions.
- *Direct coupling of current* - the user accidentally activates the generator while the active electrode is near another metal instrument. The secondary instrument will then become energised.

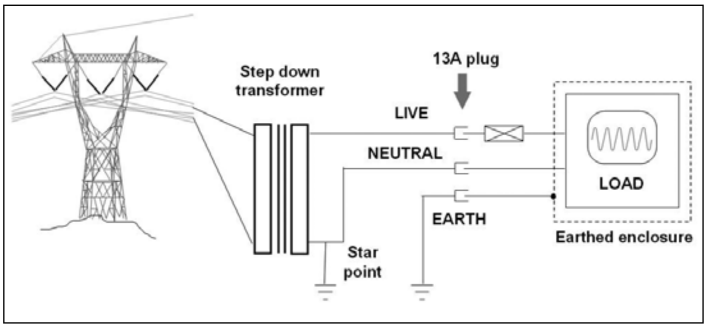

Figure 18. *Distribution of 240V mains electricity*

- *Capacitive coupled current* - an 'inadvertent capacitor' may be created by the surgical instruments. The conductive active electrode is surrounded by nonconductive insulation. If this, in turn, is surrounded by a conductive metal cannula, the current in one conductor can, through the electrostatic field, induce a current in the second conductor.

OTHER ELECTRICAL HAZARDS

Mains electricity

Hazards mainly arise from mains powered equipment.

Primary protection from hazards

Insulation

Basic protection against electric shock from mains powered equipment is provided by insulation. All 'live' parts in equipment are separated from each other by non-conducting material. If damaged, a live component may 'short' to the case raising it to mains voltage, constituting a single fault condition. Medical equipment must remain safe under single fault conditions and so *secondary protection* is required.

Secondary protection from hazards

There are three classes of secondary protection (Table 2):

Equipment should only become hazardous if two faults are present simultaneously, for example a short to the case *and* a broken earth lead. The result of a 'two fault' state such as this would be a *live enclosure* - if touched current will flow to earth through the patient or a staff member. This is prevented by regular servicing and testing for both types of fault separately, aiming to detect a single fault condition before the second fault occurs.

Prevention of microshock

Microshock is hazardous when there is a low impedance piece

Table 2. *Classes of secondary protection*

Class I	All exposed electrically conductive parts are connected to earth potential by a conductor which will convey any leakage current to earth.
Class II	No protective earth. Basic insulation is supplemented by a second layer of insulation (double insulated). No exposed conductive parts can contact the live conductors.
Class III	Protection relies on supply of power at safety extra low voltage (SELV) - 24V (Root mean square).

of equipment placed in contact with the patient. An example is an intracardiac catheter (central line), which should contain 5% glucose, not an ionic (and therefore conductive) solution such as 0.9% saline.

Stringent criteria are set for the maximum permitted leakage current from equipment placed in contact with a patient and this depends on the nature of that contact. Three groups of equipment are considered suitable for direct connection to patient - these are coded B, BF and CF. 'F' denotes that the part applied to the patient is isolated from all other parts of the equipment, i.e. it is 'floating'. The maximum leakage current (British standard, BS 5724) for each class of equipment is shown in Table 3.

Table 3. *Maximum leakage standards for different classes of equipment*

BS 5724 standards	**BF**	**CF**
Earth leakage	500 (1000)	500 (1000)
Enclosure circuit	100 (500)	10 (500)
Patient circuit	100 (500)	10 (50)

All currents are in microamps (mcA).

(Bracketed figures) denote permitted leakage current in a single fault condition.

Type BF - can only be applied to body surface.

CF – the category for equipment with potential direct cardiac connection.

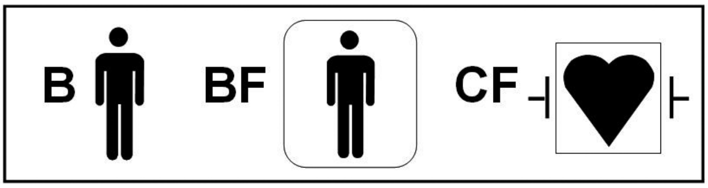

Figure 19. *Labels identifying classes of equipment used in contact with patients*

Other methods of protection

Maintenance

Programs of regular maintenance are essential to detect and correct faults.

Isolation

The major means of protection is isolation of the applied part, meaning that the input circuitry is electrically isolated from the other components of the equipment. Isolation is achieved through:

- Earth leakage contact breakers. These are not sensitive enough to detect microcurrents and may be too slow to guarantee protection.
- Isolation transformers provide an *earth-free mains* connection.
- Opto-isolation is used in most electronic equipment. An optical isolators is a device that uses a short optical transmission path to transfer a signal between elements of a circuit.

Practical considerations for theatre

- No long cables,
- No distribution blocks,
- Pendant (hanging) electrical supplies,
- Beware of and change chaffed cables,
- Keep the patient's skin dry,
- Check maintenance reports regularly,
- Use earth leakage circuit breakers.

CONCLUSION

Electricity is now available in most theatres around the world and many of the technologies available for patient care, monitoring and safety rely upon it. Whilst many anaesthetists will not seek a detailed understanding of the circuitry within their equipment, some basic knowledge is essential to minimise any risks of harm to the patient by inadvertent exposure to electrical current. This is particularly important where the facilities for regular servicing are stretched or unavailable, when the ability to keep equipment safe and functional is the responsibility of the anaesthetist.