Electricity & Electrical Safety

Dr Dominique van Dyk
Dept of Anaesthesia & Perioperative Medicine
University of Cape Town

There are 4 ways in which electricity may cause harm to a patient or operating room staff:

1) Current flow through the body → electrical shock
2) Loss of electrical power → equipment failure
3) Interference with function of implanted devices, e.g. pacemakers or defibrillators
4) Thermal injury- fires, burns, explosions

These notes will focus on the prevention of electrocution of our surgical patients, operating room colleagues and us as anaesthetists!

South African legislation of relevance to electrical safety in operating rooms:

The Occupational Health and Safety Act, 1993 (Act No. 85 of 1993)-

- Refers to the Electrical Installation Regulations of 2009 and the Code of Practice for Wiring of Premises SANS 10142-1.
- Is managed by the Department of Labour
- Covers the use of products in electrical installations, generally applicable to products for fixed installations such as socket outlets, wall switches and circuit breakers.
- Prescribes the Wiring Code (SANS 10142-1) for the wiring of fixed installations in the work environment.

SANS 60601-1:2013 is the South African National Standard that delineates the “General requirements for basic safety and essential performance” of medical electrical equipment.

Basic concepts

Atoms, electrons, charge
Matter is composed of atoms. Atoms are composed of electrons (-) orbiting around a nucleus of protons (+) and neutrons.

Electric charge is the physical property of matter that causes it to experience a force when placed in an electromagnetic field.

Electrons have a negative charge. Protons have a positive charge. Opposite charges attract. Like charges repel.

An electric (force) field surrounds any charged object – it spreads out and weakens with distance. Charge is measured in Coulombs. 1 Coulomb = the amount of charge transported by a current of 1 ampere in one second.

The charge of one electron is -1.6 X 10^-19 Coulombs.

1 Coulomb = \( \frac{1}{-1.6\times10^{-19}} \) = 6.25*10^{18} electrons

The number of protons in an atom determines what the element is. For instance: Hydrogen- 1 proton and 1 electron; Aluminium- 13 protons and 13 electrons. Electrons orbiting the atomic nucleus are organized into shells. In the case of aluminium, its 13 electrons are organized into three shells: 2 electrons in the innermost shell, 8 electrons in the middle shell, and 3 electrons in the outermost shell. The 3 electrons in the outermost shell are the valence electrons.
Free electrons and current
When a valence electron in any atom gains sufficient energy from some outside force [e.g. friction (static), thermal (thermocouple), light (photocell), chemical (battery) or electromagnetic (generator)], it can break away from the parent atom and become what is called a free electron. Atoms with few electrons in their valence shell tend to have more free electrons since these valence electrons are more loosely bound to the nucleus. In some materials, like copper, the electrons are so loosely held by the atom, and are so close to the neighboring atoms, that it is difficult to determine which electron belongs to which atom. Under these conditions, the free electrons tend to drift randomly from one atom to its neighboring atoms. Under normal conditions the movement of the electrons is truly random, meaning they are moving in all directions by the same amount. However, if some outside force acts upon the material, this flow of electrons can be directed through materials and this flow is called electrical current.

So, the flow of free electrons through a conductor is called current. Current will only flow when a circuit with a voltage source is completed. If there is the choice of two paths in parallel to complete a circuit, the greater current will flow along the path with the lower resistance.

Conductors and insulators
Materials that have free electrons and allow electrical current to flow easily are called conductors. Good electrical conductors are copper, aluminium, gold, silver, and platinum.

Many materials do not have any free electrons. Because of this fact, they do not tend to share their electrons very easily and do not make good conductors of electrical currents. These materials are called insulators. Insulators are used to isolate electrical components and prevent current flow. Good electrical insulators are rubber, porcelain, glass, and dry wood.

Insulator Characteristics:
1) Resistance- The ability of the insulator to resist current leakage through and over the surface of the insulator material.
2) Dielectric Strength- The ability to withstand a maximum voltage without breakdown damage to the insulator.

Ohm’s Law: \( V = I \times R \)
where \( V \) is the electromotive force (potential difference between two points) in Volts, \( I \) is the current in Amperes, and \( R \) is resistance in Ohms.

