Shock Hazards in Operating Rooms and Patient–care Areas

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THE NATURE of operating room hazards has undergone a subtle change during the past 20 years. In 1948, the electrocautery unit was essentially the only electronic equipment which found routine use. Occasionally it was supplemented by the portable x-ray, the electrocardiograph or the electromanometer. The electric shock hazard was far outshadowed by the risk of ignition or explosion of flammable anesthetic agents, and so received little attention.

An effective discipline evolved for protection against the fire or explosion danger. The electrostatic spark was recognized as hazardous, and procedures were enforced to eliminate it. Maintenance of a humidity of 50 per cent or greater produced a relatively safe environment. Restriction of the use of unmodified cellulose-base materials reduced the charge buildup, and a requirement for conductive footwear and flooring dissipated the electrostatic charge.

National codes were formulated for protection during the use of flammable agents. In the U. S. A., NFPA Code 56 gained acceptance, as did CSA Code Z 32 in Canada. Both codes stipulated requirements for elimination of spark ignition and electrostatic charge and provided protection against gross electric shock to patient and staff.

Conventional electric power service has one of its two current-carrying conductors at ground potential. It was apparent that the presence of conductive and grounded flooring in the operating room increased the danger of shock from accidental contact with the other "live" conductor. The codes therefore specified that the electrical service in operating rooms have both conductors isolated from ground. To ensure the integrity of this isolation, they called for "ground fault detectors" to monitor continuously between either side of the service and ground, and to signal an alarm if a fault current of one or two milliamperes (0.001–0.002 amperes) occurred.

The level of 1–2 milliamperes was selected because this is the approximate threshold of sensation for electric shock on the body surface. It also limits the energy of an electric spark to below the ignition level. At the time, it represented the maximum capability of the detector equipment.

The codes, evolved primarily for ignition and electrostatic protection, have continued to be the electrical safety standards in operating rooms to the present time. However, the operating room environment has changed. This report will attempt an examination of the new environment and of the new hazards which it has produced.

The Changing Environment

SURGICAL ADVANCES

The development of new surgical procedures has been a prime factor in the changing operating room environment. Consider the case of heart surgery. The introduction of hypothermia 20 years ago opened the door to several cardiac surgical techniques. Later, the development of extracorporeal bypass procedures further extended the acceptable period of interrupted circulation and made possible more complicated surgical intervention. Valve, vessel and heart transplant techniques added another dimension to the changing pattern. Other areas of surgery contributed equally dramatic examples to the trend.

A common feature of these advances was the requirement for supporting instrumentation. The operating room had to open its

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doors to heat exchangers, bypass pump–oxygenators, cardiac resuscitators, new electrosurgical tools, patient monitors, and a host of other newcomers to the electrical scene. All at once the O.R. became packed with electrical equipment, all necessary for the fulfilment of the surgical procedure. Any one of these items could be used alone with relative impunity. In combination they produced an unpredicted hazard of giant proportions. The *interaction* of various units connected to the patient demanded a system approach which was foreign to the training of medical staff.

Diagnostic and Therapeutic Techniques

At the same time, new techniques were being developed for diagnosing physiologic alterations and for maintaining body functions. Many of these involved the insertion of probes or electrodes *within* the body. Immediately the old standards of electrical safety were invalidated. The cardiac catheter or pacemaker electrode provided direct electrical pathways to the heart. When combined with other monitoring equipment, ventricular fibrillation frequently resulted. The introduction of the *internal* electrode has been the leading factor in the present high incidence of accidents in hospital patient-care areas.

New Electronic Instrumentation

Into this potentially-hazardous environment was thrust a multiplicity of new electronic instruments. Industrial and space research yielded techniques of apparent value to medicine, and many manufacturers turned to this lucrative market. In some instances, a partial understanding of the medical requirement led to dangerous designs. In the hands of medically-oriented users, routine electrical and electronic safety principles were not always observed, and the results were occasionally disastrous. Provision of too much versatility invited misuse.

The instrument manufacturer tended also to be oblivious to the problem of interaction with other equipment, probably because he was not familiar with medical procedures, and saw his product as an entity in itself, rather than as part of an overall system.

These are the factors which have reshaped the pattern of hazards in the operating rooms and, indeed, in all patient treatment areas of our hospitals. Unfortunately, the building facilities and staff orientation have not kept pace with this change. We must reassess the status of electrical safety in hospitals and adjust to the new environment if we are to halt the rising incidence of fatal accidents.

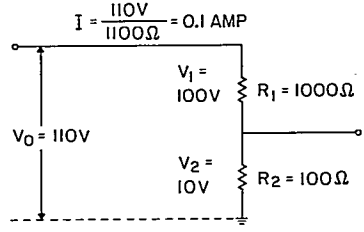

Fig. 1. The voltage distribution between series resistors is proportional to their resistance values. The current developed will be the voltage divided by the total series resistance.

Basic Electrical Concepts

In order to understand the rationale of electric shock hazards, we must review some basic electrical parameters. The flow of electricity is determined by three parameters: *voltage, current* and *resistance.* Voltage (V) is comparable to *pressure* in water flow. Current (I) is the *amount* of electrical charge, and is analogous to the flow *rate* of a hydraulic system. Its unit of measure is the *ampere,* defined as one *coulomb* of electrical charge per second. Resistance (*R*) is a measure of the ability of a substance to conduct an electrical current. Thus, electrical conductors have low resistances while insulators have very high values. The unit of resistance is the *ohm.*

Ohm's Law relates these terms in the equation $I = V/R$. It is apparent that if we measure two of the parameters we can determine the third. The voltage across a series of resistances divides in proportion to the individual resistance values, as shown in figure 1. This proportional division of voltage becomes important in understanding the nature and magnitude of accidental shock currents, as we shall see.

