As hazards from the combustion of flammable anesthetics have subsided, the dangers from shock and electrocution have increased because of the greater use of electrical equipment in the operating room. Anesthesia personnel are, in many cases, the only people who continually monitor the total patient during surgery. For this reason, they must be familiar with the hazards created by the use of electrical equipment in the operating room, the associated electrical theory, and how such hazards can be minimized.

Prior to the early 1950's, explosive anesthetics posed the greatest danger to the patient and to the operating room team, with the exception of surgery and anesthesia. A single discharge of static electricity could produce the heat necessary to create an explosion that could kill the patient and the surgical team or leave them seriously burned. With the introduction of halothane in 1956, the use of explosive anesthetics has been on the steady decline, being used today only in teaching institutions. Some institutions have banned the use of explosive anesthetics altogether.

As the use of explosive anesthetics declined, the use of electrical monitoring and surgical equipment was on the increase. It is estimated that today, 60% of the patients coming to the operating room will have at least one electrical device intimately attached to their bodies.

Many will have two or more devices in use. The pieces of equipment most often used are the ECG monitor and an electrocautery device. These two pieces of electrical equipment are associated with a majority of the electrical shocks and burns that occur during surgery.

Estimates of the number of patients electrocuted in hospitals by medical electrical equipment range from 1,200 to 5,000 annually, and electrocution has been referred to as the biggest single hazard of hospitalization.

Bruner and associates found that 42% of all electrical accidents in hospitals occurred in the operating room. Based on this percentage, operating room electrocutions range annually between 500 and 2,100. Inadequate reporting systems presently in use account for the wide range in the statistics. Work to improve the validity of these statistics was begun in 1967 by Bruner, Aronow, and Cavicchi and the Association for the Advancement of Medical Instrumentation; however, national results of this more accurate reporting system were not available at the time of this writing.

Many hospitals are unwilling to admit that electrocutions have occurred, either because of the medical-legal implications or because, in fact, they do not really know that the accidents occurred. Consumer groups estimate electrocutions to be very high. A better and more accurate data collection system will help researchers plan a true probability of the danger, and thereby enable the
equipment developers and hospital planners to invest equipment dollars for helping the greatest number of patients. Irrespective of the actual statistics, it is a documented fact that electrocutions, burns, and arrhythmias do occur during surgical procedures as a direct result of electrical shocks.

Anesthesia personnel are, in many cases, the only people who continually monitor the total patient during surgery. For this reason, they must be familiar with basic electricity, the pathways of stray electrical currents, the technology presently available to limit stray currents, and the safety precautions necessary to minimize the dangers both to the patient and to the surgical team.

Basic electricity

A limited number of terms and concepts should be understood in any discussion of electricity and current flow. An ideal insulator blocks the flow of electricity. On the other hand, a conductor allows the flow of electricity. Current is the flow of electricity and is measured in amperes (A). Frequently, electrical measurements will be expressed in a fraction of the unit value, such as milliamperes (1 milliampere = 1/1000 ampere; 1 mA = 0.001 A) or microamperes (1 microampere = 1/1,000,000 A; 1 μA = 1 x 10^-6 A).

Voltage or potential difference must be placed across a conductor to make current flow through the conductor. If equivalent voltage levels are applied across a conductor, no current will flow within the conductor between the points of contact. If, however, the voltage level differs, then current must flow. By definition then, for current to flow across a conductor, there must exist a potential difference or voltage between the points of contact of the conductor. Voltage or potential difference is measured in volts (V) or a fraction of a volt such as millivolts (mV) or microvolts (μV).

Impedance, the third and last important element of electrical flow, is a measure of the ease with which a conductor allows current to flow. While insulators have a very high impedance and limit the flow of current, conductors have low impedance and, therefore, allow electricity to flow easily. Impedance is made up of three components: resistance, capacitance, and inductance. (Only resistance will be discussed in this article because the relative significance of the other two are minor in comparison to it.) Resistance is measured in ohms (Ω) and represents the number of volts necessary to conduct one ampere of current flow through a conductor.

