Continuing Medical Education Article

Electrical safety in the operating room

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Notwithstanding the advances in safety of electrical equipment in the operating room over the last 20 years, there remain potential electrical hazards to patients and operating room personnel. It therefore behoves the practicing anaesthetist to have a basic understanding of the principles of electrical safety.

Basic principles

Electrical current should stay confined to the circuit in which it is intended to do work. If it "leaks" outside the protective insulation of electrical wires, or to the casing of an electrical appliance, it could follow an unintended pathway causing shock, interference with readings from electrical instruments (misinformation), or explosion in the presence of flammable anaesthetics. Of these, the most important hazard is electrical shock, which is due to passage of electric current through the body and which can result in burns,[1-5] ventricular fibrillation,[3-7,8] neural injury,[5] and possibly secondary injuries due to recoil from the shock sensation.

Electric current is the flow (measured in amperes) of electrical charges past a given point in an electrical conductor per unit of time, propelled by the driving force, voltage.[9]

Every conductor (and each appliance in a circuit) has an inherent resistance (R) to current flow depending on its physical properties. Voltage (V), current (I) and resistance (R) are related by Ohm's Law:

$$V = IR \text{ or } I = V/R \qquad \text{(References 9–11)}$$

In the operating room, appliances are connected to the electrical circuit in parallel (Figure 1), with each appliance forming a branch circuit.[10] Each branch circuit draws an amount of the total current which is inversely proportional to its resistance. The human body can form a branch circuit if it touches a conducting circuit in two places (Figure 2). The amount of current running through the body in this case depends on its resistance and on the applied voltage.

Pathophysiologic effects of electric current

Current can take one of two forms. Direct current (DC) flows in one direction only (e.g., flow from a battery). Alternating current (AC), on the other hand, oscillates back and forth at a specific frequency. Electric current from power lines is alternating current.

A single electrical stimulus can precipitate ventricular fibrillation if it is intense enough and lasts long enough or if it arrives at the heart during the vulnerable period of the cardiac cycle.[12] The risk of ventricular fibrillation increases with repetitive shocks at a frequency greater than 5/sec and then diminishes at very high frequency.

Macroshock is high-flow current applied to the skin at two points so that the heart is included in the current pathway and receives enough current to cause ventricular fibrillation. Extrapolation from animal studies suggests that the minimum externally applied current at mains frequency (60 Hertz) necessary to cause ventricular fibrillation in man is 100 milliamperes (mA).[13]

Microshock is low-value current conducted directly to the heart via, for example, external pacemaker wires or fluid-filled cardiac catheters. In patients undergoing heart surgery, as little as 200 microamperes (μA) applied to intramyocardial electrodes and 67 μA to endocardial electrodes will fibrillate the heart.[7]

Factors which influence the pathophysiologic effects of electric current

Alternating current vs direct current

Alternating current is more physiologically harmful than the same amount of direct current. Whereas only 100 milliamperes of alternating current might cause ventricular fibrillation, three amperes of direct current have been passed through the human body without ill effect.[5]

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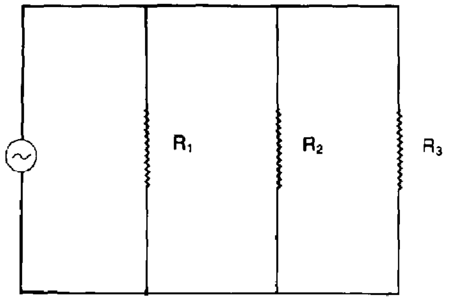

FIGURE 1 Three parallel branch circuits, each with its own resistance (R_1, R_2, R_3). ~ is the symbol for voltage. The amount of current flowing through each branch circuit is directly proportional to voltage and inversely proportional to each individual resistance.