Power is the product of voltage and current, expressed in *watts.*

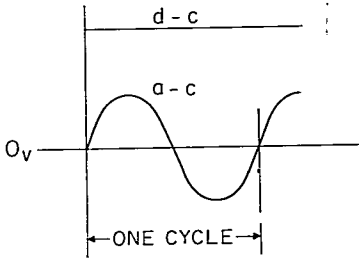

FIG. 2. Direct current may vary in intensity or potential but does not change its polarity with reference to the "zero" baseline. Alternating current reverses its polarity twice in each repetitive cycle.

Energy is the rate of power consumption, expressed in *watt-seconds* or *joules* or, for larger amounts, in *kilowatt-hours*.

Direct current denotes a unidirectional current flow. The current may be interrupted but does not reverse its direction. *Alternating current* reverses direction, usually in a cyclic manner, the interval between identical points on two consecutive complete alternations being designated a *cycle* (fig. 2). The rate of alternation, or *frequency*, is expressed in cycles per second, or Hertz (Hz). The conventional electric power frequency in North America is 60 Hz, and the distribution potential is nominally 110 volts. In other areas, 50-Hz, 220-V systems are common.

Alternating voltages may be "stepped-up" or "stepped-down" by the use of *transformers*. A low-frequency transformer consists of two conductive coils mounted on an iron core. Current flowing through the *primary* is transferred to the *secondary* coil by electromagnetic induction, and the voltage inducted is proportional to the ratio of turns of the primary and secondary coils. There is no electrical connection between the input and output currents. The transformer is thus an isolated device, and is used as such in operating-room service installations, to isolate both electrical conductors from connection to ground (fig. 3).

The concept of *grounding* may be confusing to nontechnical hospital staff. As stated in the introduction, it is the practice of electrical power distributors to supply power with one current-carrying conductor at ground or earth potential. Installed controls need switch only the "live" conductor to deactivate a circuit with such a system. In electrical control systems, it is standard practice to use one ground wire as the common conductor for several signals. Electronic designers usually utilize the metal chassis of equipment as a ground conductor. The chassis can then be "tied" to the building grounding system by a third conductor in the power cable, or by a separate wire to a water pipe or other grounded conductor. The latter compromise is necessary in some older hospitals which do not have three-pin-grounded receptacles. It is necessary to ground many power-operated instruments which contain sensitive amplifiers, in order to eliminate 60-Hz inductively-coupled interference. The electrical safety connotations of grounding will be examined in discussion of the hazards.

When using Ohm's Law in determining the parameters of alternating-current circuits we must substitute the term *impedance* for resistance, as some components have a capacitive or inductive reactance as well as an ohmic resistance.

Impedance Z (ohms) $= \sqrt{R^2 + X^2}$, where X is the reactance (ohms). A capacitor is composed of two sets of conductive surfaces, separated by an insulator, and is used to store an electrical charge. In a continuous direct-

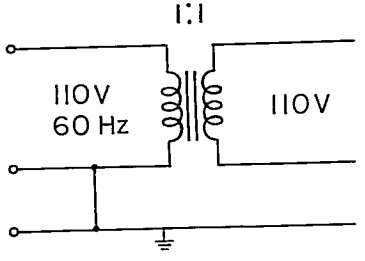

FIG. 3. The transformer produces a voltage in its secondary winding proportional to the turns ratio of the secondary/primary windings. It may also be used as illustrated to isolate power from the grounded mode shown on the primary side.

current circuit it acts as an open circuit. When the voltage across it changes, however, it transfers a charge proportionate to the voltage change. It thus becomes an active component in an ac circuit, and the larger its capacitance, the smaller becomes its capacitive reactance. Stray capacitance can exist between two conductors or between a component and the chassis, introducing an unwanted impedance path to ground, as we shall see.

Electrical definitions:

Current density — current per unit of

$$\text{contact area} = \frac{\text{I}}{\text{electrode area}}$$

prefix *micro* denotes one-millionth, *e.g.*,

$$1 \text{ microampere} = \frac{1}{1{,}000{,}000} \text{ or } 10^{-6} \text{ A.}$$

prefix *milli* denotes one-thousandth, *e.g.*,

$$1 \text{ millivolt} = \frac{1}{1{,}000} \text{ or } 10^{-3} \text{ V.}$$

prefix *kilo* denotes one thousand, *e.g.*,

$$1 \text{ kilowatt} = 1{,}000 \text{ or } 10^{3} \text{ W.}$$

prefix *mega* denotes one million, *e.g.*,

$$\text{A megohm} = 1{,}000{,}000 \text{ or } 10^{6} \text{ ohm.}$$

Thresholds and Effects of Electric Shock

In 1936, Ferris *et al.*[1] concluded from 60-Hz tests on animals that current rather than voltage was the determining factor in establishing electric-shock effects. They further observed that the current required to produce ventricular fibrillation bore a direct relationship to the size of the heart. Kouwenhoven *et al.*[2] in a classic investigation of fibrillating/defibrillating currents, found that currents up to about 1 ampere, applied through large paddle electrodes to the exposed canine heart, produced ventricular fibrillation, while larger currents induced momentary cardiac "standstill." We now know that much smaller currents can fibrillate the heart and recognize that *current density* is a more meaningful criterion of the hazard. A large electrode distributes the current flow over a wide area, while a small electrode concentrates the same current into a limited tissue mass. This would explain Ferris' observation that larger hearts require greater fibrillating currents.

