ELECTRICAL SAFETY IN THE HOSPITAL ENVIRONMENT

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I. INTRODUCTION

One source estimates that 1200 hospital patients die each year from electric shock.(1) This unfortunate situation is a consequence of the increased use of electrical monitoring and support equipment in providing modern health care. It is the purpose of this paper to examine the physiological and electrical parameters which combine to produce a potentially lethal shock condition in the hospital environment and to describe the means by which these parameters may be adjusted to minimize the possibility of electrocution.

The problem of hospital electrical safety is unique in that it is impossible to obtain accurate statistical data on the number of patients that are killed each year by electrical shock. This is true for a number of reasons. Death from low level electric shock is often indistinguishable from death due to natural heart failure. Thus a patient connected to an ECG monitor may die as a result of either natural heart failure or of heart failure due to a shock current produced by a defect in the monitoring apparatus. In addition, an electric shock may not produce any anatomical or physiological changes which would be observable in an autopsy.(2) If electric shock was suspected as a cause of death, instruments and electrical apparatus in contact with the victim at the time of death could be inspected to determine whether or not they could have produced a lethal shock. It must be understood, however, that this is not a fool proof method for determining cause of death. An electric shock may have been produced by a momentary instrument fault or by a transient in the power line voltage neither of which would show up in post mortem testing of the equipment involved.

Some members of the medical profession maintain that there is no significant problem in hospital electrical safety. One of these is Dr. Arnold St. Jacques Lee, Director of the Department of Electronics and Instrumentation at Presbyterian Hospital, New York City. In an interview in *Modern Hospital*(3) Dr. Lee said,

> "The electrical shock problem in Hospitals has been purposely confused and complicated out of all proportion by power supply and patient monitoring system manufacturers, self-styled medical safety engineers, engineer-surgeons who cannot decide what they are specialists in, and other persons who are eager to publish and have found a ready made subject in hospital electrical problems."

Dr. Lee further states that in 15,000 cases handled in the operating room at Presbyterian Hospital, there were only six electrical accidents, four of which were caused by defective electrocautery equipment and none of which resulted in fatalities. Such an outstanding safety record would tend to indicate that all the research recently devoted to hospital electrical safety is purely academic.

The hospital safety problem presents a very paradoxical situation. On the one hand there are authorities devoting large quantities of money and time to decreasing the probability of accidental electrocution in the hospital while on the other hand equally qualified authorities are stating categorically that no problem exists.

To resolve this paradox one must consider many factors. First, in a hospital as large as Presbyterian Hospital in New York there is a qualified staff whose responsibility is to insure that all electrical systems in the hospital are functioning properly and are electrically safe. A smaller hospital would not be financially capable of employing qualified personnel to insure an electrically safe patient environment. Secondly, Dr. Lee's data includes only electrical accidents which could have had no other cause. This does not rule out the possibility that fatalities attributed to heart failure could have been caused by small electric shock currents. Thirdly, the data does not include information concerning other areas of the hospital such as Radiology or Intensive Care Units which are among the most common areas in which electrical hazards are found. Likewise inconclusive is the 1200 deaths per annum figure mentioned previously. No statistically reliable substantiation of this figure is available so one must resort to other means to establish the real magnitude of the problem.

The method commonly employed to estimate the hazards involved in utilization of electrical equipment in the hospital environment is two fold. One must first determine the physiological effects of electric shocks of various types and then determine the kind of electric shocks that commonly used hospital electrical equipment can produce. By combining the findings of these two investigations one may predict the electrical safety of the patient-environment system as a whole and modify it to minimize the possibility of an electrical hazard.

Physiologically speaking, shock currents on the order of 100ma passing through the body from one hand to the other can produce ventricular fibrillation and death.(4) However, if electrodes are in direct contact with the myocardium it is possible for a shock current as low as 20 microamps to produce fibrillation.(4) These are representative values of the magnitudes of shock current that must be considered when evaluating the safety of the patient-electrical environment.

In the following pages the physiological effects of shock currents will be evaluated and the conditions which can produce a dangerous level of shock current in representative types of hospital electrical equipment will be discussed. Finally, several suggestions will be made concerning the means by which hospital electrical systems and electrical apparatus may be made electrically safe.

An extensive bibliography containing articles pertinent to the subject of hospital electrical safety has been included to provide the reader with a source of detailed information in specific areas of this field.

II. THE NATURE OF ELECTRIC SHOCK

For the purpose of this discussion electric shock will be defined as the existence of an externally induced current anywhere in the body. This section describes the parameters which determine the effect of an electric shock on the body and the physiological events which are initiated by such a shock. Specifically, the physiological response of the body to an electric shock depends upon the following properties of an electric current: magnitude, path, wave form, frequency and duration. Magnitude, the first of these is of particular importance to this study since it is the simplest of these characteristics to control in a practical situation. Consequently, parameters which determine current magnitude in the body will be the first topic.

2.1 Factors Determining Shock Magnitude

In order for a current to flow through the body there must be a source of current and closed path in which the current exists. Assuming that such a condition exists, the magnitude of the current supplied by the source is determined through application of Ohm's Law to the following parameters: the magnitude of the voltage sources in the path and the impedances of the voltage sources, the external conductors, the conductor-skin interfaces, the skin, and the internal tissues of the body. Fig. 1 shows an equivalent circuit of a shock path.