The three principle components of electricity or electrical flow are empirically described and equated by Ohms Law in Equation 1.

\[ E = IR \]

(1) Potential Difference (E) = Current (I) X Resistance (R) or \[ E = IR \]

Ohms Law states that the potential difference (E) measured in volts (V) is equal to the current (I) measured in amperes (A) flowing between the points of potential difference times the resistance (R) measured in ohms (Ω) of the conductor connecting the points of potential difference.

An analogy can be drawn between the flow of current in a circuit and the flow of water in a pipe as shown in Figure 1. The pressure causing the water to flow may be measured as the height of the top of the water column. The pressure causing electricity to flow is measured in volts. The flow rate of water may be measured in gallons per minute. The analogous measurement for electricity is amperage. The flow rate
of water is limited by friction in the pipe and by the valve which impedes or resists the movement. Similarly, all electric circuits have resistance to current flow which is measured in ohms.6

Figure 2
Schematic of an electrical circuit.

A circuit must exist in order for current to flow. The circuit must contain the three integral ingredients: voltage, current, and resistance. An electrical circuit is schematically represented by a group of lines that are interconnected. The schematic shown in Figure 2 is not a true circuit until switch (S) is closed allowing current (I) to flow across the resistance (R) because of the potential difference (E). If, for example, the resistor in Figure 2 has a resistance of 500Ω and a potential difference of 120V were placed across the circuit, when switch (S) was closed, a current of 0.24 A or 240 mA would flow.

\[ E = IR \]
\[ I = \frac{E}{R} = \frac{120\, V}{500\, \Omega} = 0.24\, A \text{ or } 240\, mA \]

Physiological effects of electric current

Now that the basic electrical concepts have been introduced, we can proceed to discuss the physiological effects of electrical current passing through the human body. Electrical current is the element that causes damage to tissues, burns, and produces arrhythmias. Voltage and resistance set up the framework for current to flow. The magnitude of the current is the important element. Looking at Ohm's Law rearranged in Equation 2 to equal current (I), it can be seen that even at high voltages, if the resistance is sufficiently high enough, little current will pass through the circuit. In the context of electrical shock to a patient, the circuit is principally the body. (2) \( I = \frac{E}{R} \)

Figure 3 depicts a typical electrical hook-up of a patient to an ECG monitor and a cautery unit. The anesthetist, whose hand is on the temporal pulse, is providing a potential pathway to the grounded operating room floor through his electrically conductive shoes. Theoretically, the patient is not grounded lying on the operating room table, except through wet drapings to the operating room table, through the conductive anesthesia circuit, and the leg ground lead of the ECG monitor.

Figure 3
Typical electrical hook-up of a patient to an ECG monitor and cautery unit during surgery.

With these various grounding routes, if a stray electric current (say from the cautery tip with a defective grounding plate) was to pass through the patient, it would be dissipated in various pathways to ground. The pathways would be the ECG grounding lead, the operating room table, the anesthesia circuit, and the anesthetist's body. This concept is shown schematically in Figure 4.

The amount of current that will pass through each of these pathways is proportional to the inverse of the resistance of the pathway with the total of all pathway currents exactly equal to the current passing through the cautery tip. A concept which has application here is "current will follow the pathway of least resistance."

With these resistive pathways in
Figure 4
Electrical schematic of patient on an operating room table being exposed to electro-cautery without a functioning cautery grounding plate. E is the potential difference between the cautery tip and ground. \( R_1 \) is the patient's resistance between the tip of the cautery and the ECG grounding electrode. \( R_2 \) is the patient's resistance between the ECG grounding electrode and the remainder of his body; therefore, the patient's total resistance is \( R_1 + R_2 \). \( R_{ecg} \) is the resistance of the ECG monitor grounding lead. \( R_c \) is the resistance of the anesthesia circuit; \( R_t \) is the resistance of the O.R. table; and \( R_a \) is the resistance of the anesthetist making contact with the patient's temporal pulse. \( I_0 \) is the total current flowing through the patient. This current is divided into two secondary components: \( I_1 \), the current conducted by the circuit, table, and anesthetist, and \( I_2 \), the current conducted by the ECG grounding electrode. Therefore, \( I_0 = I_1 + I_2 \). The values of the resistances will determine the current that will pass through each secondary leg of the circuit. In this circuit, a majority of the current will flow through the ECG monitor grounding lead because its resistance is lower than the combined parallel resistance of the other pathways.