Electrical power formula: \( W = V \times I \)
where \( W \) is the power in Watts, \( V \) is the electromotive force in Volts, and \( I \) is the current in Amperes.
From Ohm’s Law, \( W = (I \times R) \times I = I^2R \). The watt (abbreviated W) is the SI standard unit of power (energy per unit time), the equivalent of one joule per second. Wattage can be considered not only as a measure of work done, but also of heat produced in an electrical circuit.

Direct vs alternating current:
Direct current (DC) is current that flows consistently in one direction, e.g. a torch powered by batteries. For DC, Ohm’s Law holds true.

Alternating current (AC) is current in which the direction of electron flow switches back and forth at regular intervals or cycles, e.g. normal household electricity that comes from a wall outlet. A graph of Voltage vs Time resembles a sine wave. Advantages of AC: (1) relatively cheap to change the voltage of the current, (2) far less energy lost when current is carried over long distances as AC vs DC.

For AC, the “resistance” to current flow is more complex, and is called impedance (Z). Impedance is the sum of forces opposing electron movement in an AC circuit, which include resistance (R), inductance and capacitance. For AC, Ohm’s Law is defined as \( V = I \times Z \), and the current flow is inversely proportional to the impedance. The amount of current flowing through a given device is
frequently referred to as the *load*. A very high impedance circuit allows only a small current to flow and thus has a small load. A very low impedance circuit will draw a large current and is said to be a large load. A short circuit occurs when there is a zero impedance load with a very high current flow.

**Inductance** is a property of current-carrying conductors whereby a change in current can result in generation of voltage (called electromotive force) in the conductor itself as well as a conductor placed in its vicinity. Inductance occurs because of fluctuations in the surrounding magnetic field and is described by Faraday's law of inductance.

**Capacitance** is the ability of a device to store electric charge. An electronic component that stores electric charge is called a capacitor. The simplest capacitor consists of two flat conducting plates separated by a small gap. The potential difference, or voltage, between the plates is proportional to the difference in the amount of the charge on the plates. This is expressed as \( Q = CV \), where \( Q \) is charge, \( V \) is voltage and \( C \) is capacitance. The capacitance of a capacitor is the amount of charge it can store per unit of voltage. The unit for measuring capacitance is the farad (F), named for Faraday, and is defined as the capacity to store one coulomb of charge with an applied potential of one volt. *Alternating current can flow through a capacitor, whereas DC cannot.*

**Generation of electricity**

Almost all the electronic devices used by anaesthetists run on mains electricity, supplied by Eskom.

In the case of a coal-fired plant like Medupi, pulverized coal enters a furnace, to heat water circulating through pipes to make steam. High-pressure steam spins a turbine, which rotates a central shaft connected to a generator. The generator converts the mechanical energy of the spinning shaft into electrical energy. The operation of a generator is based on the principles discovered by Faraday. He found that when a magnet is moved past a conductor, it causes electricity to flow. In a large generator, electromagnets are made by circulating direct current through loops of wire wound around stacks of magnetic steel laminations. These are called field poles, and are mounted on the perimeter of the rotor. The rotor is attached to the turbine shaft, and rotates at a fixed speed of 3000 rpm. When the rotor turns, it causes the field poles (the electromagnets) to move past the conductors mounted in the stator. This, in turn, causes alternating current to flow at a frequency of 50 Hz, and a voltage to develop at the generator output terminals. The stator of the generator has 3 armature windings, at 120° of offset to each other, and this gives rise to our 3-phase electrical supply, with each phase at a frequency of 50 Hz and 120 degrees out of phase with the other 2 currents. This makes it possible for a steady stream of power to be delivered at a constant rate, making it possible to carry more load (i.e. current), and allows for greater conductor efficiency than single-phase.

The generators in Eskom’s power stations produce electricity at ±20 000 volts (20kV). This voltage is raised by step-up transformers before it is sent out. The high voltage transmission system in Eskom comprises a 132 000, 275 000, 400 000 and 765 000 volt system. In order for electricity to be transmitted safely and efficiently over long distances in the network of overhead transmission lines (the National Grid), it must be at a high voltage and a low current. This is because if the current is too high, the lines would heat up too much and even melt (the heating effect of a current is given by \( W = i^2R \)). If the voltage were too low, hardly any energy would be carried.

**From the National Grid to local distribution to the home:**

From the high voltage network, the electricity is transformed down, for example, to 11 000 volts for local distribution, and then to 220/230 V for domestic use in South Africa. The 220 V is the effective voltage, also called the root mean square, or RMS.