Since the impedances of metallic conductors and the internal impedances of the voltage sources are generally very small (in comparison with the impedance of the body tissues) they will be neglected. The

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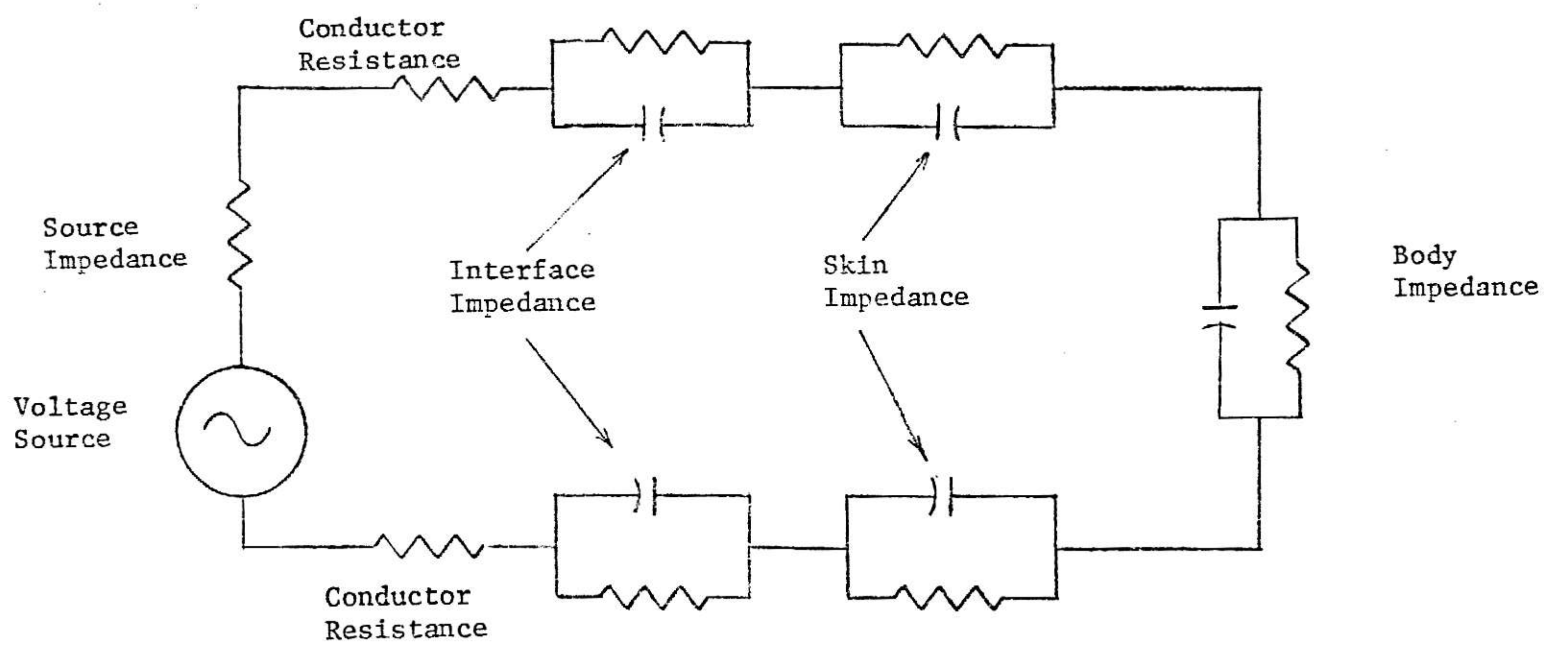

Fig. 1 An Electrical Analogy of a Shock Path

remaining factors, skin conductor interface impedance, skin impedance, internal body impedance and voltage source magnitudes, determine the magnitude of the shock current.

2.2 Tissue Impedance

Body and skin impedances are both frequency dependent and are commonly modelled as a parallel combination of a pure resistance and a capacitance.(5,6) The capacitive shunting in the skin impedance is much greater than that in the body tissues and has a value of about .28μf according to Stephens who described several properties of human skin.(6) By measuring the impedance to an alternating and direct current separately, and then measuring the impedance to a combination of these currents he also established that a direct current will lower the impedance of the skin to an alternating current while the converse is not necessarily true. In addition he showed that the drop of A.C. impedance due to a direct current is more pronounced when the polarity of the applied D.C. voltage is negative at the active electrode. Stephens gives the current voltage relationship of human skin as

$$i = 170v + 67v^2 \text{ (microamperes)}$$

which is an empirical result and indicates that skin impedance is a decreasing function of current magnitudes.

Values for the resistivity of internal body tissues have been extensively tabulated by Geddes and Baker.(7) Several values which are pertinent to the study of electric shock are listed in Table I. These values were obtained from canine tissue but serve as indicators of the magnitudes which might be expected in human tissue. All of these values were determined for low frequencies.

TABLE I.

