Basics of electricity for anaesthetists

Shiv Kumar Singh MB BS, FRCA
Rachel Ingham MBChB, FRCA
James Peter Golding MBChB, FRCA

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Key points

In electronics, solids are classified into conductors, insulators, and semi-conductors, based on their ability to move or 'conduct' electrons.

Ohm's law describes the relationship between the three basic quantities of electricity: current (*I*), voltage (*V*), and resistance (*R*).

Mains voltage (240 V) is the root mean square (RMS) voltage: the peak voltage is 1.413×RMS voltage.

To understand electrical safety, it is important to realize that the neutral wire is attached to the earth at the substation.

The four common classes of components encountered in electrical circuits are resistors, capacitors, inductors, and transformers. The defibrillator is an example of the use of these four components in an electrical circuit.

Shiv Kumar Singh MB BS, FRCA
Consultant Anaesthesia
Royal Liverpool University Hospitals
11th Floor
Prescot Street
Liverpool L7 8XP
UK
Tel: +44 151 7062430/44 7730505310
Fax: +44 151 7062933
E-mail: shiv.singh@rlbhut.nhs.uk
(for correspondence)

Rachel Ingham MBChB, FRCA
Consultant
Mersey Deanery
Liverpool
Merseyside
UK

James Peter Golding MBChB, FRCA
Consultant
Mersey Deanery
Liverpool
Merseyside
UK

Modern anaesthetic apparatus and monitors are powered by electricity and it is therefore important to understand the basic principles involved. Electrical hazards may not be completely eliminated but can be minimized by an understanding of the importance of electricity and its theoretical basis. In this article, we discuss the basics of electricity and its relevance to anaesthesia.

Electronic classification of solids

In electronics, solids are classified into three main groups: conductors, insulators, and semi-conductors. This is based on their ability to move or 'conduct' electrons. *Conductors* have outer electrons of their atoms loosely bound and are free to move through the material under the influence of an electrical potential, that is, they can conduct electricity. Most conductors are metallic, but certain non-metals like carbon are also good conductors. Solutions containing ions, such as saline, can also conduct electricity. *Insulators* have outer electrons which are firmly bound, and application of an electrical potential has no effect on them. Rubber, mica, and glass are examples of insulators. *Semiconductors* are a group of materials that normally behave as non-conductors, but in certain circumstances (like with change in temperature), they can be transformed so that they behave like conductors. Thermistors, transistors, and diodes are all examples of semiconductors. Silicon, germanium, lead sulphide, selenium, and gallium arsenide are semiconductor materials.

Direct and alternating current

The voltage from a battery or a thermocouple drives a steady or direct current (DC) around a circuit. This means that the charge flows in one direction: the current (or voltage) does not change with time. The main voltage varies sinusoidally, driving an alternating current around the circuit which reverses its direction in a sinusoidal manner from positive to negative and back, repeating the pattern 50 times s^{-1} (50 Hz frequency). High frequencies cannot be economically transmitted over long distances and therefore lower frequencies are chosen, but unfortunately at low frequencies, excitable tissues such as the muscle and nerve are at greatest risk of excitation and damage, increasing the risk of electrical shock.

Generation of electricity and electrical supply

A magnetic field is the region throughout which a magnet or a current-carrying conductor exerts its effects. Moving a magnet in and out of a conductor coil or moving a coil in and out of a static magnetic field produces movement of electrons in the conductor. This property of electromagnetic induction is utilized in the generation of electricity at power stations. Water or steam is used to drive the turbine, which is connected to a generator. A generator consists of a magnet surrounded by coils. The spinning of the magnet generates movement of electrons in the surrounding coils, producing electricity (Fig. 1). In the UK, mains voltage is 240 V, this is the root mean square (RMS) value of the voltage. The peak voltage is 1.413×240 V, that is, 340 V (where 1.413 is the square root of 2). Transmission voltage in the UK is at least 16 kV. The current in the transmission cables can cause resistive heating, wasted energy that does not reach the consumer. In a cable of resistance *R* carrying a current *I*, the resistive power loss is I^2R. Since the power loss is proportional to I^2, electricity is transferred at high voltage so that the current can be kept small for a given power load (see Ohm's law and section on 'Power and watts'). This high voltage is gradually brought down using step-down transformers at the substations (Fig. 1). The two conductors in a cable coming from the substation are said to be neutral (or 'return')