A typical power cord consists of two conductors. One, designated as *live* (*hot* in the USA; the brown wire when you wire an electrical plug) carries the current to the impedance; the other is *neutral* (the blue wire), and it returns the current to the source. The potential difference between the two is effectively 220 volts. In a *grounded* system, the *neutral* wire is intentionally connected to the ground by
an earth wire (the green wire), which is at the same potential as the neutral wire. Eskom does this as a safety measure to prevent electrical charges from building up in their wiring during electrical storms, and to prevent the very high voltages used in transmitting power by the utility from entering homes in the event of an equipment failure in their high-voltage system. The ground is considered a current sink, meaning it can accept and carry virtually unlimited amounts of current.

The figure below shows the neutral grounded power supply to a typical home; note that there are the two lines, live and neutral. The neutral is connected to ground by the power company and again connected to a service entrance ground when it enters the fuse box. Both the neutral and ground wires are connected together in the fuse box at the neutral bus bar, which is also attached to the service entrance ground.

1) ELECTRICAL SHOCK

A shock is experienced when electric current passes through the body. The amount of current that flows will be a function of the voltage difference across the body and the resistance to current flow presented by the body. There must be a complete circuit for current to flow. Two points of contact must therefore exist for current to flow through the body. Oftentimes, one of these contacts is established as a result of standing on the ground, so only one other point of contact needs to be made in order for current to flow and a shock to occur. The primary objective in electrical safety is to prevent patients or staff from becoming a part of that complete circuit.
Ground or grounding: This refers to two separate concepts- the first being the grounding of electrical power, and the second being the grounding of electrical equipment. So, power can be grounded or ungrounded and power can supply electrical devices that are themselves grounded or ungrounded. Anything connected to ground, whether intentionally (e.g., an equipment case or the OR bed) or unintentionally (e.g., a patient or staff person contacting a source of electrical power) will be held at a reference voltage that is by definition 0 V. In addition, the connection to ground provides a low-resistance pathway that permits current to return to its source. Ideally, patients (and other individuals) should never be grounded, thus removing any possibility of becoming part of the electrical circuit.

However, this can be difficult and impractical to accomplish, so instead the entire OR is kept isolated from ground (see later). Conversely, electrical equipment should always be grounded, to provide a low-resistance pathway for current to return to its source, rather than through some alternate pathway, such as a person. For example, if a piece of equipment was not grounded, but it had a fault such that electrical power was in contact with the case, an individual coming into contact with that case would then serve as the sole pathway for the fault current to flow back to the source. By keeping the equipment grounded, the bulk of the fault current will be conducted by the ground connection and only a small portion will flow through the person, thus significantly reducing the risk of shock.

<table>
<thead>
<tr>
<th>Current</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Macroshock</strong></td>
<td></td>
</tr>
<tr>
<td>1 mA (0.001 A)</td>
<td>Threshold of perception</td>
</tr>
<tr>
<td>5 mA (0.005 A)</td>
<td>Accepted as maximum harmless current intensity</td>
</tr>
<tr>
<td>10–20 mA (0.01–0.02 A)</td>
<td>“Let-go” current before sustained muscle contraction</td>
</tr>
<tr>
<td>50 mA (0.05 A)</td>
<td>Pain, possible fainting, mechanical injury, heart and respiratory functions continue</td>
</tr>
<tr>
<td>100–300 mA (0.1–0.3 A)</td>
<td>Ventricular fibrillation will start, but respiratory centre remains intact</td>
</tr>
<tr>
<td>6,000 mA (6 A)</td>
<td>Sustained myocardial contraction, followed by normal heart rhythm; temporary respiratory paralysis; burns if current density is high</td>
</tr>
<tr>
<td><strong>Microshock</strong></td>
<td></td>
</tr>
<tr>
<td>100 μA (0.1mA)</td>
<td>Ventricular fibrillation</td>
</tr>
<tr>
<td>10 μA (0.01mA)</td>
<td>Recommended maximum 60 Hz leakage current</td>
</tr>
<tr>
<td>1 A (amperes)</td>
<td>=1,000 mA (milliamperes) =1,000,000 μA (microamperes)</td>
</tr>
</tbody>
</table>

Injuries that result from electric shock include burns and tissue damage, ventricular fibrillation, and death (see above). The injury that occurs will depend on the magnitude and duration of current flow through the body, as well as the cross-sectional area through which it flows. This is embodied in the concept known as current density, which is defined as the amount of current flowing through a given cross-sectional area, and can be thought of as a measure of how “concentrated” the current is.