Physiological Resistivities
from L. A. Geddes and L. E. Baker (7)

Tissue	Resistivity (ohm-cm)
Cardiac Muscle	750
Fat	2880
Lung (maximum inflation)	2170
Lung (maximum expiration)	401
Skeletal Muscle (random orientation)	950
Skeletal Muscle (longitudinal)	300
Skeletal Muscle (transverse)	1600

The impedance of the conductor-skin interface is the most variable of the impedance parameters which determine the magnitude of a shock current. Its value depends upon the area of the skin in contact with the electrode, and the condition of the skin surface at the interface. For a moist surface, interface resistance may be as low as several hundred ohms per square centimeter, while dry skin can easily cause a resistance of over one hundred kilohms per square centimeter. Unlike other impedances discussed in this section, the interface impedance is a function of time. As the duration of contact increases, the impedance of the interface decreases. In addition, at voltages in excess of two hundred and fifty volts the skin is immediately pierced producing burns at the point of contact and the skin-interface impedances are effectively bypassed.(8)

For the purpose of calculating expected values of shock currents for low frequencies and low voltages (below the skin breakdown voltage mentioned above) the value of 1500 ohms has been suggested by Dalziel.(8)

2.3 Physiological Effects of an Electric Shock

When an electric shock occurs in the body there are several events which may occur. If the magnitude of the shock is small it will have little or no effect on the body. If the magnitude is larger several physiological phenomena may be initiated. The victim may have a sensation of tingling and/or pain in the path of the shock, and muscular contractions may be induced in the muscles through which the shock passes. The extent of this pain and the degree of muscular contraction increase in proportion to the magnitude of the current.

2.3.1 Death resulting from asphyxia

If the victim should grasp a live conductor in one hand and a grounded conductor in the other, thus forming a complete electric circuit through his arms and chest, a shock current could cause contraction of the muscles of the arm and hand as well as those associated with respiration. In addition if the current was strong enough, the electrical stimulus would cause tetanic contractions of the flexor and extensor muscles of the hand. Since the flexor muscles are inherently the more developed and stronger of the two, the victim would be unable to let go of the conductors as long as this current existed in the circuit. The value of this "let go" current is given by Dalziel as 16 milliamperes R.M.S. for men and 10.5 milliamperes R.M.S. for women. These are average values and were obtained using a 60 Hertz line current with one band electrode attached to the upper arm and a hand held electrode consisting of #6 (A.W.G.) copper wire.(9) A current density similar in magnitude to that produced in the arm by the 16 ma current would cause tetanic contraction of all the muscles in which it existed. In the case of the arm to arm circuit a large current density in the chest would cause cessation of breathing due to incapacitation of the respiratory muscles. Since the value of current in the arms necessary to produce this condition is greater than the "let go" current, the victim would be asphixiated if the source of the current could not be removed in time. This is the one hazard of electric shock.

2.3.2 Death due to respiratory paralysis

Since electric currents passing through body tissues can initiate responses similar to those produced by nervous stimulae it follows that an electric current could affect certain neurological functions when present in nerve tissue. Experimentally this has been confirmed,(10) for if a current of sufficient magnitude is impressed on the respiratory center of the brain, cessation of normal respiration takes place. The normal function of the respiratory system may not be reestablished for some time even after the source of the current is removed. This is a second possible cause of death.

2.3.3 Ventricular fibrillation

Loss of normal rhythm in cardiac muscle can be caused by as little as 20 microamperes of current flowing through the heart. For this reason ventricular fibrillation poses the greatest threat to life due to electric shock encountered in the hospital environment and will be discussed in greater detail than the preceding mechanisms of electrocution.

Normal heart rhythm consists of the contractions of cardiac muscle fibers according to an established order, over a set period of time, at a fixed rate. This rhythm is dictated by cardiac cells which have the property of spontaneous depolarization. These cells are present throughout the heart and have varying rates of depolarization depending upon their location. It is these properties which establish natural cardiac rhythm by a mechanism which is explained below.

The automatic cells having the fastest firing rate are located in a tissue bundle on the right atrium of the heart called the sino atrial node. When a cell in this area depolarizes, adjacent cells are excited causing a wave of depolarization to propagate across the atria producing depolarization and contraction of the muscle fibers in its path. When this wave reaches the atrioventricular node, which is a bundle of tissue similar to the sino atrial node, several phenomena occur. First, the wave undergoes a propagation delay due to a change in conduction velocity from about one meter per second in the atrial tissue to .05 meters per second in the middle of the A-V node.(11) After this delay, the wave travels down the Bundle of His at increased speed (3-4 m/sec) and finally branches out into the Purkinge fibers and enters the ventricular muscle causing it to contract.(11) In order for this sequence to occur, it is imperative that the automatic cell having the fastest firing rate to be in the sino atrial node since it must initiate the sequence and cause the wave of excitation to arrive at the other pacemaker cells in the heart before they have spontaneously depolarized to their respective threshold potentials. If these other automatic cells reach their threshold potentials before they are caused to depolarize by the sino atrial pacemaker, they will initiate an excitation wave of their own which will lead to an irregular cardiac rhythm.