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mind, we can now talk about the physiological effect of electrical current passing through the human body. The usual electrical outlet voltage in the United States is 60 cycle per second or 60 Hertz (Hz), 120 V, alternating current. Most individuals can not detect any sensation of 60 Hz current of less than 1 mA. Above 5 mA, the sensation becomes painful and may cause jerking away from the current source, resulting in a fall or other injury.\(^7\)

Muscle stimulation by currents in excess of 10 to 20 mA results in tetany to certain muscles with the inability to let go of a current carrying conductor. When currents which have been applied at the skin surface and have traveled through the trunk attain levels in the neighborhood of 100 mA, ventricular fibrillation may ensue.\(^7\) At the multi-ampere level, the heart goes into sustained contraction; but, it usually resumes its rhythm when the current flow stops, provided the duration of the shock has not been too long. This last statement is specifically how a clinical defibrillator operates when a patient is in ventricular fibrillation.

The current, applied to the body surface, tends to disperse over multiple pathways as it passes through the trunk. Thus, the density of the current passing through the heart will be considerably lower than the density at the points of entrance and exit on the body. In some circumstances, however, currents may be conducted directly to the heart, as for example, by a pacemaker wire or cardiac catheter. In these circumstances, all the current is concentrated at the myocardium. The current density for a given total current at that location is much greater.\(^8\)

The smallest 60 Hz current that will cause fibrillation when applied directly...
to the heart is not known. The figure of 10A has often been cited as the threshold current; however, Raftery found that under controlled studies, 80μA of 50 Hz current was required. The patient with an externalized conductor to the vicinity of the heart is popularly referred to in the literature as "the electrically susceptible patient".

In addition to ventricular fibrillation and other arrhythmias, muscle tetany, and pain, a patient is susceptible to electrical burns. Burns usually occur at the points of entrance and exit of the current to and from the body. Currents of 100 mA or greater are required to produce burns. Controlled burns are the attribute of an electrosurgical unit. The point of unwanted burns is the exit point of the current from the body.

The amount of heat produced depends on the current density and the resistance. If either the current or the resistance is zero, no heating can occur. It is the application of this principle which requires that the electrode grounding plate of a radiofrequency electrosurgical apparatus be placed carefully on a patient (with conductive paste between plate and patient), so as to provide the lowest possible resistance path over a wide area of the patient's skin for the flow of current.

If a grounding plate is malfunctioning or improperly placed (limited skin contact say under a boney prominence) or lacks conductive paste, the current may pass less easily through this plate or pass more easily through the grounding plate of the ECG monitor. The current density will be much higher across the ECG plate, resulting in a potentially severe burn. Burns, therefore, can occur wherever current passes across an area of increased resistance and low surface area. The amount of heat dissipated (that is, produced) in unit time by a current is expressed in the unit of power, the watt, which is the product of voltage and amperage. (Equation 3).

\[ \text{Energy (watts)} = EI \]

Substituting Ohms Law and assuming a constant potential difference yields Equation 4, an expression of energy in terms of current and resistance. From Equation 4, it can be seen that if the energy is dissipated over a wide area (large Bovie grounding plate), then a burn will not be produced. If on the other hand, the energy is dissipated over a relatively small area (the ECG grounding electrode), a burn will result.

\[ \text{Energy (watts)} = (IR)I = I^2R \]

**Macro versus micro shock**

Now that the physiological effects of electrical current on the human body have been discussed (including the thresholds for the shock), differentiation must be made between large and small shocks or macroshocks and microshocks. Adverse effects produced by electrical current in the milliampere range and above are called macroshock.