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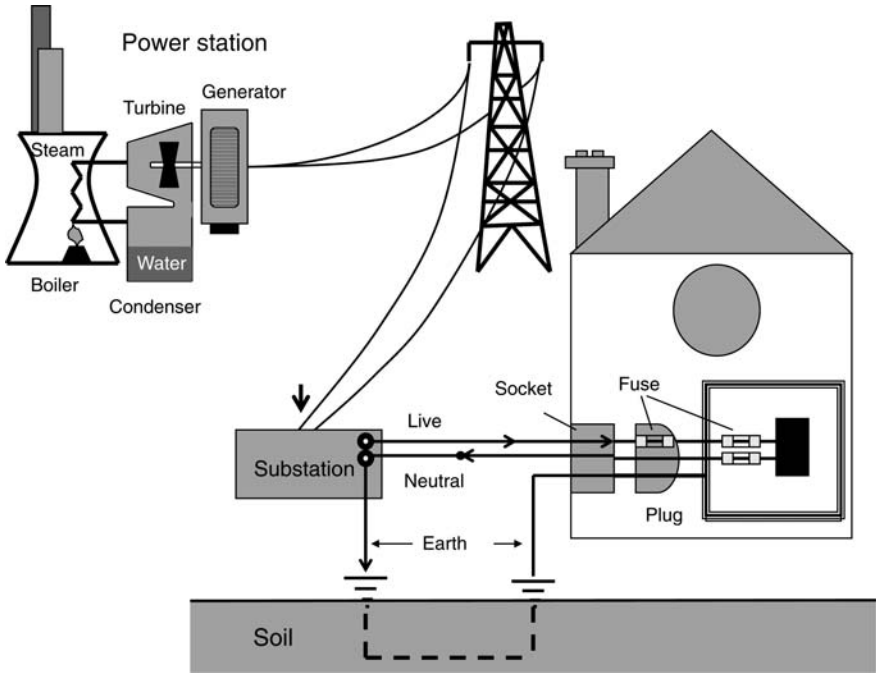

Fig 1 Electricity generation and electrical supply showing the live, neutral, and earth connections. Note that the neutral and earth wires are connected together at the substation.

and live. The conductor that is at the same potential as the earth (because it is connected to the earth at the source) is said to be neutral (or 'return') and the other becomes the live conductor. However, a normal electrical supply wire (electrical cord) consists of three conductors, the live, the neutral, and the earth. The earth wire is normally connected to the casing of the equipment and is termed 'protective earth'. It ensures that under faulty conditions, such as an internal short circuit in the equipment, the chassis and enclosure of the equipment will not be rendered live.

The basic quantities and units

The three basic quantities in electricity are current, voltage, and resistance.

Current (I) is any movement or flow of electrical charge and is a measure of the number of moving electrons flowing past a point along a wire during any time interval, divided by that time interval. The unit of current is the ampere (A), often as abbreviated as 'amp'. One ampere is a flow of 1 coulomb of charge each second past a point in the conductor. The coulomb is a unit of electrical charge equivalent to 6.24×10^{18} electrons.

Voltage, or potential difference, is the electrical force which drives the electric current. The word voltage comes from the unit of potential, which is the volt (V). One volt is the potential difference between two points on a conducting wire carrying 1 amp of current between which 1 watt of power is dissipated. It is also equal to 1 joule of energy per coulomb of charge (1 volt=1 joule per coulomb).

Resistance (R) determines the amount of current that can flow when a given potential is present. For a given potential, low resistance results in a higher current and high resistance results in a lower current. The resistance of an object depends upon both the material used and its shape. A good conducting material has low resistance while good insulating material has high resistance. A long wire has higher resistance than a short one. A thick wire (having a large cross-section) has lower resistance than a thinner one. Resistance is defined by the ratio of potential (V) to current (I). The unit for resistance is the volt amp^{-1}, called an ohm, and is denoted by the Greek symbol omega (Ω).