The electrocardiogram is a graphical representation of the average state of depolarization or repolarization of the cardiac muscle. If the heart is functioning normally as described above the ECG will appear as shown in Fig. 2. The $\overline{\text{QRS}}$ segment of the ECG is produced when the ventricles of the heart contract due to depolarization, while the section of the curve labelled "T" is produced when the ventricles relax and repolarize to their normal resting potential. The atrial contraction which initiates the cardiac cycle is indicated by the "P" portion of the ECG while relaxation of the atria takes place at about the same time as the depolarization of the ventricles and its effect on the ECG is masked by the dominant $\overline{\text{QRS}}$ complex. The relation of cardiac output to the ECG is shown in Fig. 2, in which blood pressure

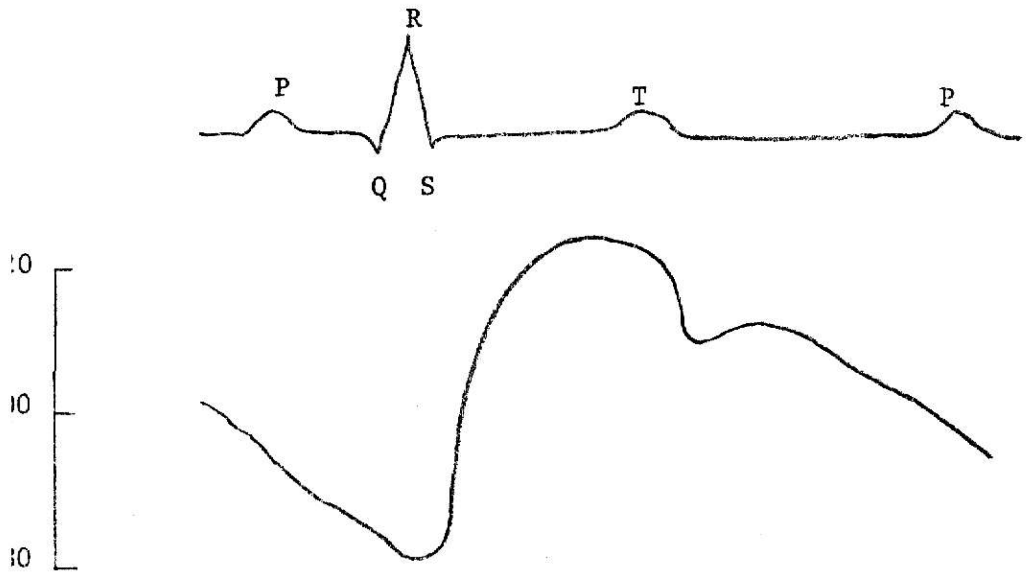

Fig. 2 The Relation of Blood Pressure to Electrocardiogram

is used as an indication of cardiac performance.

Ventricular fibrillation is a condition of the ventricles in which normal rhythmic contractions are replaced by those which are random in time and origin. The totally arrhythmic nature of these contractions make the heart incapable of maintaining a viable flow of blood to the body and death results. Fig. 3 illustrates the occurrence of ventricular fibrillation and the corresponding drop in blood pressure.

2.3.4 Electrically induced ventricular Fibrillation

As stated earlier an electric shock can induce ventricular fibrillation. Its ability to do so is a function of its time of occurrence in relation to the cardiac cycle, its magnitude, its waveform, and its duration. The specific role of each of these characteristics is the topic of this section.

It has been well established that the ventricles are most susceptible to fibrillation from an electric current during the crest of the "T" wave of the electrocardiogram.(11,12,13,14) Physiologically this corresponds to the part of the cardiac cycle during which the muscle fibers of th ventricles are undergoing rapid repolarization, and systole is about to end.

Yamashita and Tsuchiko(14) studied the effect of current pulses of short duration on the heart during the susceptible period described above. Their findings indicate that for pulses which included part of the ascending portion of the "T" wave, the minimum current necessary to produce fibrillation was inversely proportional to the duration of the pulse. They also demonstrated that the product of the fibrillating