Macroshocks may be induced by the impression of stray electrical currents through the thorax flowing between electrical conductors in contact with the surface of the skin. As the current passes through the thorax, it is diffused and only a small portion of it passes directly through the heart. Thus, a significant current in the range of 0.1 amperes must be impressed across the thorax to cause ventricular fibrillation. Macroshocks are also the source of burns. From Equation 4, it can be seen that in order to produce a large power dissipation at a skin site, the current must be of sufficient magnitude.

Very small amounts of current, in the range of 10 to 100μA (0.01 to 0.1 mA), can cause ventricular fibrillation if concentrated in the vicinity of the heart. This type of adverse electrical effect is called microshock. Patients who either have externalized conductors from cardiac pacemakers or who have catheters containing electrolytes placed within one of the chambers of the heart or in its immediate vicinity are vulnerable to microshock.

The significance of such tiny currents can be better appreciated when it
is realized that leakage currents within this order of magnitude develop, not uncommonly, in the electronic medical equipment in use today. Leakage currents are unintentional currents flowing through impedance paths between electronic components and the chassis of an instrument. They may appear on a patient's electrode and complete a circuit to ground through the patient.\(^1\)

The elimination of these unwanted currents from electronic devices is difficult and is a major problem in electronic design. They can be minimized by careful design and construction. In addition, the patient can be protected from them by a number of methods, all of which depend upon the continuous normal functioning of each piece of electronic equipment. For this reason, regular qualified maintenance of all such equipment is most important. The risk to the patient is particularly high when two or more pieces of equipment are being used, and a fault develops in one instrument.\(^1\)

Theoretically, there are two means of stopping the flow of fault currents. The first is to make the voltage difference between the equipment chassis and the patient zero by effective grounding; this is the commonest safety principle employed in all but the most newly constructed facilities. It is also the most often violated; for, the single most common factor in operating room electrocutions is the same as that found in the house or in industry, an undetected open or disconnection of an earth grounding connection.

The second means is to make resistance (R) infinitely large, creating an "isolated" or "floating" circuit.\(^1\) Safety is dependent on complete isolation of the whole circuit from ground. Under these circumstances, if inadvertent contact is made between one side of the circuit and earth, no danger exists, because current will not flow.

**Electrical safety devices in the operating room**

A great majority of operating rooms are electrically wired with a system called neutral-ground or service entrance grounding electrical distribution systems. A schematic of this system is shown in Figure 5. For any electrical device to operate, there must be at least two conductive paths of electricity to the source of generation. Electricity is delivered via the hot line (1) and returned via the neutral line (2).\(^9\)

Not all electricity is returned through the neutral conductor because some has leaked through real (imperfect) insulators onto conductive surfaces (for example, the chassis of the operating room electrical equipment). An attempt is made to recover the "lost" electricity to the service entrance neutral via grounding conductor (3). The neutral and ground conductors are connected together and "earthed" only at the service entrance of the building. Earthground is utilized as the master voltage reference point (zero volts) of the facility supplied with electricity.\(^9\)

If a grounding conductor on an electrical device breaks, leakage electricity has no way to escape from the frame or chassis. Should a grounded patient come in contact with this device, then the leakage electricity in seeking ground, will flow through the patient. An electrically susceptible patient might be one who is being treated with an externalized electrical conductor, such as a probe, catheter, or other electrode connected to the heart. Ten microamperes of current could be lethal. The patient's resistance is estimated to be 500Ω; therefore, Ohms Law justifies the point that as little as 5 mV potential difference between chassis, patient, and ground could be dangerous.\(^9\)

If, however, the grounding conductor is not broken, the grounded patient will receive far less current, because the resistance of the wire conductor is much less than that of the patient. Current will "split" and now take two paths to ground: mostly through the wire, and a little through the patient.\(^9\)

On the other hand, because the hot
line of the service-entrance-ground electrical distribution system is referenced to the ground conductor, a grounded patient who inadvertently comes in contact with the hot lead will receive a macroshock in the range of 240-500 mA, which is potentially lethal even to the most healthy of patients. This condition could occur through insulation breakdown in the electrical equipment power cord or within the device itself.\textsuperscript{14}