Frequency of alternating current

Alternating current is most dangerous at 10 to 200 Hz. Animal experiments have shown that 22–28 times more current at 3,000 Hz is required to induce ventricular fibrillation than at 60 Hz.[13]

Power companies use 60 Hz (mains frequency) despite its danger because higher frequencies produce greater power loss over a long distance; at lower frequencies, flicker from light sources becomes detectable to the eye.[5]

Current density

Current density is the amount of current per unit area of tissue.[14] Burns result when current density overwhelms the ability of capillary blood flow to dissipate the resultant heat. This can be due either to high current itself or to conditions which limit blood supply. The higher the current density through the heart, the greater the chance of ventricular fibrillation.[5]

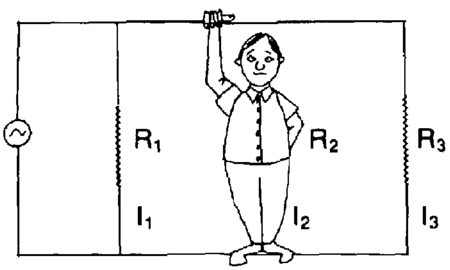

FIGURE 2 The human body as a branch circuit. I_2 is the current flowing through the body and depends directly on voltage and inversely on the body's resistance to flow of electrical current.

Body resistance

Skin resistance is normally high; even when lowered by wetting or by abrasion, skin resistance is still more than 1,000 times that of a three metre length of #18 wire.[13,15,16] This high resistance to current flow tends to protect the body from electric shock.

Current pathway

The current pathway is the route the current follows from its entry point in the body to its exit point. This pathway is influenced by relative resistances of the tissues between the contact points. If the heart is directly in this pathway (e.g., left arm to right leg), the risk of ventricular fibrillation is higher than if the heart is not directly in the pathway (e.g., right thumb to right index finger).

Duration of exposure to current

Short pulses of current (less than ten milliseconds) can be used therapeutically for cardioversion or cardiac pacing. The longer the duration of the stimulus, however, the higher the risk of deleterious effect, both with respect to burn[5] and ventricular fibrillation.[12]

Electrical circuit concepts

Power distribution

In order to understand the distribution of power, it is first necessary to understand the function of a transformer (Figure 3). Current flow induces a surrounding magnetic field. Alternating current induces an oscillating magnetic field which in turn can induce voltage in a secondary circuit without direct contact between the wires of the circuits. Transformer efficiency is achieved by coiling adjacent wires in the primary and secondary circuits.

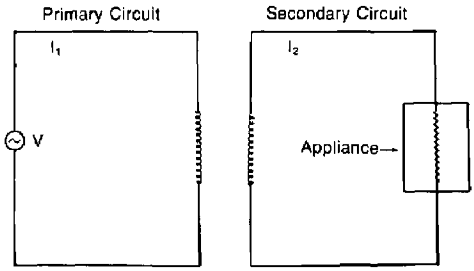

FIGURE 3 Transformer. The primary circuit can induce current in the secondary circuit without direct contact between the circuits. Transformer efficiency is increased by coiling adjacent wires as schematically shown. The size of current in the secondary circuit depends on current flow in the primary circuit and the ratio of coils (primary to secondary winding).

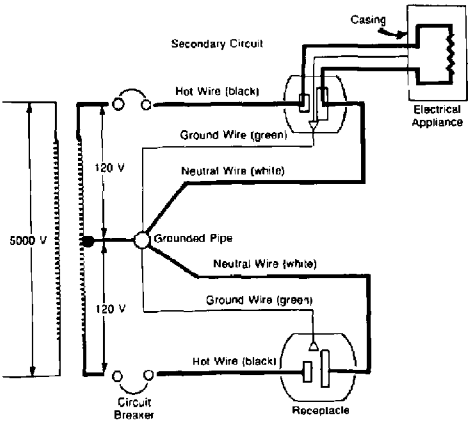

FIGURE 4 Conventional power distribution showing, from left to right, high voltage industrial supply transformed to 240 Volts end-to-end of the secondary coil which is divided into two 120 Volt circuits by the grounded central tap (diagram adapted from Olson).[17] Note that the ground wire runs from the casing of the appliance to ground. It provides an alternate path of low-resistance run off of current leaked to the casing (see text).

A high voltage source from the power company supplies the hospital where it is converted by a step-down transformer to a 240-volt source for the secondary circuit. The 240-volt source can be used to power heavy duty appliances such as x-ray machines. More commonly, a central tap on the secondary winding provides two 120-volt circuits between either end of the winding and the central tap, which is then connected to the earth (ground) usually via a heavy copper wire. A simplified diagram of power distribution adapted from Olson[17] is shown in Figure 4.