Macroshock refers to currents on the order of 1 mA or larger that are applied externally to the skin, that is, currents that are perceptible. There is a second phenomenon known as microshock that involves currents below the threshold of perception.

Microshock occurs in what is known as an electrically susceptible patient, that is, a patient with a direct conductive connection to the heart (e.g., a temporary pacemaker wire or a saline-filled catheter) that bypasses the skin. This is important as the skin is normally a source of considerable resistance. Not only does the direct connection provide a low-resistance pathway to current flow, the connection
contacts the heart in a very small area. As a result, despite the low current levels flowing (as low as 10-100 μA), the resulting current density is sufficient to cause ventricular fibrillation. Because the current levels associated with microshock are so low, below the threshold of perception, normal methods to detect hazardous situations and prevent shock don’t work. For example, line isolation monitors (LIMs) (see below) do not help to protect against microshock. It is a functioning equipment ground wire that protects against microshock (FIGURE below).

Most ORs utilise power sources that are isolated from ground, that is, isolated power supplies. These differ from the grounded type of power supplies used in the home and other hospital locations in several important ways. A grounded power supply will have one live lead and one neutral lead, which is physically connected to the ground conductor. If a person (who is typically going to be in contact with ground) should come into contact with the electric circuit (e.g. by touching a faulty piece of equipment), there is a potential for some current to flow from the point of contact through the individual to ground and thus back to its source, as in the figure below.

Because the equipment is grounded, however, most of the current will flow along established low-resistance grounding pathways, and only a small fraction through the much-higher-resistance person.

In contrast, isolated power supplies provide electrical power through two leads, line 1 and line 2, neither of which is connected to ground. The two lines are electrically isolated from ground by an isolation transformer located in the OR. Electrical equipment is still grounded through a third conductor; however, there is no pathway for current to flow from either line 1 or line 2 back to its
source via the ground. As a result, if a person in contact with ground comes into contact with either line 1 or line 2, there is no pathway for establishing a complete circuit, and no shock can result. Only if the individual comes into contact with both lines 1 and 2 does a complete circuit result, thereby allowing current to flow and a shock to occur. The use of isolated power supplies thus provides an added layer of protection against electrical shock.

**FIGURE below: An isolated power supply**

---

**FIGURE below: A safety feature of the isolated power system is illustrated.** An individual contacting one side of the isolated power system (point A) and standing on the ground (point B) will not receive a shock. In this instance, the individual is not contacting the circuit at two points and thus is not completing the circuit. Point A (cross-hatched lines) is part of the isolated power system, and point B is part of the primary or grounded side of the circuit (solid lines).

---

Isolation is not perfect, however, and leakage currents do exist. What is important is that the leakage can become significant enough to defeat the isolation, in which case the power supply changes from an isolated to a grounded supply.

This will not affect equipment function, nor does it cause a shock, but it does remove that extra layer of protection. Since equipment continues to function, such a change will go unnoticed. A line isolation monitor (LIM) is used to monitor the quality of the isolation from ground and will alarm if the impedance to ground drops low enough that significant current (5 mA) could flow.
FIGURE above: When a faulty piece of equipment is plugged into the isolated power system, it will markedly decrease the impedance from line 1 or line 2 to ground. This will be detected by the LIM, which will sound an alarm.

The power grid supplies grounded power, with the neutral lead physically connected to the ground conductor. In the OR, after passing through an isolation transformer, line 1 and line 2 supply electrical power, but there is no connection with ground. Consequently, contact with either line 1 or line 2 cannot result in current return via the ground conductor. There are two ways in which isolation could fail. The first occurs when a piece of equipment has a “ground fault,” that is, when there is an unintended connection between either line 1 or line 2 and ground. The second way in which a system could lose isolation is if enough pieces of equipment, each with about 100 μA of leakage, are plugged into the supply. This would lower the impedance to the point of converting the isolated system to a grounded supply. As previously noted, in both situations equipment will continue to function normally, hence the need for the LIM.