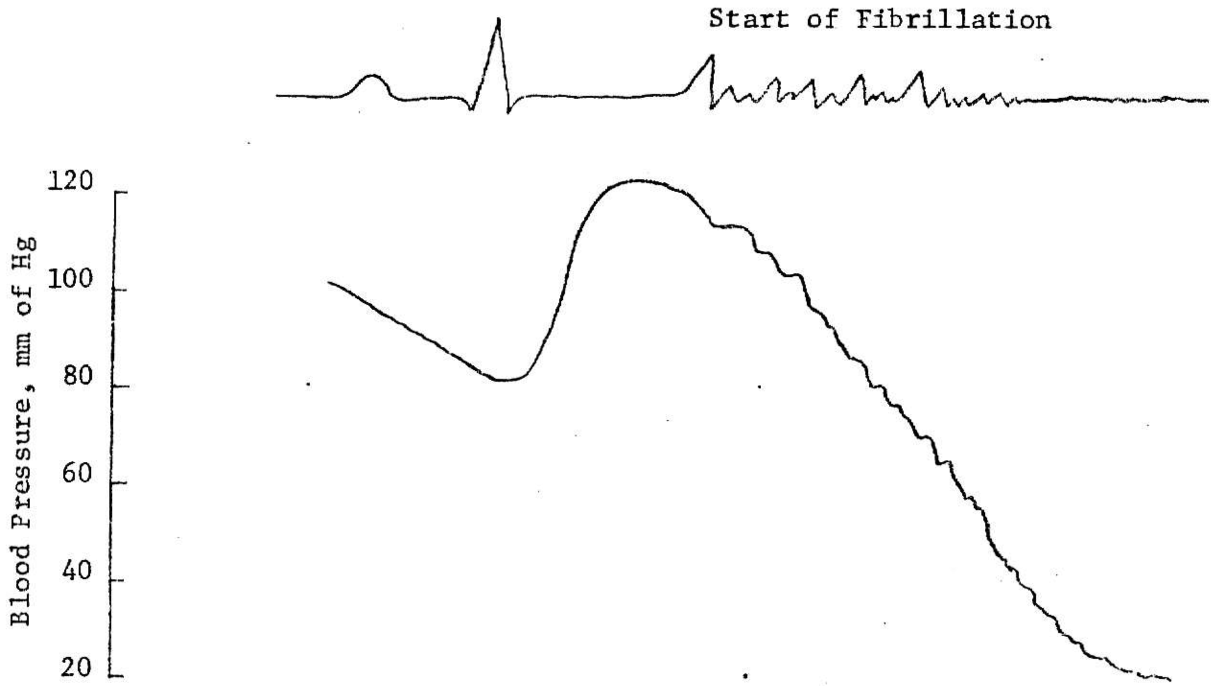

Fig. 3 The Effect of Ventricular Fibrillation on Blood Pressure

current and the pulse duration under these conditions was a constant equal to one millicoulomb. This suggests that the total charge passing through the ventricles over the period encompassed by the shock is the determining factor in producing fibrillation. This seems reasonable if one considers the physiological phenomenon which occur during this period of repolarization. At this point in the cardiac cycle the cell membranes are exceedingly permeable to potassium ions which are diffusing across the cell membrane to reestablish the resting potential. It is conceivable that a disturbance which results in the movement of charge through the ventricles, when they are undergoing this process involving redistribution of ion gradients, could initiate a spontaneous depolarization. There has been no experimental research done to confirm this or to establish an exact mechanism to explain it.

If a spontaneous depolarization does occur due to an electric shock there are a number of possible cardiac arrhythmias which may develop.(12,13 In many cases the cell which first depolarized will take on the function of the sino atrial node and initiate a premature beat which is followed by a period of recovery. The sino atrial node then regains control and the heart rhythm returns to normal. Wegria and Wiggers(12) reported that a D.C. shock which began during the vulnerable phase of the cardiac cycle and induced a premature beat, could cause ventricular fibrillation if it ended during the vulnerable phase of the induced premature beat. This suggests that the duration-current product discussed previously is not the sole factor in determining the onset of spontaneous depolarization. These findings indicate that the heart is also susceptible to changes in current magnitude with respect to time.

This theory is supported by empirical results obtained by Dalziel et al.(15) who demonstrated that the minimum current necessary to produce muscular contraction in man is dependent on frequency. For a given current magnitude the probability of inducing fibrillation is maximized for frequencies between 10 and 300 hertz. For frequencies higher or lower than these extremes the value of current necessary to produce muscular contraction increases markedly.

It was stated earlier that there were cells throughout the heart that were capable of depolarizing spontaneously and thus initiating a beat. If an electric shock initiates a premature beat, Wegria and Wiggers(12) showed that there is a possibility that spontaneous depolarization of a cell during the susceptible period of the induced beat can cause a partial contraction of the ventricles and further disrupt the cardiac rhythm to the point where fibrillation ensues. This mechanism for fibrillation occurs primarily for shocks having a duration on the order of one or more cardiac cycles.

This mechanism explains the drastic reduction in threshold fibrillating current for shocks on the order of one cardiac cycle or longer demonstrated by Ferris et al.(16) Their data consisted of values for the minimum 60 Hz current necessary to produce ventricular fibrillation in sheep for a given shock duration. The shock was applied externally between the right fore and left hind legs and the data plotted with the logarithm of the minimum fibrillating current on the abscissa and the logarithm of the ratio of shock duration to the length of the cardiac cycle on the ordinate. The resulting graph showed that the magnitude of the minimum fibrillating current drops off only slightly for duration/

cardiac cycle ratios from .05 to .5 and for ratios greater than 3.0. In the interval from .5 to 3.0 however, the minimum fibrillating current drops off by more than a decade, giving the curve the appearance of a step function.

Alternating currents produce effects similar to direct currents of similar duration with the exception that the magnitudes of current needed to produce the same effect vary with frequency as mentioned earlier. The effect of various combinations of periodic waveforms and direct currents was analyzed by Dalziel et al.(17) Their findings indicate that the effective value of a complex wave form is the sum of the amplitude of the periodic component and the magnitude of the D.C. component. In addition, the polarity of the D.C. component affects the response induced by the current. It was shown experimentally that a negative D.C. polarity at the active electrode had a 12.5% lower current threshold than a positively polarized current which evoked the same response. This may be explained by noting that applying a negative potential to the outside of a cell lowers the effective transmembrane potential to a value which is closer to the cell's threshold potential.

This section discussed the physiological effects of electric shock and described in a qualitative manner the part that several circuit and current parameters play in producing these effects. The following sections will be concerned with the actual determination and control of these parameters as they apply to electrical safety in the hospital environment.

III. HOSPITAL POWER SYSTEMS

It has been established that an external source of current to the body can induce numerous physiological disorders. In this section the sources of shock currents will be discussed in terms of commonly used hospital power systems.

Electrical power is supplied to the hospital through two transformers each of which provides electricity independently to an "emergency system" or to an "equipment system" in addition to supplying power for general lighting and miscellaneous power receptacles.

3.1 The Equipment Power System

The equipment system consists of several branches which serve the electrical needs of heavy equipment in the hospital such as elevator service, autoclaves, ventilation, etc. Since the possibility of lethal electric shock from this equipment is relatively minor, this system will not be discussed further.