The most common cause of macroshock is reversed polarity of either the device or the receptacles. This reversal causes no particular problem as long as only one device is being used; but, when two or more devices are being used simultaneously (such as, an ECG monitor plugged into a reversed polarity receptacle and a electrosurgical unit plugged into a properly wired receptacle), the stage is set for a macroshock.\textsuperscript{14}

Many safer systems have been developed and are in use to protect the patient from electrical shocks. Electrical isolation units have been introduced that place an electrical "buffer" between the patient and the device. Examples of this are the various ECG patient isolators. These have extremely high output resistance relative to the equipment and high input resistance relative to the patient. In this way only small physiological signals are allowed to flow from the machine to the grounded patient.\textsuperscript{9}

Available also is the ground fault interrupter which, upon sensing excessive equipment ground leakage, will shut off power. Although this system has merit, the shutting off of life-support equipment makes this system impractical.\textsuperscript{9}

A safe environment can be provided by insulating equipment surrounding the patient. Nonconductive enclosures (for example, wooden or plastic) can serve as relatively inexpensive protection. This system is called the double-insulation system. A problem with this type of equipment enclosure is that equipment is exposed to rough handling and to possible housing fracture, resulting in a pathway for leakage current.\textsuperscript{9}

Several methods for delivering electricity can replace the neutral-grounded distribution system. One example is the use of battery-powered devices. Trickle chargers, which plug into the conventional power outlets, are sometimes utilized to charge the batteries. Generally, it is wise not to use the charger while the equipment is in contact with the patient, for the safety provided by the battery supply is then apt to be defeated.\textsuperscript{9}

Due to the fact that broken grounds appear to be the most common failure within the hospital electrical complex, redundant grounding wires and a common patient grounding bus appear to be a worthwhile investment. Under this system all grounding lugs of receptacles, redundant grounding wires, and the operating room floor are connected to a single electrical reference point called the "equipotential point." This may be accomplished through use of an equalizer ground bus (a large low-resistance conductor) to which all smaller grounds and redundant ground leads are connected.\textsuperscript{15}

All electricity at the location of the patient is measured relative not to ground, but to this equipotential point, which in turn, is connected to a grounding conductor, eventually returning to earth. In addition to minimizing the danger to the patient of a broken ground conductor, it would also prevent two grounded devices to which the patient is connected being at different potentials relative to ground. Without the common ground bus, if this difference exceeds 5 mV, then 10\textmu A could flow from device number one through the patient to device number two.\textsuperscript{15}

An additional technique of providing a safer, but still not absolutely safe, environment for the patient is the isolation transformer. This approach is more complex than all the other examples, has led to much controversy and confusion, is expensive, and is not the ultimate electrical safety device.\textsuperscript{9}

\textit{Isolated power distribution systems} have been referred to as ungrounded
systems. Owing to the use of the word "ungrounded", some have been led to believe that equipment which is served with isolated power need not be grounded. This is truly a misconception which could lead to real danger. As shown in Figure 5, the neutral conductor is grounded to the hospital service entrance. Consequently, the conventional distribution system is referred to as "neutral-grounded". There are three conductors: a hot conductor, a neutral conductor, and a grounding conductor. Full-line voltage exists from hot to neutral and from hot to ground.

In the isolated power system, there is no "hot" conductor and no "neutral". Instead, the two power conductors may be referred to as "line 1" and "line 2", in Figure 6, both of which are "ungrounded" or "floating". Between these is provided the potential difference of 120 V. Line voltage, however, does not exist from either line to ground. A grounding conductor is still employed to clear any leakage current which should seek ground; but the available leakage current is much less, since neither power line is directly referenced to ground.

The grounding conductor at the ser-
vice entrance could be removed with the isolation transformer system and little change would be seen if one were to measure between secondary voltage lines and ground. The output is said to be floating relative to ground. This indicates the key advantage of isolation. Should a grounded patient or other grounded conductor come in contact with either secondary terminal, virtually zero current would flow through the conductor to ground. This is the reason for the isolation transformer minimizing the chance of macroshock to the patient or to operating room personnel.