Leading to the live side of the wall socket is a live wire (normally covered with black insulation) directed through a circuit breaker which shuts the circuit off if the rated current (usually 15 amperes) is exceeded. Plugging in the appliance brings current to it via its own live wire. The electricity energizes the appliance and the circuit is completed via a neutral wire (normally covered with white insulation) which returns to the plug-in receptacle and completes the secondary circuit to return to the source. The neutral wire is grounded before it returns to source. The ground wire, the third wire, is separate from the circuit and connects the casing of the appliance to a grounded strap at the distribution box.

Ground (earth)

Current can only flow in a closed loop. In the conventionally grounded circuit already described, there is a 120-volt potential difference between the live and the grounded neutral sides of the circuit. Because the earth is a good conductor, any alternate path to ground from the live side of the circuit can complete the circuit and will conduct an electrical current (Figure 5).

Current leak

Current can leak from the circuit to the casing of an electrical appliance in three ways: (1) Direct contact by a bare wire due to faulty insulation or construction. The resulting leak is large. (2) Inductance of a small current in the casing by the oscillating magnetic field of the current driving the appliance. (3) Capacitative coupling.[18] A capacitor consists of two conductors separated by insulation. The conductors could be of any shape, but it is convenient to refer to them as plates. The insulation between them is known as a dielectric. When the plates are connected to a source of voltage (Figure 6) plate A accumulates a negative charge which repels electrons from plate B, giving plate B a net positive charge. Thus a potential difference is generated between the plates which can be recovered as electrical current if the plates are joined by a conductor. As alternating current is applied to the capacitor the net charges on the plates change from

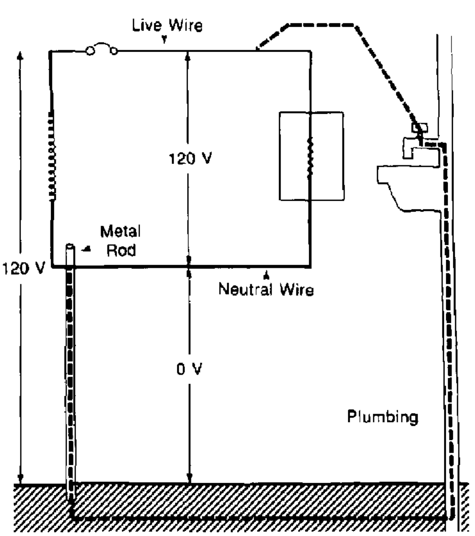

FIGURE 5 Conventional Grounded Circuit. The neutral wire is ground-referenced through a metal rod. Because of this, any alternate pathway between the live wire and ground (through a human body, for example) can form a closed loop and complete a circuit which carries current as shown by the dark hatched line.

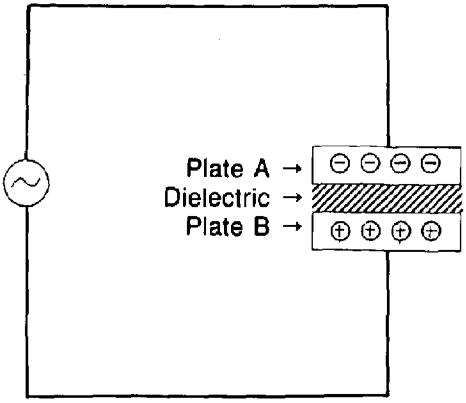

FIGURE 6 Capacitor. The voltage source drives electrons into plate A which repel those in plate B giving the plates a net charge. Although in this diagram plate A is negative and plate B is positive, the plates change their charge with the frequency of the alternating current.

positive to negative at the frequency of the alternating current. The oscillating electrons in an AC circuit can have similar effect on the casing of an appliance supplied by the circuit. The wire of the circuit can be thought of as one plate of a capacitor, the metal parts of the casing as the other plate, and the insulation of the wire and surrounding air as the dielectric. The back and forth movement of electrons in the metal parts of a casing can allow for a tiny current flow if the casing is connected to ground either by the ground wire or by any other accidental means.