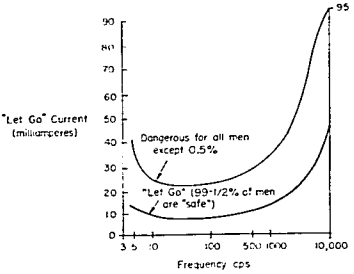

FIG. 4. "Let-go" current levels for frequencies from dc to 10 kHz. (Taken from "Shock Hazards of Electric Currents," A. R. Morse, J. Eng. Inst. Canada, Nov. 1959, pp. 3–7.)

Ferris also noted that fibrillation occurred more frequently during a specific portion of the heart cycle. Wiggers and Wegria[3] investigated this *vulnerable period*, which for ventricular muscle occurs during the upstroke of the T-wave, and concluded that a shock current of less than 0.1-second duration could induce fibrillation if applied at that time.

Electric-shock effects fall into two categories: nerve or muscle excitation and heat generation. In some instances the latter may be the mechanism which triggers the neural response. In either category the current duration is significant in determining the electrical energy of the shock. A subthreshold current of short duration may become dangerous if continued for a longer period. Similarly, a higher current of long duration has an appreciable heating effect. Thus, current *intensity*, *density* and *duration* are all contributing factors to shock effects.

Although body tissues present to alternating current a capacitive reactance which is frequency-dependent, there is little difference in response from 10 to 1,000 Hz, as shown in figure 4. At 10,000 Hz, nerve–muscle response to stimulation drops to about one-fifth, and the sensation threshold is accordingly five times greater, as it is for direct current. However, the *interruption* of dc produces a very painful sensation. In medical therapy using dc

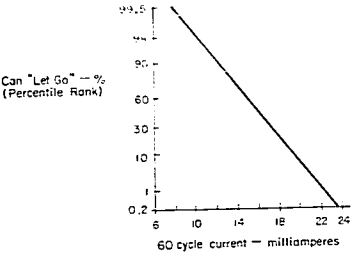

FIG. 5. Response levels for shock currents on the surface of the body. (Taken from "Shock Hazards of Electric Currents," A. R. Morse, J. Eng. Inst. Canada, Nov. 1959, pp. 3–7.)

stimulation, the current should always be increased and decreased gradually to avoid this phenomenon.

The threshold effects of shock currents differ greatly between those applied to the surface of the body and those applied internally. They are outlined in the following sections.

SHOCKS APPLIED TO THE SURFACE OF THE BODY

A. R. Morse[4] has reported the shock effects of 60-Hz current on the body surface, shown on the logarithmic scale in figure 5. He suggests that the threshold of perception is 0.3 milliampere, a lower level than the commonly accepted 1-mA density. Current density becomes a consideration here. A very small point contact can undoubtedly be felt at 0.3 mA, but for a larger contact the 1 mA level is acceptable. Depending upon the size of contact, the pain sensation becomes objectionable between 1 and 10 mA.

The "cannot let go" point occurs between 9 and 20 mA, when it is impossible to release a hand-held electrical contact. The maximum "let-go" current varies between individuals and is generally higher for men than for women or children. Dalziel[5] defines the let-go current as that at which 99.5 per cent of the healthy male population can release contact. Figure 6 indicates a normal (Gaussian) distribution among male subjects. If we accept an arbitrary figure of 10 mA as the let-go point, it can be seen that it applies to about 98 per cent of the population.

From the let-go point up to about 25 mA, 60-Hz currents cause muscular cramps, which may lead to exhaustion or loss of consciousness if continued. Between 25 and 80 mA this phenomenon is accentuated, and respiratory paralysis may persist for some time. Respiratory resuscitation may prevent death in such cases. Extended contact in this current range may be fatal.

Shocks in the current range of 80 mA to 8 amperes produce ventricular fibrillation and subsequent death unless cardiac resuscitation procedures follow promptly. Above this range the shock current is more likely to depolarize the entire heart muscle mass, with resulting cardiac standstill. These are not the currents required to induce or abolish ventricular fibrillation with the open chest. Electrodes placed on the myocardium offer a low impedance path, and in this condition currents below 1 mA will invoke fibrillation, while currents above about 1.7 amperes (applied through large paddle electrodes) will revert it to normal rhythm. The disparity between these two values may be explained by the fact that ventricular fibrillation can be triggered from a discrete irritable focus, while the entire muscle mass must be involved in instantaneous depolarization to arrest fibrillation.

Above 8 to 10 amperes, shock currents enter a range where severe tissue destruction may result from the heating effect. Hemorrhage, poisoning by combustion products, and severe traumatic shock may follow. It should be noted that the electrical resistance of body tissues is current-dependent. Large currents break down cells and, in depolarizing muscle, destroy the membrane impedance structure. As the resistance drops, the energy dissipated in heat increases.