3.2 The Emergency Power System

The emergency system consists of three separate branches which are, the life support branch, the critical branch, and the life safety branch. The first of these, the life support branch, is of primary concern since it serves only those areas which are provided for electrically susceptible patients i.e., those patients who are connected to any electrical equipment through internally implanted conductors such as catheters or internal pacemaker electrodes. The critical branch serves areas in which essential patient care functions take place. In some special instances the critical and life support branches may be combined subject to compliance with section 517-11(b) of the *National Electrical Code* (1971) (18). The life safety branch provides power to operate emergency apparatus such as fire alarms, communications apparatus, exit lights, etc. These branches of the emergency system must be kept physically and electrically isolated from the equipment system and from all other general wiring in the hospital. This is done to prevent over currents in these systems from causing loss of power to equipment supplying vital patient needs.

The life support and critical branches supply power to patient areas by one of two means, a grounded system or an isolated system. Each of these must be treated differently when evaluating the potential shock hazard of each electrical system in conjunction with patient monitoring equipment.

3.3 Grounded Power Systems

A grounded system is shown in Fig. 4. The transformer which supplies power to the system is grounded on its secondary side to some earth ground (water pipe, structural steel, etc.). This provides the system with two distinct poles, the grounded conductor (referred to as "neutral" and having white insulation), and the "live" or "hot" conductor (whose insulation is usually black or red to distinguish it from the neutral conductor). When these conductors are wired into a three prong receptacle, the polarity shown in Fig. 4 must be observed (19,20).

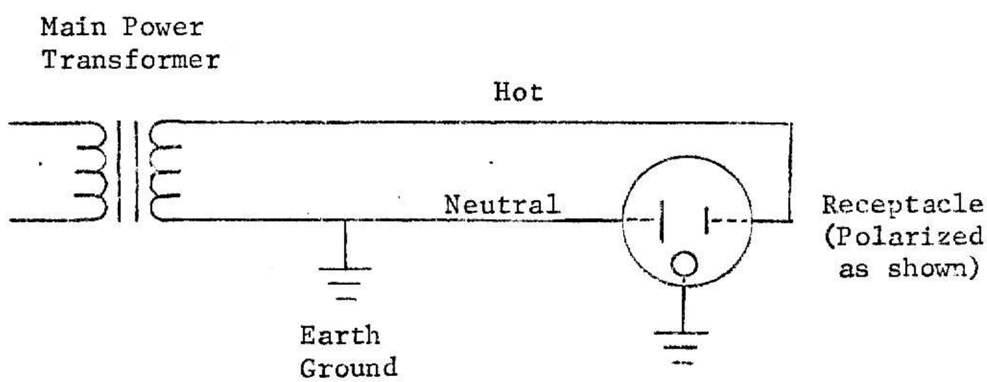

Fig. 4 A Typical Grounded Power System

3.4 Isolated Power Systems

An isolated system is shown in Fig. 5. The characteristic which distinguishes this system from the grounded one is that the secondary winding of the supply transformer is ungrounded. For the isolated power systems the conductors which distribute power to the receptacles are referred to as "floating" since neither one of them is tied to ground.

3.5 Grounding Systems

In addition to the power supply systems just discussed every electrical installation must include a grounding system separate from the power distribution system. A typical grounding network is shown in Fig. 6. The purpose of this network is to insure that all conductors with which the patient may come in contact are at the same electrical potential or at least within five millivolts potential of each other.(18) As shown in Fig. 6, each patient has a metal grounding bus to which all metal objects in his vicinity and each power ground is attached by means of #12 A.W.G. or larger stranded copper wire.(18) Each patient grounding bus is connected to a room grounding bus by #10 A.W.G. or larger stranded copper wire. This assures that all patient ground busses are at the same potential. The room grounding bus is attached to the nearest available earth ground which may be a water pipe or exposed structural steel beam in the room. Grounding busses consist of highly conductive metal strips to which large stranded conductors may be connected without appreciable resistance at the junction.