We can alter the energy storage in a capacitor by changing: (1) the dielectric (altering insulation); (2) the geometry of the "plates" relative to one another; (3) the voltage.

The current leaks from inductance and capacitative coupling are small but if conducted directly to the heart by external pacemaker wires, for example, they can cause ventricular fibrillation. The ground wire connects the casing to ground and has much less resistance to current flow than the human body. If someone accidentally touches a faulty appliance and simultaneously grounds himself, much more of the leaking current will flow to ground via the ground wire than through the individual. The intact ground wire is a safety feature in this situation. This is the reason that the ground prong in a wall plug is longest, so it is the last to lose contact if the plug comes out part way.

A ground fault detector compares current in the live and neutral parts of the main distribution circuit.[11] These two should be equal unless there is a leak to the casing of any appliances powered by the circuit. Then the neutral side would have less current than the live side by the amount of the leak. The ground fault detector alarms when the current difference exceeds three milliamperes and may be equipped with an interrupter which shuts the circuit off. If the leak is smaller than three milliamperes the alarms will not be activated though the amount of leaked current could be lethal. A ground fault detector, despite its name detects current leak, not a broken ground wire in an appliance. Therefore the appliance should be checked for an intact ground wire by a qualified individual at regular maintenance intervals.

Circuit isolation

In a conventionally grounded circuit any alternate pathway to ground (e.g., via the casing of an appliance through its ground wire) can complete a circuit and allow current flow. Even if a low-resistance ground wire channels most of the leaked current to ground, the remaining current, though small, may be hazardous if channelled directly through the myocardium.

Hazard from such a situation can be attenuated by isolating the circuit.[16] The isolated circuit is powered by an additional transformer and the return wire is not connected to ground (Figure 7). This makes almost impossible the formation of a closed loop from live wire through victim to ground and back to neutral wire as can occur in the conventional circuit. In the ideal isolated circuit, no current flows from either limb through an accidental connection to ground. There should be no electrical hazard arising from accidental simultaneous contact with the circuit or the casing and ground.

Unfortunately the ideal isolated circuit does not exist, because it acts as one plate of a capacitor with a grounded appliance acting as the other and with the intervening insulation and air as the dielectric. When an alternating current passes through the isolated circuit, the to and fro motion of electrons has a small capacity to move charges in the grounded casing without physical contact between circuit and casing. This sets up a small potential difference between the circuit and its appliance casings like the potential difference between two capacitor plates. If the ground wire of one appliance casing is broken, and an individual grounds the casing through himself, current can flow through the individual to ground with a return path of current via capacitance in the other appliances (Figure 8).

The potential difference between the plates of a capacitor can be diminished by altering the dielectric, that is by improving insulation of the wires in the circuit. It can be increased by increasing current flow. Thus the addi-

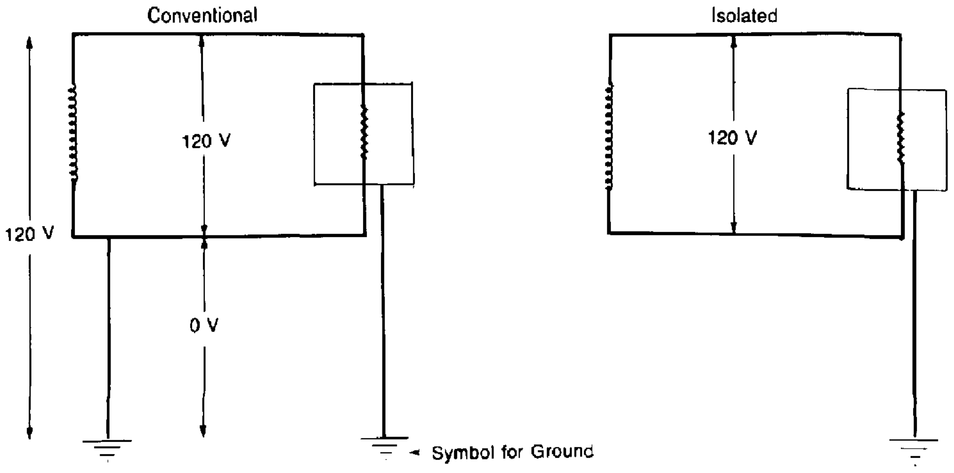

FIGURE 7 Conventional vs Isolated Circuit. The isolated circuit is not ground-referenced. While the casing of the appliance is grounded, no part of the actual circuit is connected to ground. Therefore simultaneous contact between the circuit and ground does not form a closed-loop and, ideally, no current flows.