The total body resistance comprises the electrode contact value, the skin resistance, and the body resistance between contacts. The contact resistance varies of course with the nature of the contact. The skin resistance fortunately is high, offering the principal defense against shock currents. It varies, however, with site and moisture content, but is generally above 500 ohms. Thus, the total resistance between contacts is generally above 1,000 ohms. For conventional 115-volt service shocks, the

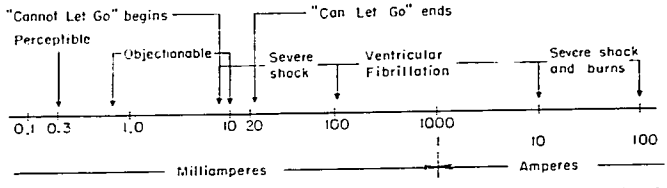

FIG. 6. "Let-go" distribution curve for 60-Hz shock currents applied on skin of male subjects. (Taken from "Shock Hazards of Electric Currents," A. R. Morse, J. Eng. Inst. Canada, Nov. 1959, pp. 3–7.)

current developed is below the fibrillation level.

SHOCK CONTACTS WITHIN THE BODY

If one electrode or both contacts are *within* the body, the protection of the skin resistance is lost. Further, the contact resistance is generally low and the conductive path may be through the blood, which also has a low electrical resistance. A path through the vascular system leads to the heart—probably the most vulnerable organ in the body.

The most common effect of internal shock is the induction of ventricular fibrillation. A Lancet editorial in 1960[6] cited a case of fatal shock induced by a cardiac monitor. In 1961, Noordijk *et al.*[7] and Pengelly and Klassen[8] reported the hazard that exists with myocardial electrodes. Mody and Richings[9] and Bousvaros *et al.*[10] published accounts of catheterization shocks in 1962.

Most reports of this early period did not offer quantitative data on the lethal shocks involved. In 1962, Weinberg *et al.*[11] published the results of extensive tests with dogs, in which they found that currents as low as 35 μA produced fibrillation between a catheter electrode within the ventricle and the chest wall. The average fibrillation current was 170 μA. Hopps and Roy reported in 1963[12] two cases of accidental fibrillation during catheterization for angiography. In one, a dog's heart was fibrillated with a 175-μA shock current, and in the second instance, a 26-year-old man was resuscitated after fibrillation with a calculated 270-μA shock. In 1964, Weinberg[13] stated that currents as low as 20 μA can produce ventricular fibrillation in a dog. Studies by Levy and Lillehei,[11] in 1933, suggested that the threshold of fibrillation in man may not be much higher than in the dog. Since ventricular fibrillation can be initiated from a single irritable focus, the size of the heart is not a dominant factor.

The significance of current density on the fibrillation threshold is demonstrated in results of a recent experiment in which Roy[15] produced fibrillation in a dog with a 17.5-μA current flowing from a 0.7 mm^2 intracardiac catheter electrode to the chest wall. The current density was 25 μA/mm^2.

In addition to disrupting the cardiac activity, internal shock current may excite or disrupt phrenic-nerve control of respiration. Gross internal shocks undoubtedly produce the same tissue necrosis effects that result from external shock currents.

Internal Shock Hazards

LEAKAGE CURRENTS

Most electrical or electronic equipment, if powered from an alternating-current source, presents some capacitive reactance between its components and the metal case or chassis. This reactance represents a high impedance path through which fault currents flow. In addition, the insulation, through deterioration or the deposit of dirt or high humidity, may present a resistive path for minute currents. Inductive coupling occasionally contributes an inductive reactance. Careful design reduces these *leakage current* pathways but does not eliminate them.

A completed circuit is required for the flow of current. Conventional electrical service has its "neutral" current-carrying conductor at

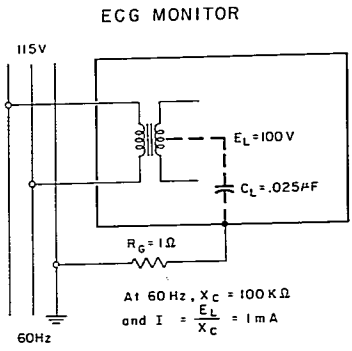

FIG. 7. The dotted line shows a capacitive leakage path from the power transformer to the chassis of an electrocardiograph. If the case is effectively grounded, the leakage current is safely bypassed to ground.

ground potential. Thus, a leakage current arising from the power supply of an ac-operated equipment has but to flow to ground to complete its circuit. It is in the routing of ground pathways that a serious shock hazard is created.

Figure 7 illustrates a representative example. Between the windings of the power transformer and its grounded core, a stray capacitance of 0.025 μF presents a reactance of 100 kilohms at the 60-Hz power line frequency. A leakage potential of 100 volts—not an unlikely level—will then develop a leakage current of 1 mA (by Ohm's Law). If the chassis is grounded by a wire with a nominal 1-ohm resistance value, its potential with reference to ground will be (1/100,001) × 100 V = 1 mV. The "power level" at the chassis will then be (I × V) = 1 mA × 1 mV = 1 μW (microwatt), too low to constitute a shock hazard.

If we now connect a patient to the equipment, the right-leg lead will tie the patient to the chassis and thence to ground. He will then be "floating" at a 1-mV potential. Connection of a second patient ground (an electrocautery indifferent electrode, an ear oximeter housing, contact with a grounded table or bed, etc.) will produce a parallel path to ground, with a resistance of perhaps 5,000 ohms. However, the current in the two paths will be in inverse proportion to the resistance, and so the 1-ohm ground wire will carry virtually all of it. Thus, the ground wire on the equipment (in this instance an ECG monitor) will protect the patient against the leakage current.