Although the primary and secondary windings of the isolation transformer are isolated, a little of the secondary output is not isolated from ground due to leakage which does exist between the two. The magnitude of this unavoidable leakage is one major factor which determines the quality of a transformer used for purposes of isolation. Since there is no such thing as perfect isolation from ground, and since power cords and equipment augment the total leakage to ground, it is necessary that some instruments measure and indicate the status of the system isolation. One popular instrument is a dynamic ground-fault detector, or line isolation monitor.

The line isolation monitor measures two criterion: (1) the state of isolation of the secondary winding of the isolation transformer, so that a warning will sound if leakage across the transformer is greater than a predetermined maximum, and (2) the flow of electricity out of line one of the secondary winding as compared with the return through line two. If the current out exceeds the current back by a predetermined amount, an alarm will sound, indicating that excessive leakage exists in some equipment in the operating room being powered by this source. If either alarm sounds, the patient should be immediately disconnected from the power source until the trouble can be found.

Unfortunately, even with the use of isolation transformers and line isolation monitors, the electrically susceptible patient is still exposed to minute leakage currents. Only by the use of redundant grounding, aggressive preventive maintenance, quality receiving inspection, and a watchful eye by the surgical team can his danger be minimized.

**Electrical safety check list**

A check list of electrical safety precautions is presented here to aid operating room personnel in providing maximum protection from electrical hazards to each patient who comes to the operating room, as well as for themselves. The anesthetist is probably the only person in the operating room who is concerned with the total patient continuously. He or she must be familiar with electrical theory, the electrical distribution system in use, the electrical function of all equipment that comes in contact with the patient, as well as the safety precautions to be followed each time a patient comes to the operating room. For this reason, the anesthetist has been referred to as the “operating room safety officer.”

**Electrical safety check list**

1. Electrical equipment that is not functioning correctly should be immediately disconnected from the patient, tagged, and sent for repair before someone attempts to use the equipment again.

2. All patients should, as much as possible, be isolated from ground. All equipment and personnel that could come in contact with the patient should be grounded. All equipment, especially electrical equipment, should be redundantly grounded to an equipotential grounding bus whenever possible.

3. A periodic electrical testing program of all electrical equipment and grounding devices should be instituted. This testing should be performed by a qualified electronics technician to assure that all safety systems and equipment are in proper working order.

4. Have isolation transformers and line isolation monitors installed in all operating rooms (especially in all new constructions) to protect patients and operating room personnel from macro-
shocks. Several states now require this safety equipment be installed in all newly constructed facilities.

5. Be particularly watchful of all safety precautions when an electrically susceptible patient is in the operating room.

6. Organize and institute an aggressive receiving inspection procedure for all new electrical equipment purchased for the operating room to assure that the equipment is wired correctly and that it meets or exceeds current electrical safety standards.

7. If battery operated equipment is used, do not connect the charger to the electrical distribution system while the equipment is connected to the patient, since the whole purpose of the safety device is defeated.

8. Placement of patient monitoring electrodes and electrosurgical grounding plates should be carried out by personnel familiar with the hazards of these devices. Electrode and grounding plates should never be in contact with each other.

Conclusion

The patient coming to the operating room for a surgical procedure, in addition to being exposed to the dangers of anesthesia and surgery, is exposed to the danger of electrical shock. Electrical shock has the potential for producing pain, burns, and ventricular fibrillation. Patients, as well as operating room personnel, are exposed to macroshocks from equipment malfunctions, equipment and receptacle miswiring, and equipment misuse. Electrically susceptible patients, in addition, are exposed to microshocks which could cause ventricular fibrillation.

In this article, I have attempted to outline the basic theory of electricity and how electrical shocks can occur within the operating room. In terms of preventive value, safety equipment and procedures to reduce the risk of electrical shock were reviewed.

REFERENCES

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