If an LIM should alarm, the cause needs to be determined. Is it a faulty piece of equipment or just too many pieces of equipment? The recommended practice is to unplug equipment, one piece at a time, starting with the last piece plugged in. A faulty piece of equipment is likely to be associated with a larger change in the hazard current than just having too many items plugged in. If the cause for the alarm is still unclear, equipment can be taken to another room and plugged in; if faulty, it should alarm there, too. A faulty piece of equipment should be removed from service.

A significant advantage of the LIM is that equipment will continue to function, and critical life support functions will not be interrupted. An alternative piece of equipment that also protects against shock and ground faults is known as a ground fault circuit interrupter (GFCI). It differs in one important way from an LIM. Rather than an alarm that notifies the user that isolation has been overwhelmed, it stops the flow of current. Any electrical equipment connected to a circuit utilizing a GFCI will cease to function. This is an obvious disadvantage in situations where life support equipment is being used, and for that reason, these devices are not used in the OR.
ISO classification of medical equipment according to its *method* of protection against electric shock:

**Class 1**: Class 1 equipment has a protective earth. The basic means of protection is the insulation between live parts and the exposed conductive parts such as the metal enclosure. In the event of a fault which would otherwise cause the exposed conductive part to become live, the supplementary protection, i.e. protective earth, comes into effect. A large fault current will flow from the live wire to earth via the earth wire, which causes a protective device (usually a fuse) in the live wire to melt, disconnecting the equipment from the power supply.

**Class 2**: The method of protection here is either double insulation or reinforced insulation. In double insulated equipment, the basic protection is afforded by the first layer of insulation. If basic protection fails then supplementary protection is afforded by a second layer of insulation preventing contact with live parts. The symbol for Class 2 equipment is 2 concentric squares, indicating double insulation.

**Class 3**: Here, the protection against electric shock relies on the fact that no voltages higher than safety extra low voltage (SELV) are present. SELV is defined in the relevant standard as a voltage not exceeding 25 V AC or 60 V DC.

**Type designation of equipment**: describes the degree of protection, based on the maximum permissible leakage currents under normal and fault conditions. The reason for the existence of type designations is that different pieces of medical electrical equipment have different areas of application and therefore different electrical safety requirements. For example, it would not be necessary to make a particular piece medical electrical equipment safe enough for direct cardiac connection if there is no possibility of this situation arising.

**Type B (Body)**: Type B classification is given to applied parts which are generally not conductive and may be connected to earth. May be any class (see above), but the maximum patient leakage current under normal conditions is 100 µA. There is the risk of microshock.

Equipment that is connected to patients (e.g. via surface electrodes) **must** be designated as type BF or CF.

**Type BF (Body Floating)**: Type BF classification is given to applied parts which are electrically connected to the patient and must be floating and separated from Earth. This classification does not include applied parts which are in direct contact with the heart. Allowable leakage currents are as for Type B, but here a mini isolation transformer is employed to create an isolated circuit with no direct connection to the main circuit.

**Type CF (Cardiac Floating)**: Type CF classification is given to applied parts suitable for direct cardiac connection. These parts must be floating and separated from earth. This equipment uses an isolated circuit; maximum patient leakage current under normal conditions is below 10 µA.

**SYMBOLS**

- Type B
- Type BF
- Type CF
2) BURNS

The amount of heat produced by current flow depends on the magnitude of the current and the resistance. A given current flowing through a small area will produce more heating than the same current flowing through a large area. The situation most commonly associated with burns in the OR is related to the use of an electrosurgical device (ESU or “diathermy”). Electric current passes from a “pencil” through the patient to a dispersive pad (often incorrectly called “the grounding pad”). Because the pencil tip is small, a high current density exists and significant heating occurs.

However, the dispersive pad occupies a much larger surface area, resulting in much lower current density, effectively protecting against skin burns. However, if the conductive gel is dried out, the pad is incorrectly applied so it does not make good contact with the skin throughout its entire surface, or it is removed and reapplied, current can be concentrated at the point(s) of contact, resulting in skin burns. Ideally, the pad will be applied over well-muscled areas, such as the thigh, arm, or buttocks. It should not be placed over hairy areas (it won’t stick well) and over bony prominences or metal prostheses (the current can be concentrated at these points), and it should not be reapplied if it is removed (insufficient gel may remain). Alternatively, current may seek other pathways, such as through ECG electrodes, again resulting in a high enough current density to cause burns.

