Electricity and magnetism

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Abstract

This article introduces essential concepts of electricity and magnetism relevant to anaesthesia. Simple analogies are used to explain current electricity and the action of electronic components in common use. The concept of electric and magnetic fields is introduced with examples of their practical application.

Keywords Electricity; electronics; magnetism

Royal College of Anaesthetists CPD Matrix: 1A03, 2A04, 3J00

Learning objectives

After reading this article, you will be able to:
- describe key concepts of static and current electricity
- explain the principles and application of common electronic components
- describe the relationships between electricity and magnetism

Static and current electricity

Static electricity involves redistribution of electrons ('charge separation') between two or more insulators, such that one insulator acquires an excess of electrons ('negative charge'), and the other develops a deficit of electrons ('positive charge'); but there is no net gain or loss of charge (Q; coulomb, C), or ongoing movement of electrons (hence 'static'). The *elementary charge 'e'* carried by a single electron is 1.602×10^{-19} C. Like charges repel and unlike charges attract. Redistribution of electrons may be achieved by rubbing two insulators together to transfer electrons, or by attraction or repulsion of electrons by an adjacent charged object ('induction'). Charge may rapidly flow to earth via a conductor, causing ignition of flammable agents, or cardiac arrest due to microshock.

Current electricity involves a supply of energy in the form of an *electromotive force* (EMF)($\mathscr{E}$; volt, V) which produces a *potential difference* (PD)(V; volt, V) between two points on a conductor. If there is a continuous unbroken loop of conductor (circuit), and a source of energy (EMF) to 'push' the electrons around the circuit, electrons will flow through the conductor as electric current (I; ampere, A) from a point of high PD to low PD in a manner analogous to the flow of water through a pipe (Table 1), or rotation of an unbroken column of marbles around a hula hoop. EMF can be provided by, for example, a single *cell* or *battery* of interconnected cells that converts chemical potential energy into kinetic energy of electrons via chemical reactions which may be irreversible ('primary' cell) or reversible ('secondary' or 'rechargeable' cell).

Individual electrons move very slowly through the conductor at a *drift velocity* of ~1 m in 75 minutes, but interaction between adjacent electrons causes an almost instantaneous 'wave' of conduction at the speed of light ($\sim 3 \times 10^8$ m s^{-1}). Electrons move from a region of excess (negative charge) to deficit (positive charge); however, *conventional flow notation* used in all circuit diagrams, formulae and laws describes current as flowing in the opposite direction (i.e. from positive to negative).

If the direction of current flow is constant, the current is said to be '*direct current*', DC. If the direction of current flow periodically reverses at a given frequency (f; hertz, Hz), it is termed '*alternating current*' (AC). The fluctuating voltage in AC circuits may be described in terms of the peak voltage (V_{peak}); however, for most of the time the voltage is less than V_{peak}, and is therefore usually described (and indicated by test equipment) as the *root mean square* (V_{RMS}), which is the DC voltage that would have an equivalent heating effect. For a sinusoidal waveform:

$$V_{RMS} = V_{peak} \big/ \sqrt{2} = 0.707\ V_{peak}$$

$$V_{peak} = V_{RMS}\sqrt{2} = 1.414\ V_{RMS}$$

Hence European domestic mains voltage of 230 V_{RMS} is 325 V_{peak}. Similar equations apply to current.[1]

Components

Electric current may be put to use by the addition of components, which may be arranged in a circuit in *series* or *parallel* configurations (Figure 1). *Kirchhoff's Current Law* states that the sum of all current entering any point in a circuit equals the sum of all current leaving any point in a circuit (i.e. charge is conserved). *Kirchhoff's Voltage Law* states that the sum of all the potential drops in any closed loop of a circuit equals zero (i.e. energy is conserved). *Passive components* (e.g. resistors, capacitors, inductors) do not generate a current or PD.

Resistors ('load') oppose current flow and dissipate the 'lost' energy as heat.[2] Resistance (R; ohm, Ω) depends on properties of the material (resistivity, ρ; Ω: conductivity, $\sigma = 1/\rho$), and increases with increased length, decreased diameter, and increased temperature. Most conductors obey *Ohm's Law*: $V = IR$. Fuses and safety cut-out devices break a circuit if current exceeds normal flow. The *Power Law*: $P = VI$ ($=I^2R$) may be used to select the correct fuse rating (A) for a given application if supply voltage and power consumption (P; watt, W) are known. In combination, resistors can be used to make a *potential divider* that allows connection to a smaller PD (e.g. for a power supply), or a *Wheatstone bridge* that translates a small change in

[1] Audio amplifier power output is often quoted as 'Watt RMS'; but this is misleading. Average Power ($=V_{RMS} \times I_{RMS}$ for resistive loads) should be used instead.

[2] N.B. The PD across a resistor drops, but the current passing through it remains constant: current is not 'used up' as it passes through a resistor.