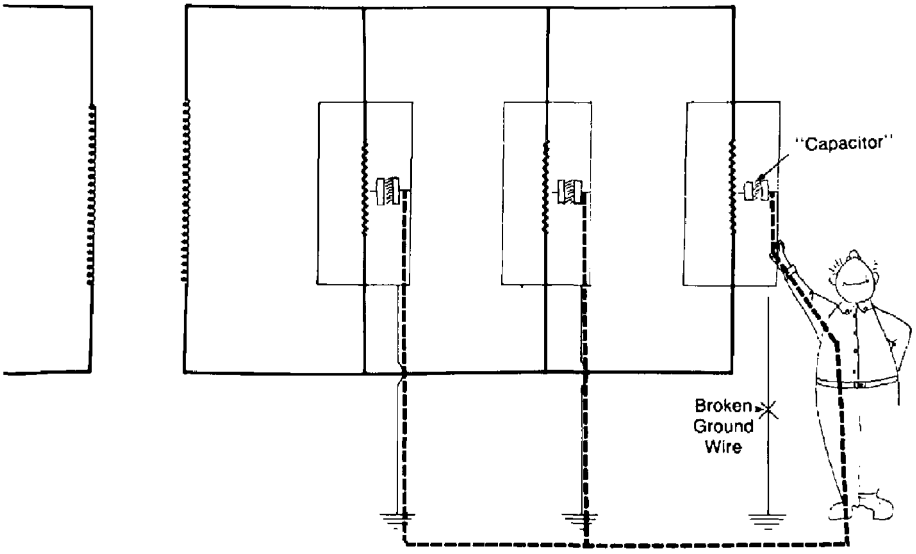

FIGURE 8 The Isolated Circuit. Current path (broken line) via a victim and ground despite an isolated circuit. Capacitative leak (represented by the hypothetical "capacitor") decreases isolation of appliances with ground wires. If a ground wire is broken and the victim provides a grounded pathway a small current will flow through the victim.

tion of progressively more appliances to the isolated circuit increases the potential difference (albeit to a small degree) and decreases "isolation."

The isolated circuit thus behaves as though it were grounded through a ground wire with a very high resistance. This high equivalent resistance is a measure of isolation. By convention, in acceptably isolated systems, if one wire were grounded, a maximum of 1.4 milliamps would flow to ground. Equivalent resistance in this pathway (120 volts divided by 0.0014 amps) is 86,000 ohms. Thus operating room line isolation monitors may be calibrated in either current or resistance units.

In an isolated circuit, hazard exists only when three conditions are met:[16] (1) current leak to an appliance casing; (2) decreased isolation; (3) a broken ground wire from the casing of the appliance in question.

A current leak to the casing can occur by any of the three means previously discussed. The greatest hazard exists when there is an actual insulation fault, with contact between bare wires of a circuit and the casing. As has already been suggested, isolation is diminished as more appliances are connected to and powered by the same circuit. A great many appliances must be running from one circuit in order for the potential difference between that circuit and ground to be anywhere near that of a conventionally grounded circuit.

A line isolation monitor does not detect current leak or a broken ground wire from appliances. Frequent maintenance of the appliances by qualified personnel serves this purpose. However, the line isolation monitor detects deteriorating isolation. It does so by alternately grounding each wire in the circuit and measuring the current that flows to ground. If this exceeds two milliamperes an alarm sounds. The line isolation monitor itself contributes very little to the deterioration of the isolation of the circuit because it grounds through a very high resistance wire and computes what the current would be if the wire were of low resistance.