Let us now examine the situation where the monitor is ungrounded, as shown in figure 8. A right-leg patient ground connection will couple the leakage potential to the patient, but if there is no other body ground point, no current will flow. Completion of the ground path by any of the contacts mentioned above will permit the current to flow through the patient to ground. Since the 5,000-ohm resistance of the body is negligible compared with the 100,000-ohm leakage reactance, the developed current will still be approximately 1 mA. A conscious patient might feel it, but the danger of induced fibrillation would be small.

However, if we replace the second ground contact with one *within* the body, we are in difficulty. In this instance, the drop of body resistance to 500–1,000 ohms will not appreciably affect the current magnitude, but now the 1 mA will flow internally, and enough of it may pass through the heart tissue to induce fibrillation. If the implanted contact is a

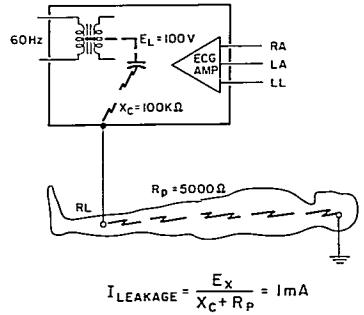

FIG. 8. The right-leg patient lead can provide a current path through the patient from a floating electrocardiograph. If the patient ground connection is on or in the heart, ventricular fibrillation may result. Effective grounding of the ECG eliminates the hazard.

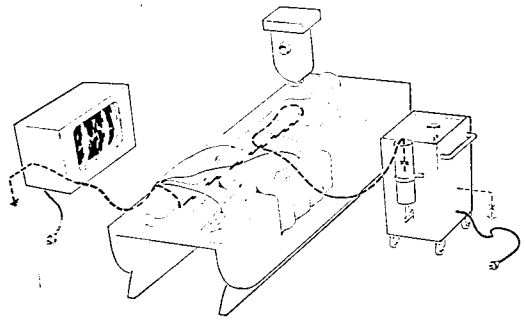

FIG. 9. During electroangiography, the fluid content of the catheter can provide a conductive path to the heart. If either the monitor or the "dye" injector is ungrounded, a leakage current may kill the patient.

grounded cardiac catheter or pacer electrode, the heart will certainly be involved in the internal circuit and fibrillation will be inevitable, provided the current continues through two or three vulnerable periods.

HAZARDS OF CATHETERIZATION AND ANGIOGRAPHY

Catheterization for diagnostic or therapeutic purposes has become common in recent years. Sensing catheters may have electrodes or transducers at their distal tips for intracardiac shunt detection, ECG recording, blood pressure measurement or other diagnostic procedures. If a tip electrode or sensor is grounded, a ground path through the heart is provided for a fault current applied elsewhere on the body.

A fluid-filled catheter is not normally considered to be an electrode. However, the fluid may be conductive, or metal guide wires may be inserted. The proximal end may be grounded to a clamp or stand, through a metal syringe, or by other means. If the catheter is used for injection of radiopaque medium, the "dye" has a greater conductivity than saline, and the power injector may employ a grounded metal injection cylinder. The heart is then connected to ground through the column resistance, which may be too low to limit a large fault current applied elsewhere on the body.

An ECG monitor and a power-injection syringe combined to produce hazardous shock currents in the two cases cited by Bousvaros *et al.*[10] and Hopps and Roy.[12] In the first case, a catheter was positioned in the region of the apex of the right ventricle of a 26-year-old man for cineangiographic studies of the right ventricular outflow tract and pulmonary valve. The injection syringe was primed with 50 per cent diatrizoate (Hypaque) solution. When the saline-filled catheter was coupled to the syringe, the ECG display showed 60-Hz interference. Decoupling the catheter restored the trace, but it was then apparent that the heart was in fibrillation. Open-chest cardiac massage and countershock treatment reverted heart action, and six weeks later the patient underwent uneventful surgery for pulmonary stenosis. An investigation of the incident revealed that the three-pin power plug of the European injector had been replaced with a two-pin North American plug *without ground provision*. A 79-volt leakage potential then existed between the floating case of the injector and ground. At the moment of connection of the catheter, this leakage potential was transferred to the patient's heart through the saline column. The ECG right-leg lead completed the conduction path to ground, as shown in figure 9.

The second incident occurred during a coronary arteriography procedure on a dog. The injection catheter ran from the femoral artery, over the arch of the aorta and down to the coronary-bearing sinuses. When the fluid-filled catheter was connected to the power syringe, fibrillation was observed. In this instance, the syringe was adequately grounded, but the ECG monitor was not. A 100-volt

leakage potential developed the fault current through the dog's heart.

It is usually difficult to isolate a catheter injection system from ground. To ensure that the injector itself does not supply the fault current, it is necessary to provide an effective ground. Even then, some injectors develop a transient voltage at the moment of firing.

Grounding Considerations

We have seen that effective grounding of the case or chassis of monitoring equipment bypasses leakage currents from the patient. It has also been stated that a hazard may be caused by grounding some but not all of the equipment connected to the patient. If this is so, why should we ground *any* of it? There are many reasons. Equipment using high-gain electronic amplifiers usually requires a ground connection to eliminate power frequency interference. Also, if multiple pieces of equipment have their cases ungrounded, fault currents could still flow *between* them through the patient. Again, using a "floating" system could produce disaster if the patient chanced to touch a grounded bedframe, call signal, waterpipe, etc. Since it is almost impossible to avoid such grounds we must then organize our patient protection on the grounded system concept.