Ohm's law

An understanding of electrical hazards is impossible without understanding Ohm's law and some of the derivations of this equation. Georg Simon Ohm determined the relationship between the current and potential difference. He measured the current through wires as he changed the voltage across them. He discovered a very important relationship (Ohm's law), which he published in 1826. He noted that at steady temperature:

Potential difference (V) across a conductor=current (I) through the conductor×a constant (resistance R of the conductor) or $V=I\times R$.

The equation can be also be rearranged as $R=V/I$ and $I=V/R$.

Power and watts

The power (measured in watts, W) consumed in a conductor is the product of the potential difference (measured in volts) between the ends of the conductor and the current (measured in amperes) flowing through it. Thus, power=voltage (V)×current (I)=(joule coulomb^{-1})×(coulomb s^{-1})=joule s^{-1}=watt

$$V = I \times R \text{ (Ohm's law)}$$

therefore,

$$P = V(I \times R) \times I = I^2 R$$

For AC circuits, the voltage and the current are RMS or effective values.

Fuse

Fuse is an abbreviation for fusible link and is a type of over-current protection device. A fuse consists of a metal wire or strip which will melt when heated by an electric current. This will open the circuit of which it is a part, and so protect the circuit from an overload condition. Most wire fuses use a fusible material like silver, copper or tin. Fuses are rated for the safety of electrical appliances to allow the passage of normal current only (3, 5, and 13 A are the commonest in the UK). The fuse required depends on the load. For example, the load of a 3 kW appliance running at 240 V is 3000/240, that is, 12.5 A, and therefore will require a 13 A fuse.

Electrical components

In electrical circuits, we encounter four classes of components. Their symbols are depicted in Figure 2.

(i) Resistive elements which dissipate energy.
(ii) Capacitors which store energy in an electric field.
(iii) Inductors which store energy in a magnetic field.
(iv) Transformers which adjust the levels of voltage and current.

Resistive elements: impedance and reactance

Impedance (symbol Z) is a measure of how much the circuit impedes the flow of current and like resistance is measured in ohms. Impedance takes into account the effects the capacitance and inductance have on the opposition of a circuit to the current. Since the effects of capacitance and inductance vary with frequency so does the impedance. The effect of resistance on the other hand is constant regardless of frequency. There are therefore four electrical quantities that determine the impedance of a circuit: resistance (R), capacitance (C), inductance (L), and frequency (f). Impedance can therefore be split into two parts:

(i) Resistance R that is constant regardless of the frequency.
(ii) Reactance X that varies with frequency due to capacitance X_C and inductance X_L (discussed under capacitors and inductors).

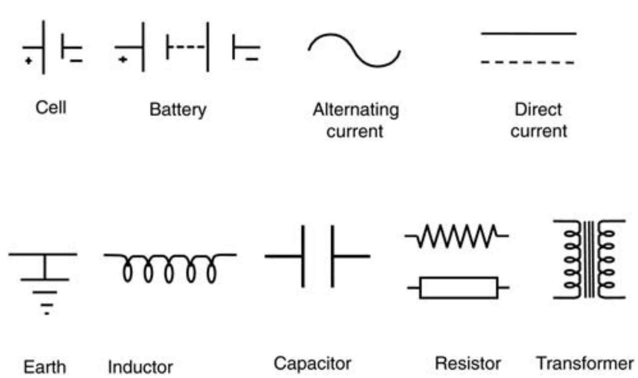

Fig 2 The symbols for the common electrical components used in electrical circuits.