3) LOSS OF ELECTRICAL POWER

A loss of electrical power is a potentially catastrophic situation that requires prompt and effective management to minimize the risk to patients. The cause of an electrical power failure can be external to the institution, due to an interruption of the power company’s supply to the hospital, or to internal failures, which may affect only a portion of the facility. The risk to patients can result from equipment that stops functioning, for patients whose lives depend on critical life-support equipment, or from the interruption of and interference with surgery or other invasive procedures. As such, a power outage represents a very different problem than electrical shock.

Whereas shock will generally affect only a single patient, the loss of electrical power can affect many patients. Electric shock produces an immediate result, such as ventricular fibrillation, but the consequences of a power outage may extend over time. Finally, there is usually some form of backup electrical supply to maintain equipment function in the event of an outage. This can take the form of a battery, such as in the anesthesia machine, or hospital generators.

Should there be a loss of power, several issues must be considered. First, patient status must be ascertained. Second, the status of the anaesthetic and the surgery must be established. If the surgical procedure must continue, how will the anaesthetic be provided? It is possible to use a portable monitor, intravenous infusion pumps to provide a total intravenous anaesthetic, oxygen from tanks,
and ventilation via an Ambu-bag, and these will all potentially need to be sourced in the case of a power failure during an operation.

Light can be provided from torches and laryngoscopes. All OR personnel should be familiar with the location of emergency light sources. Nonetheless, if it appears that the power outage will be of significant duration, steps should be taken to conclude the surgical procedure. Third, equipment function needs to be evaluated. The status of the anaesthetic machine, monitors, light sources, and any powered surgical equipment must be clarified, so decisions about whether or not to continue surgery can be made. Finally, and perhaps most importantly, the scope and duration of the outage must be determined. Is it confined to a single OR, to a collection of ORs, or to some larger entity, such as one or more floors, the hospital or facility, or an entire community? The expected duration of the interruption in power must be determined, as it will significantly influence decision making.

It is important to realize that having backup power is no guarantee of continued operations. There have been several instances where the backup supply has failed, resulting in the OR, or institution, being completely without power.

Because a loss of power may occur, it is necessary to know which items of equipment have internal battery backup. It’s important to keep the batteries fully charged and to know how long the backup batteries will last; what functions will continue on backup power; how to provide light, computer, phone, and paging services; and how to provide alternatives to primary equipment and functions (e.g., portable monitors in place of normal physiologic monitors, or intravenous anesthesia via infusion pumps in place of inhaled anesthetics delivered by the anesthesia machine).

In addition, it is important to understand how electrical power is provided to the OR, that is, which sockets are intended to function only under normal conditions (usually white sockets), and which will provide emergency power in the event of a power failure (usually red sockets). Essential equipment, such as anaesthesia machines, should always be plugged into emergency (red) sockets.

4) IMPLANTED DEVICES

The fourth and final category of electrical hazard has to do with patients who have implanted electronic devices, such as pacemakers, implantable cardioverter-defibrillators (ICDs), cochlear implants, and spinal cord or other stimulators. The risk is that these devices may be damaged or malfunction as a result of exposure to electrical currents, which may result in harm or death.

The malfunction of pacemakers and ICDs due to electromagnetic interference from electrosurgical devices poses the greatest risk to patients. The typical reason for malfunction is that electrical currents from the electrosurgical unit pass in proximity to the implanted device or leads emanating from it, resulting in a change to the device’s mode of operation (reprogramming), accidental firing of an ICD or stimulator, or damage to the device. Simple steps can usually prevent this from being a problem. The dispersive pad should be placed so the current does not cross the device, but instead travels away from it. For example, if a patient has a pacemaker on the left side of the chest, and surgery is being conducted on the right shoulder, the dispersive pad should not be placed on the left shoulder, or anywhere on the left side.

Bipolar electrosurgical devices should be considered in place of the usual monopolar device, as this will confine the current between the tips of the bipolar device. ICDs should be programmed OFF for the duration of surgery, and reprogramming can be used to convert pacemakers to an asynchronous mode of function.
References:

1. **Part 1 ARC 2010** – chapter on Electrical safety by Prof Ivan Joubert

2. **Anesthesia Equipment: Principles and Applications**, 2nd edition, 2013- Ehrenwerth, J; Eisenkraft, J; and Berry, J.
   The use of diagrams from this source is gratefully acknowledged.