It is necessary that we understand the meaning of "effective ground." When we have multiple ground points in a room, we have no guarantee that they are all at the same potential. A voltage gradient may exist between the case of a wall outlet and a nearby waterpipe. It can even exist between two outlets! This is commonplace in older hospitals when a second service has been provided to handle the increased power demands of recent years. The new service may come from a different part of the building, and its ground conductor can easily show a gradient of a volt or more from that of the older service. The hospital electrician may reduce this voltage gradient with a bonding wire, but it should have a high current-carrying capacity. Currents of *several amperes* have been measured in such jumper wires, due to phase imbalances which load the grounded neutral conductor and transfer current to the protective ground system.

It is less apparent that two outlets on the same power service will show a potential gradient between their ground contacts as a fault current is developed by equipment connected anywhere in the service. Weinberg [13] suggests that in critical hospital areas, the conventional ground conductor is grossly inadequate to protect against a fault current of 10 amperes or more.

An example may clarify this point. Let us suppose that a 115-V, 60-Hz grounded service supplies power for two or more patient areas in a ward. If insulation deterioration causes a breakdown between the "live" conductor and the case of one item—perhaps an electric space heater or a large therapy unit—the current flowing through the protective ground wire to the outlet can be of any value up to the protective rating of the equipment fuse or circuit breaker. (In actual fact, it can be many times greater for the transient period before the fuse or breaker acts to open the circuit.) For the sake of argument, let us assume that a 10-ampere current flows for one or two seconds.

The 10-ampere fault current will flow through the system ground and will appear at the next outlet and thence at its connected load. If the power cords are each ten feet long and the distance between outlets is ten feet, the fault current will traverse 30 feet of conductor. This length of 14-gauge wire has a resistance of approximately 0.08 ohms. By Ohm's Law, the voltage drop along the wire will then be $V = I \times R = 10 \times 0.08$, or 0.8 V. Now let us assume that the equipment plugged into the second outlet incorporates a grounded electrode implanted in a patient. The resistance between this electrode and a skin contact might be about 500 ohms. 0.8 V flowing through 500 ohms will develop a current of 1,600 μA—well above the threshold of hazard. *The patient in the second bed may be electrocuted by a fault current initiated at the first bed.* If this appears improbable, consider the wide range of instrumentation used in an intensive or coronary care unit. Internal probes or electrodes are not uncommon in such locations and electrical breakdowns have occurred as long as there has been hospital equipment!

Cardiac Pacemakers

The first heart stimulators were external units, power-line operated and generally with one side of the output grounded to the chassis. One of the two leads, sutured to the myocardium or anchored in the trabeculae of the right ventricle, then tied to the heart to ground potential through a relatively low impedance path. Fault currents between the heart ground and external electrodes left the patient vulnerable to ventricular fibrillation. There is no doubt that many unexplained incidents of cardiac arrest should be attributed to this cause.

Implanted pacers have replaced the external units for long-term pacing, but it is common hospital practice to connect intracardiac catheter electrodes to an external stimulator for short-term control or assessment of conduction-block patients. To perform this procedure with safety, the electrodes must be isolated from ground. The safest way to ensure this is to use a battery-powered pacer which provides no possibility of ground connection. If power-operated stimulators are used, internal or external output-isolating circuits are necessary.

It is essential that external instrumentation not destroy the integrity of such isolation. Figure 10 shows an oscilloscope monitoring the performance of an isolated battery pacer connected to a heart. However, one terminal of the oscilloscope input is grounded, and this ground connects to the heart electrode. To eliminate the hazard, a differential-input oscilloscope or isolation unit must be used.

It becomes apparent that equipment which *applies* low-frequency or direct current to the body must constitute an exception to the "ground-for-safety" maxim. If the equipment is power-line operated, its *case* should be grounded to eliminate leakage currents, but the patient electrodes should always be isolated. A word of caution, however! This rule must not be extended to include high-frequency equipment such as that used for diathermy or electrocautery. With such equipment it is essential that one patient lead be grounded, *and well grounded,* to prevent radiofrequency burns at the sites of other connected electrodes.[12]

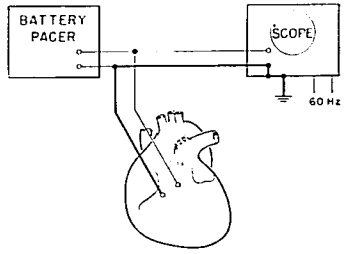

Fig. 10. The isolation of a battery-powered cardiac stimulator may be invalidated by connection of a monitor oscilloscope with grounded input circuitry. If it is necessary to monitor pacer performance while it is connected to the heart, the monitoring leads must be isolated from ground.

Electrical Service Faults

Many older hospitals in the United States and Canada were wired without any protective ground system. Two-pin receptacles were provided, often without observing the polarity rule (the longer slot is the neutral or grounded conductor). If equipment had one of its two power conductors connected to the case or chassis—at one time a common practice—there was seldom any assurance that it was not the *live* conductor. Gross electric shocks have been delivered to patients from ECG equipment because of reversed two-conductor cords or receptacles.

Later, when equipment appeared with three-pin cord connectors, hospital personnel faced the alternatives of tearing off the third pins, which made the plugs incompatible with the hospital receptacles, or changing the receptacles to fit the plugs. When the latter course was followed, there was no guarantee that the newly-installed U-ground receptacles had their third pins connected to grounding circuits. Often such circuits were nonexistent. If the grounding systems utilized conduit runs, oxidation or loosely-coupled joints produced very high resistance ground paths in many instances. Nevertheless, the national codes continue to permit conduit ground systems in hospital patient-care areas.