Skin resistance and flow of current

What is the risk of an anaesthetized patient being exposed directly to 240 V? In the case of direct contact with live main voltage, a patient will be exposed to 240 V but the current they will receive depends on the resistance to flow (I=V/R). The main resistance is in the skin. The resistance of *dry* skin is ∼50 000 Ω. The current through dry skin is therefore 240 V/50 000 Ω, which is 0.0048 A, or ∼5 mA. In contrast, the current producing ventricular fibrillation across an arm–arm or arm–leg circuit is 100 mA. Thus, a 5 mA current would only cause a localized effect (like tingling sensation) and will be insufficient to deliver enough current density to the myocardium to cause fibrillation. On the other hand, the resistance of *wet* skin is 1/100th that of dry skin, ∼500–1000 Ω ohms (this is also the resistance of ECG electrodes), and the current that can be delivered is therefore much higher in these circumstances, 240 V/500 Ω, which is 480 mA. This is well above the 100 mA threshold necessary for ventricular fibrillation.

Successful defibrillation depends on the delivery of electrical charge to the myocardium. The majority of the current delivered during DC cardioversion is dissipated through the resistance of the skin and the chest wall. Repeated administration of shocks in quick succession reduces this impedance and increase the success of cardioversion.

Capacitors

A capacitor is an electrical component capable of storing electrical energy. It consists of two metal plates (conductors) insulated from each other by a dielectric (insulator). When fully charged, the potential difference across a capacitor plate is the same as that supplied by the battery which charges it. So the maximum amount of charge (Q) that a capacitor can store is proportional to this battery voltage (V).

$Q \propto V$Q is the magnitude of charge on the plates measured in coulombs and V the voltage across the capacitor. Since Q is proportional to V, the ratio of Q/V is constant and is a measure of the amount of charge that a capacitor can store per volt. This is called capacitance, symbol C, and is a constant value for any capacitor. That is,

$$C = Q/V$$

Capacitance C is measured in farads, and one farad is 1 coulomb per volt. One farad (1 F) is a very large amount of capacitance, and most practical capacitors have much smaller values: microfarads (μF), nanofarads (nF), and picofarads (pF). The stored energy of a capacitor is given by the formula:

$$E = \frac{1}{2}CV^2$$

Capacitance can exist between any two conducting bodies, such as a patient and an electrical cable, or an anaesthetist and a patient. This may cause interference with monitoring electrical signals such as the ECG. Reactance due to capacitors (X_C) is large at low frequencies and small at high frequencies. For steady DC, which is zero frequency, X_C is infinite, hence the rule that capacitors pass AC but block DC.

Inductors

An inductor is an electrical component consisting of a coil of conducting material wrapped around a core of ferromagnetic material or air. Inductors can store energy in a magnetic field inside the coil, created when a current passes through them. Changes in the current passing through the coil change the strength of the magnetic field. This changing magnetic field induces an electromotive force (EMF; voltage) in the coil, which opposes the rising current. The result is a smoothing out of rapid changes in current. Induction of voltage in a current-carrying wire where the current in the wire itself is changing is called inductance (L) and is measured in Henries (H). High peak currents are associated with myocardial injury; inductors are often used in defibrillators to create a heavily damped sinusoidal waveform (Lown waveform) of finite duration (~5 ms). Inductive reactance (X_L) is small at low frequencies and large at high frequencies. For steady DC (frequency zero), X_L is zero (no opposition), hence the rule that inductors pass DC but block high-frequency AC.

Transformers

A transformer is a device that utilizes the principle of induction to adjust the levels of voltage and current. It transfers energy from one circuit to another. A transformer consists of primary (P) and secondary (S) windings or coils, which are tightly coupled usually on a core of ferromagnetic material. The primary coil is connected to the source of alternating voltage or current. This generates alternating magnetic flux, which induces EMF in the secondary coil. If the number of coils in the primary circuit (N_P) is greater than the secondary (N_S), then the EMF generated in the secondary coil is less than the supply EMF, and it forms a step-down transformer. If the number of coils in the secondary is more than the primary, then it becomes a step-up transformer. If the voltage on the primary side is V_P and the voltage on the secondary side is V_S, then:

$$V_P/V_S = N_P/N_S$$

Therefore,

$$V_S = V_P \times N_S/N_P$$

Isolation transformers

An isolation transformer is especially designed to enhance the electrical isolation between the primary and secondary coils, and