Thus if the line isolation monitor alarms during a surgical procedure, this is not in itself an indication to terminate the anaesthesia and surgery. It simply means that one of the three conditions necessary to create an electrical hazard has been met. The most common cause is the addition of an electrical appliance such as an electrosurgical unit to the circuit. It may also mean, however, that one of the electrical appliances in the circuit has a significant electrical fault. The approach in this case should be to unplug each appliance in turn, thereby determining whether one specific appliance is creating the problem or whether there are too many electrical appliances being powered by the circuit. However, if the alarm sounds prior to the start of a case, the source must be determined and eliminated prior to commencing the case. Otherwise the ability to detect the presence of a new hazard is lost.

Electrical hazards from operating room appliances

The electrosurgical unit

The electrosurgical unit, or ESU, allows a surgeon to coagulate bleeding vessels or cut through tissue by creating a localized radio-frequency burn.[8,10] Alternating current is delivered by the ESU at a frequency of between 400,000 and 3,000,000 Hz to the desired area through an active electrode which is small, producing a high current density and very localized heat. With a unipolar ESU the return path is via the body and a "return pad" attached to the skin with a large area of contact resulting in low current density. With a bipolar system a second electrode near the active electrode (usually the other jaw of the forceps) provides the return pathway to the ESU. The bipolar unit allows very precise application of current. It is therefore very useful in areas where tissue damage must be kept to a minimum, such as in neurosurgery.

In general the bipolar electrode presents little electrical hazard to the patient. On the other hand the unipolar system depends, for safe function, on a properly placed return pad to provide a low resistance conductive pathway for the electricity back to the ESU.[10] If this return pad does not make good contact over a large area, then high current density at small points of contact may cause burns.

If the return pad is not placed on the patient or detaches from the skin, then the ESU will not work well, and the surgeon will request higher and higher power. If under this circumstance contact can be made to a grounded operating table through a fluid medium such as blood or antiseptic solution then flow of current through a small contact area of skin (with high current density) might result in local tissue burn. Therefore it is important to check for good contact between the return pad and the skin.

It is also possible that alternate routes of current return may be sought through ECG electrodes and temperature probes, with the same potential for local tissue burn.[10]

Although it is probably prudent to keep the current pathway away from the heart, the high frequency of the current makes it less likely to induce ventricular fibrillation than leaked current at mains frequency. Placement of a return pad very near a pacemaker might lead to heavy current through the pacemaker case and cause either local tissue damage or damage to the pacemaker itself.[10] Modern ESU's and monitors contain an additional internal transformer to further isolate all circuitry in direct continuity with the leads going to the patient. This is an additional safety feature called "front-end isolation" which has almost eliminated the risk of local burns mentioned above.

The defibrillator

In simple terms, the defibrillator is a capacitor which allows stored electrical energy to be discharged through the paddles with the patient completing the circuit. Modern defibrillators are isolated. Therefore current generated from them will not flow to ground. However, hazard can occur if the electrode handles are either cracked or have a coating of conductive material on them. Then the individual holding the paddles may provide a parallel path for the discharge of the electricity. Similarly, an attendant touching the patient at two points may also become a branch circuit for a brief surge of up to 20 Amperes of current.[10]

Cardiac pacemakers

Simon[19] provides an excellent review of perioperative pacemaker function, which is beyond the scope of this paper.

Extraneous or leaked current can interact with a cardiac pacemaker in four ways. First, any extraneous electrical current (from an ESU for example), may be interpreted by a demand pacer as cardiac activity and suppress pacing.[20] Most modern pacemakers are shielded from this effect. Nevertheless it is recommended both that the pulse be monitored during the use of electrocautery in patients with cardiac pacemakers and that some means be immediately available to convert a demand pacemaker into a fixed-rate pacemaker (e.g., a magnet).

Second, the intramyocardial wires of the pacemaker can be conduits for leaked current directly to the myocardium. Such microshock currents may cause ventricular fibrillation.[21] This situation could only arise if there were the potential for an electrical hazard and faulty shielding of the pacemaker and its leads.