Starmer *et al.*[16, 17] and Bruner[18] have published comprehensive data about shock haz-

ards arising from polarity reversal or wiring errors. The frequency with which such errors create hazards has prompted the design of many testers for checking outlets or appliances.[19] The circuit of one such tester is shown in figure 11. It should be recognized that such devices cannot detect all mistakes in service wiring. Most notably, they cannot distinguish between the grounded neutral contact and the protective ground system.

Operating Room Hazards

Some of the protective procedures we have developed for reduction of the electrostatic hazard may increase the shock danger in the operating room. Multiple grounding of the patient by saline-soaked sponges, conductive rubber sheeting and anesthetic fittings may produce an environment particularly conducive to internal shock at a time when the patient is most vulnerable to it. Conductive flooring increases the danger to both patient and staff. In principle, its resistivity should be low enough to dissipate static build-up and high enough to limit shock currents. A little spilt saline solution soon destroys the latter protection.

The presence of conductive flooring makes a grounded electrical service unsafe, and so we isolate the operating room power. If isolation is complete, touching either conductor should not result in a shock current. However, the state of isolation cannot be left to chance, and so we monitor the line with a *ground fault detector* which measures the impedance from either side to ground, and sounds an alarm if the impedance drops sufficiently to develop a dangerous current flow to ground.

Most of the ground fault detectors now used in the United States are inadequate. They are *static* devices, measuring from one side of the line only, and unable to detect balanced faults. The CSA Standard Z-32 in 1963 recognized the shortcomings of static detectors and specified *dynamic* monitors capable of detecting both balanced and unbalanced faults, resistive or reactive in nature. The NFPA Hospital Committee agreed in 1968 to a revision of Code 56 which would make the dynamic detector mandatory in the U. S. A.

There is probably no more-maligned item of electrical equipment in the operating room than the fault detector. When a nurse plugs in a stand lamp and the monitor alarms, the monitor rather than the lamp is usually suspect, yet the detector is really "telling it like it is." In actual fact, many operating rooms are so poorly wired that capacitive reactance in the lines between the isolating transformer

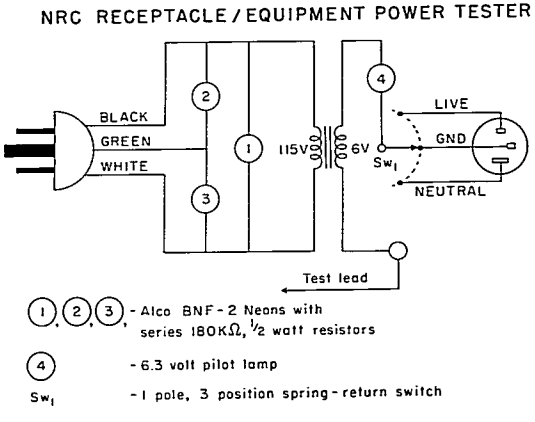

Fig. 11. A simple test circuit for checking the polarity and protective ground system of receptacles or applied loads. Lamps 1, 2 and 3 are neon indicators with series resistors; 4 is a 6.3-V pilot lamp. Note that such testers will not differentiate between the neutral conductor (white) and the protective ground system (green).

and the receptacles is only marginally above the alarm level. Almost any additional load will then drop the impedance to the danger level.

The 1- or 2-mA level at which the ground-fault monitor indicates danger is low enough for electrostatic protection, but not for internal shock prevention. However, in many instances the measured fault is the summation of several lesser defects and the fault current at any of these defects may be a small fraction of the total. The monitor, therefore, does offer protection against low-current shocks and is invaluable in warning of the onset of insulation breakdown which might lead to a gross shock hazard.

Some operating room hazards result from faulty connection of equipment. Most hospitals have at least one "cheater-cord" which allows nonapproved equipment to be connected to the O.R. receptacles. A birds' nest of extension cables may result, with unreliable connection or overloading. Worse, the extension cable may be run from outside the operating room, introducing grounded power to nullify the protection of the isolation system.

The cardiac defibrillator can produce a serious hazard for both patient and staff. It is inherently dangerous, by the very nature of its operation, and safe use requires caution by the operator. The first defibrillators employed alternating current, and developed their shock potentials through step-up transformers which effectively isolated the patient leads. The more recent types discharge high-voltage D.C. from storage capacitors. The negative side of the power supply is generally at chassis potential, as in most electronic equipment. At discharge, the patient leads may be isolated from chassis ground, but in some units they are not. It is then possible for the discharge from the live electrode to flow to *any* grounded point on the patient, as shown in figure 12. If the operator is standing on conductive flooring and touches the patient, he may share the defibrillation shock.

A recent accident illustrates a variation on the same hazard. A patient had suffered ventricular fibrillation on the operating table, and the defibrillator was quickly prepared. When it was actuated by pressing the "discharge" switch on the instrument panel, the operator

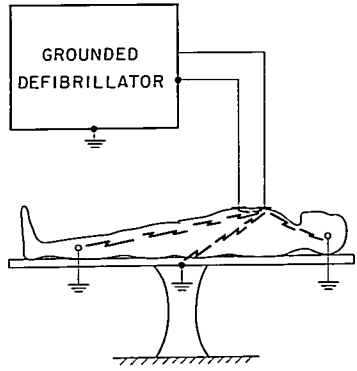

FIG. 12. A ventricular defibrillator with one patient electrode grounded permits multiple current paths during the resuscitation shock, reducing the efficacy of the shock treatment and endangering both patient and operator.

received a shock which threw him to the floor. Examination showed that one side of the output was connected to the case, *but the case was not grounded* because of a broken grounding pin. When the switch was pressed, the discharge through the patient floated the instrument to a high potential. A shock current flowed from the panel via the metal guard ring around the switch to the operator's finger, through his body and out his feet to the conductive floor. The primary cause of failure was the defective ground wire, but the case-connected output lead and the conductive floor combined to produce a serious hazard.