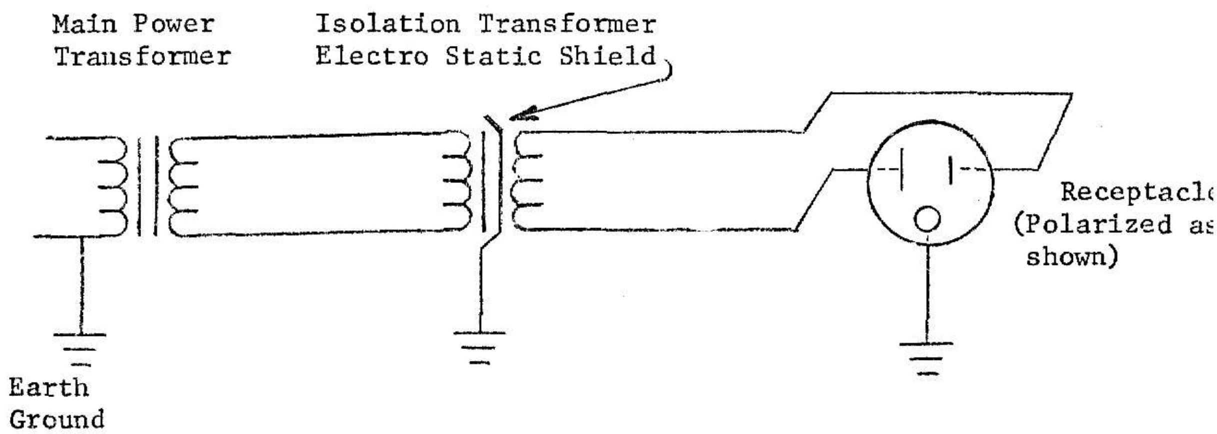

Fig. 5 A Typical Isolated Power System

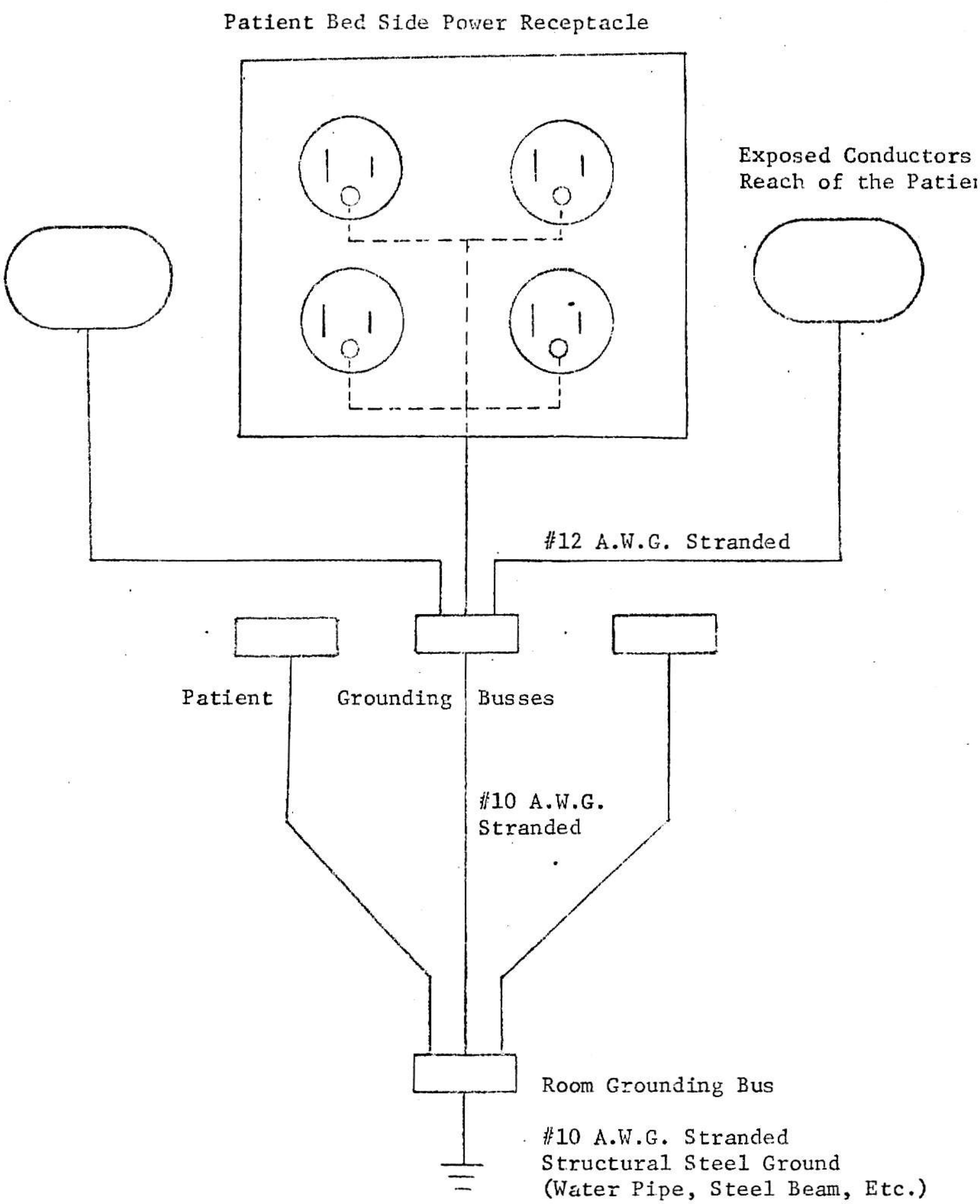

Fig. 6 A Standard Patient Grounding System

IV. SHOCK PATHS

In order for a shock path to exist there must be a complete circuit through the body which directly or indirectly includes a power system. In the simplest case for a grounded power system this path may be completed by the body between the hot conductor and either the neutral conductor or an earth ground. More often, however, the shocks occurring in the hospital environment are of a more complex origin involving the power supply of an electronic instrument or appliance. In the following sections the relationship of various power supply configurations and possible shock paths will be discussed and modelled so that their potential hazard can be visualized.

Shock sources may be divided into three categories, those originating from isolated power systems, those originating from grounded power systems, and those originating from potential differences between two grounding points.