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Comparison of water and electricity

Water		Electricity	
Property	**Units**	**Property**	**Units**
Volume (=quantity of water)	L	Charge (=quantity of electrons)	Coulomb (C)
Flow (=movement of water)	L s^{-1}	Current (=movement of electrons)	C s^{-1} or ampere (A)
Pressure	N m^{-2} or pascal (Pa)	EMF	J C^{-1} or volt (V)
Difference in pressure	N m^{-2} or pascal (Pa)	Difference in potential (PD) (=voltage)	J C^{-1} or volt (V)
Volume (L) = flow (L s^{-1}) × time (s)		Charge (C) = current (A) × time (s)	
Work (J) = pressure (Pa) × volume (L)		Work (J) = potential (V) × charge (C)	
Power (W) = pressure (Pa) × flow (L s^{-1})		Power (W) = potential (V) × current (A)	

Table 1

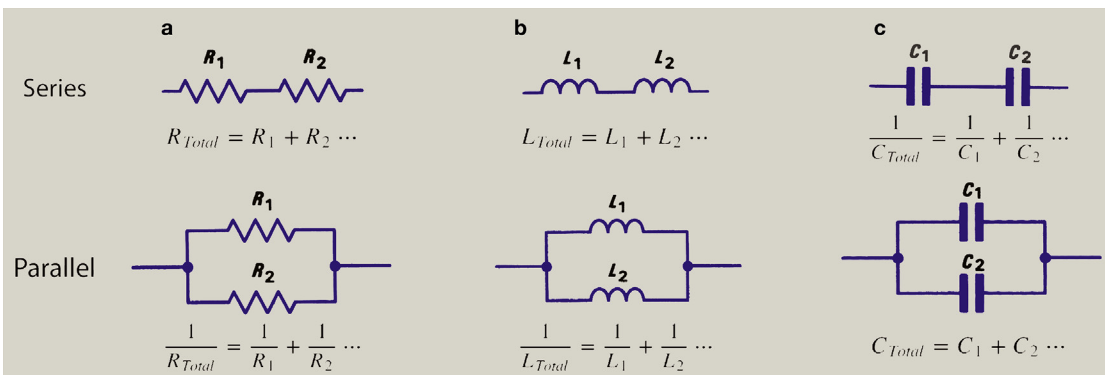

Figure 1 Components in series and parallel. Effective values of resistors (**a**), inductors (**b**), and capacitors (**c**) in series and parallel configurations.

resistance into a substantially proportional large change in PD to increase the sensitivity of sensors (e.g. pressure transducer) (Figure 2). Wheatstone bridges also help to compensate for thermal drift, and may be modified to measure other quantities (e.g. capacitance, inductance, impedance).

Variable resistors with linear or logarithmic scales (e.g. dimmers and volume controls), thermistors[3] (e.g. temperature probes and thermal cut-outs) and light-dependant resistors (e.g. motion detectors, emergency lighting) are all widely used in the hospital environment.

Capacitors typically consist of two conductors separated by an insulator ('dielectric') and store energy as electric charge. In terms of our fluid analogy, capacitors resemble a rigid container divided into two compartments by a thick rubber plate. In essence, DC cannot pass through a capacitor, but transient or AC can. Capacitance (C; farad, F) depends on the permittivity of free space (ε_0) and dielectric (ε_r), plate area (A) and separation (d): $C = \varepsilon_0 \varepsilon_r A/d$. Stored charge $Q = CV$. If 1 J energy is needed to push 1 C of charge 'uphill' against an electrical potential of 1 V, then 1 joule = 1 coulomb-volt: $E = QV$. The mean voltage during complete charge and discharge is $V/2$, therefore stored energy (or work of charging) $E = 1/2CV^2 = 1/2QV$. There is an exponential relationship between current, voltage, and electrical charge with time when a capacitor charges or discharges. Applications include storage and release of charge (e.g. defibrillator, camera flash), smoothing of AC (e.g. power supplies, suppression of radio frequency interference), touch sensors, and timing devices.

Inductors consist of a coil of wire around an air or ferromagnetic core. Inductance (L; Wb/A: 1Wb/A = 1 Henry, H) depends on the permeability of free space (μ_0) and core (μ_r), number of turns (n), cross sectional area (A) and length (l) of core: $L = \mu_0 \mu_r n^2 A/l$. Inductors store energy as a magnetic field ($E = 1/2LI^2$), and effectively add 'inertia' – analogous to a turbine with a flywheel attached – delaying onset and offset of maximal current flow. The latter effect may be employed in a defibrillator to prolong the duration of the delivered shock.

The flow of AC through passive components is more complex than DC, as frequency (f) and phase angle (ϕ) are involved as well as amplitude. The AC analogues of DC resistance are *impedance* (Z; ohm, Ω) for resistors; and *reactance* (X; ohm, Ω) for capacitors ($X_C = 1/2\pi fC$) and inductors ($X_L = 2\pi fL$). Current flow through resistors is not affected by frequency, but current passes more easily through capacitors at high frequencies, and through inductors at low frequencies. A combination of resistors, capacitors and inductors will therefore have minimum or maximum impedance at a *resonant frequency* (f_0), which occurs when X_C and X_L are equal and opposite, and this can be used in the design of high-pass, low-pass, band pass, or notch filters to selectively pass or block specific frequency bands as part of *signal processing* (e.g. in monitoring equipment and radio receivers).

[3] Depending on the type of thermistor, resistance may increase (positive temperature coefficient, PTC) or decrease (negative temperature coefficient, NTC) with increasing temperature in a non-linear fashion.

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