PROTECTION IN INTENSIVE CARE AREAS

As a hazardous environment, the operating room is rivalled by other locations such as the coronary or intensive care unit, the kidney dialysis laboratory, the catheterization room, and other areas where treatment or diagnostic probes may invade the patient's integument. The protection required in such areas is a much-debated subject.

Essentially, the problem is to protect the patient from the ground fault hazards already mentioned. We have seen that a fault current can "contaminate" the electrical service far

beyond the site of failure. It follows that electrical service in critical locations should be separated into individual patient units. Further, the outlets provided at each site should be consolidated into one "power center" to reduce inter-receptacle ground-wire resistance.

If we wish to protect against the transmission of large fault currents within the individual service, we must provide a massive grounding bus. Therefore, for the 10-ampere fault current, we would need a 1/0 or 2/0 ground wire. Such a conductor might be too large to fit the conduit, and the cost of an extensive installation would be appreciable. The alternative is to isolate the service with a transformer which incorporates an electrostatic shield to reduce its capacitive coupling. Then, of course, we need a ground fault monitor to keep the system safe. Although such a system is also expensive, most hospital planners consider it a more satisfactory solution to the hazard problem.

Remote monitoring from beds to a central nursing station can endanger the isolation of the individual patient circuits. Signal lines should be decoupled to segregate the grounding systems. Telemetry transmission provides an alternative solution.

In the x-ray room, care must be taken to prevent potential gradients between x-ray equipment and other electrical service from appearing in the patient circuit. During dialysis it should be recognized that the infusion apparatus may introduce an internal ground point within the patient.

The hazardous areas of hospitals are so extensive that it is difficult to decide which locations warrant special protection. Many of the critical procedures could, in fact, be undertaken in the ward. It is uneconomic to provide special services in such areas, but portable isolation units have been designed for use where internal shock is a potential hazard. These units connect to the conventional power service, and incorporate ground fault detectors to monitor their isolated outputs.

The Changing Pattern in Hospital Protection

The danger of internal shock has introduced a new dimension to hospital hazards. At the same time, an older specter is being laid to rest. Flammable agents have been largely replaced by safer anesthetic procedures. Several hospitals have banned the use or storage of flammable gases in their operating areas.[20]

The designers of nonflammable operating rooms press for release from the more restrictive electrostatic protection clauses in our national codes. They are in a strange predicament for *the codes offer no alternative protection for the nonflammable environment,* nor do they apply in hospital areas where anesthetic agents are not used. They were formulated at a time when it was considered that the operating room constituted the only hazardous area of a hospital.

The codemakers recognize the inadequacies of NFPA 56 and CSA Z-32 standards. In 1968 the two national groups independently decided upon similar courses of action. The codes would remain standards for safe practice in operating rooms, incorporating new standards for the nonflammable environment and revised specifications for protection against electric shock currents. In addition, new shock-protection codes would be formulated for the entire patient-care area of the hospital. These new codes are now in preparation. They will define the shock danger thresholds for internal and external currents and will specify safe practice in hospital electrical service, equipment installation, use and preventive maintenance.

The revisions in the operating room codes may eliminate the requirements for conductive flooring and footwear, explosion-proof receptacles and anti-static clothing for the nonflammable environment. However, isolated power and the ground fault monitor are likely to remain mandatory safety features. Controlled humidity and some modified electrostatic protection may be continued.

We shall probably never achieve full protection against hospital hazards. The developmental trends of the next few years undoubtedly will determine the need for further revisions of our safety standards. Meanwhile, increased awareness of the subtle shock hazard may reduce its incidence in the same manner that an enforced discipline has controlled the explosion hazards of the past.

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Muscle

NEUROMUSCULAR BLOCKADE Thirteen bicyclic bis-onium esters produced neuromuscular blockade in various intact and denervated cat, rabbit, rat, and chicken muscle preparations. One of the esters studied depolarized all of the preparations, three depolarized and denervated mammalian and the avian but not the intact mammalian muscle preparations, while the remainder lacked depolarizing capacity, producing neuromuscular blockade only by nondepolarizing mechanisms. The differential ability of the various onium esters to cause depolarization parallels that of various choline esters. They both depolarize chronically denervated preparations readily, multi-innervated avian muscles with more difficulty, and focally innervated mammalian muscles with even greater difficulty. This differential ease of depolarization relates to slight differences in the configuration of the receptor sites in various preparations. The differing depolarizing capacities of the various esters relate to small differences in stereochemical configuration with various ring and side-chain substitutions. In addition to their postjunctional blocking abilities, all of the compounds tested had some prejunctional blocking ability. Perfusion with choline reversed this, indicating that the probable mechanism is inhibition of acetylcholine synthesis in the nerve endings. (*Marshall, I. G.: The Neuromuscular Blocking Action of a Series of Bicyclic Bis-Onium Esters, Brit. J. Pharmacol. 34: 56 (Sept.) 1968.*)

ABSTRACTER'S COMMENT: This work puts more cracks in the artificial wall separating depolarizer and nondepolarizer neuromuscular blockade.