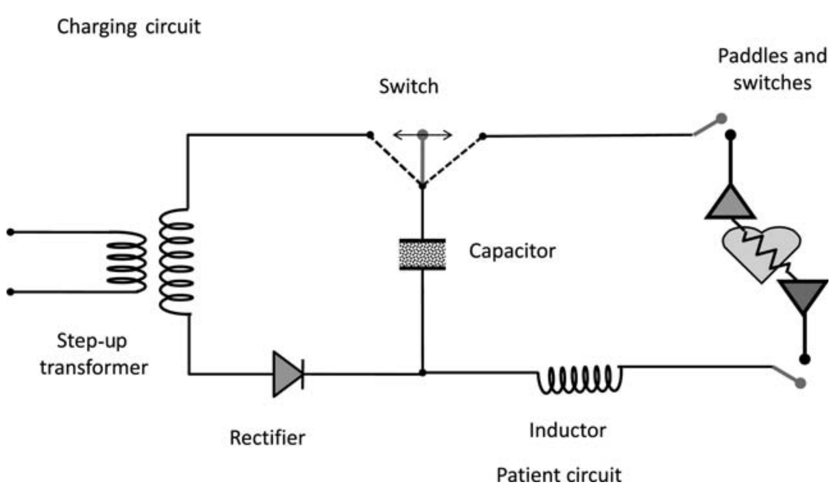

Fig 3 The defibrillator circuit showing the various components, the step-up transformer, and the rectifier are part of the charging circuit, whereas the inductor is present in the patient circuit.

between both coils and any other conductor. Isolation transformers form a very important part of modern electrical circuits, the floating circuits. If the secondary coil of an isolation transformer is not earthed, it is referred to as a floating circuit. Floating circuits help in reducing the amount of stray leakage of mains frequency current that can pass through a patient and cause electrical injury.

Defibrillators

The defibrillator is a good example of the application of components discussed in the above sections. A defibrillator circuit consists of a capacitor, a transformer, a rectifier, and an inductor (Fig. 3). The charging circuit of a defibrillator consists of a step-up transformer to increase the voltage from 240 V to almost 5000–9000 V. This voltage is then converted to DC using rectifiers (which use diodes that allow the current to flow in one direction only) to charge the capacitor. Once the capacitor is charged, the circuit switches to the patient circuit. The paddles are applied across the chest to complete the circuit. For successful defibrillation, the current delivered must be maintained for several milliseconds: this is made possible by incorporating an inductor into the patient circuit.

Summary

A basic understanding of electricity generation, supply, and components is useful in daily life. This is especially so for anaesthetists whose daily practice involves the use of potentially hazardous equipment such as diathermy and defibrillators. Ensuring patient and staff safety by minimizing risk is crucial, and knowledge is the key to it.

Conflict of interest

None declared.

Further reading

1. Davis PD, Kenny GNC. Electricity. *Basic Physics and Measurement in Anaesthesia*, 5th Edn. Oxford: Butterworth-Heinemann, 2003; 149–63
2. Davis PD. Basics of electricity. In: Davey AJ, Diba Ali, eds. *Ward's Anaesthetic Equipment*, 5th Edn. Philadelphia, PA: Elsevier Saunders, 2005; 11–21
3. Strickland DAP. Physical principles. Part II: electrical quantities. In: Scurr C, Feldmann S, eds. *Scientific Foundations of Anaesthesia*, 3rd Edn. London: William Heinemann Medical Books Ltd, 1982; 25–40
4. Macintosh R, Mushin WW, Epstein HG. Electricity. In: Mushin WW, Jones PL eds. *Physics for the Anaesthetist*, 4th Edn. Oxford: Blackwell Scientific Publications, 1987; 419–56
5. Dobson K, Grace D, Lovett D. Charge and current. *Collins Advanced Science Physics*, 1st Edn. Glasgow: Collins Educational, 2001; 200–29
6. Dobson K, Grace D, Lovett D. Alternating current and electrical power. *Collins Advanced Science Physics*, 1st Edn. Glasgow: Collins Educational, 2001; 200–29

Please see multiple choice questions 21–24.