Third, programmable pacemakers in the path of ESU current have been reprogrammed by a burst of current, usually to a faster rate.[22]

Finally, some patients may arrive wearing new implanted automatic defibrillators which are triggered by a sensor if not enough time is spent at or near the isoelectric state of the ECG. Either 60 Hz or ESU interference may trigger these. The 25 J shock is not painful but may itself induce ventricular fibrillation.[23]

Conclusion

Application of well-established principles of electrical safety to construction and maintenance of electrical equipment has reduced electrical hazard in the operating room significantly. Although anaesthetists are not involved in design and maintenance of electrical equipment they should understand how electrical hazards may arise. More informed anaesthetic practice should contribute to patient safety.

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References

1 *Becker CM, Malhotra IV, Hedley-Whyte J.* The distribution of radio frequency current and burns. Anesthesiology 1973; 38: 106–22.
2 *Battig CT.* Electrosurgical burn injuries and their prevention. JAMA 1968; 204: 91–5.
3 *Weibell FJ.* Electrical safety in the hospital – 1974. Annals of Biomedical Engineering 1974; 2: 126–48.
4 *Taylor KW, Desmond J.* Electrical hazards in the operating room, with special reference to electro-surgery. Can J Surg 1970; 13: 362–74.
5 *Monks PS.* Safe use of electro-medical equipment. Anaesthesia 1971; 26: 264–80.
6 *Raftery EB, Green HL, Yacoub MH.* Disturbances of heart rhythm produced by 50 Hz leakage currents in human subjects. Cardiovasc Res 1975; 9: 263–5.
7 *Watson AB, Wright JS.* Electrical threshholds for ventricular fibrillation in man. Med J Australia 1973; 1: 1179–82.
8 *Bruner JMR.* Hazards of electrical apparatus. Anesthesiology 1967; 28: 396–424.
9 *Cromwell L, Arditti M, Weibell FJ et al.* Medical instrumentation for health care. Prentice Hall Incorp., Englewood Cliffs, New Jersey, 1976.
10 *Spooner RB.* Hospital electrical safety simplified. Instrument Society of America, Research Triangle Park, North Carolina, 1980.
11 *Hoenig SA, Scott DH.* Medical instrumentation and electrical safety: the view from the nursing station. John Wiley & Sons, New York, New York, 1977.
12 *Geddes LA.* The conditions necessary for the electrical induction of ventricular fibrillation. *In*: Bridges JE, Ford GL, Sherman IA, Vainberg M. Electrical shock safety criteria. Pergamon Press Incorp. Elmsford, New York, 1985: 45–59.
13 *Dalziel CF.* Electric shock hazard. IEEE Spectrum, The Institute of Electrical and Electronics Engineers Inc. 1972; 9: 41–50.
14 *Finlay B, Couchie D, Boyce L, Spencer E.* Electrosurgery burns resulting from use of miniature ECG electrodes. Anesthesiology 1974; 41: 263–9.
15 *Biegelmeier G.* New knowledge on the impedance of the human body. *In*: Bridges JE, Ford GL, Sherman IA, Vainberg M. Electric shock safety criteria. Pergamon Press Incorp. Elmsford, New York, 1985: 115–32.

16 Guide for electrical systems for patient care areas in hospitals. Ministry of Health, Toronto, Ontario. March, 1983.

17 *Olson WH.* Electrical safety. *In*: Webster JG. Medical instrumentation: application and design. Houghton Mifflin Company, Boston, Massachusetts, 1978: 667–88.

18 *Halliday D, Resnick R.* Fundamentals of Physics. John Wiley & Sons, New York, New York, 1981.

19 *Simon AB.* Perioperative management of the pacemaker patient. Anesthesiology 1977; 46: 127–31.

20 *Waldemar JW, Mowry FM, Dugan NL.* Deactivation of a demand pacemaker by transurethral cautery. N Engl J Med 1969; 280: 34–5.

21 *Titel JH, ElEtr AA.* Fibrillation resulting from pacemaker electrodes and electrocautery during surgery. Anesthesiology 1968; 29: 845–6.

22 *Domino KB, Smith TC.* Electrocautery-induced reprogramming of a pacemaker using a precordial magnet. Anesth Analg 1983; 62: 609–12.

23 *Mirowski M, Reid PR, Mower MM et al.* Termination of malignant ventricular arrhythmias with an implanted automatic defibrillator in human beings. N Engl J Med 1980; 303: 322–4.