4.1 Shocks Involving Grounded Power Systems

A typical grounded power system is shown in Fig. 7. The important feature of this configuration is that the primary winding of the instrument transformer is linked to the secondary winding by two paths. One path includes the capacitors C_1 and C_2 which represent the capacitive linkage between the windings. The other path includes the common ground attached to the neutral side of the power line and the chassis of the instrument. This ground connection from the primary to the secondary is dependant upon the continuity of the conductor linking the chassis and

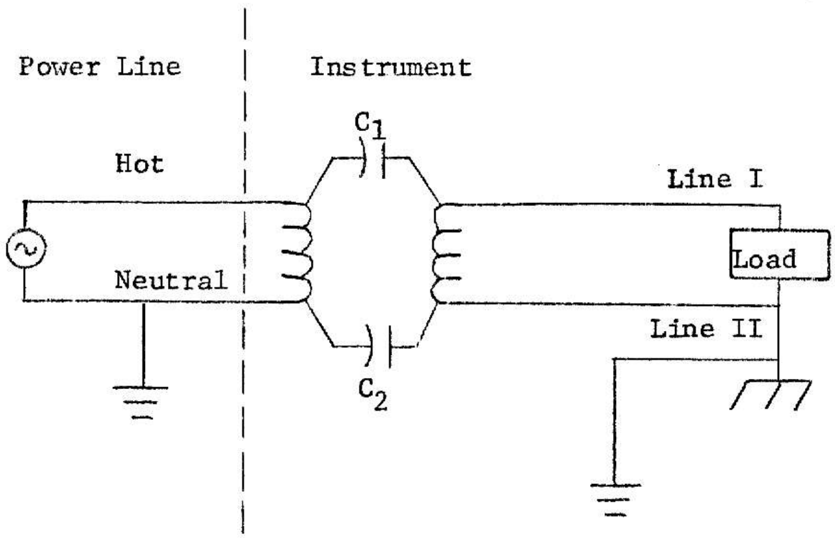

Fig. 7 Instrument Power Transformer Showing Leakage Capacitances

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case of the instrument to the third prong (ground) of the instrument power plug as shown in Fig. 8. If a break occurs in this path the only electrical connections between the primary and the secondary are the interwinding capacitances of the instrument power supply transformer. The resistive leakages between the windings of the primary and secondary circuits have been neglected since they would be extremely high if the insulation between them remains intact. Otherwise, resistive leakages would have to be included with capacitive leakages in analyzing the system. The shock paths that are possible with the grounded power system are shown in Fig. 9. In Case I the voltage across the primary winding is provided by the voltage generator V_p while the voltage of the secondary is represented by the generator V_s. This representation assumes that the magnitude of the internal impedance of the transformer is much less than the magnitude of the capacitive impedances represented by Z_c. It has also been assumed that the magnitude of the impedances due to C_1 and C_2 are equal. This is a physically realizable assumption.(8) The impedance external to the power supply and the instrument, through which the shock current may flow is represented by Z_p and includes the patient and any conductors which may be attached to him. Case I (Fig. 9) represents a shock path which involves the patient coming into contact with the chassis and an earth ground. This is a "worst case" model and assumes that the instrument is not properly grounded through the third prong of the instrument power plug. This ground path is shown in Fig. 9 and has an impedance Z_g. When the instrument case and chassis are properly grounded Z_g has a magnitude of less than one ohm. Thus an impedance of less than one ohm shunts the patient impedance, Z_p, and forms a current

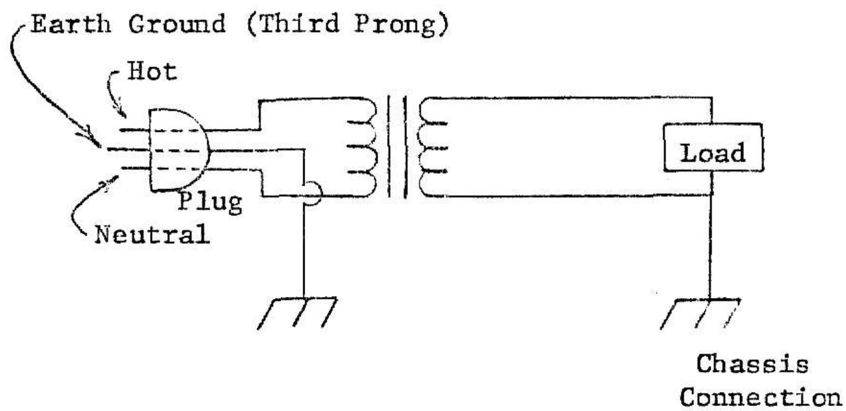
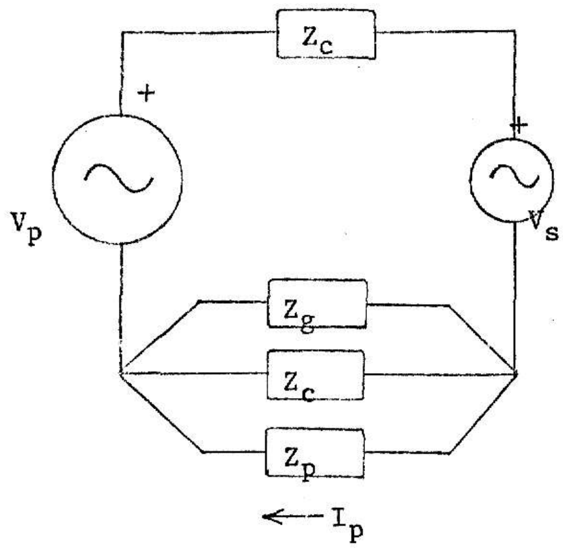


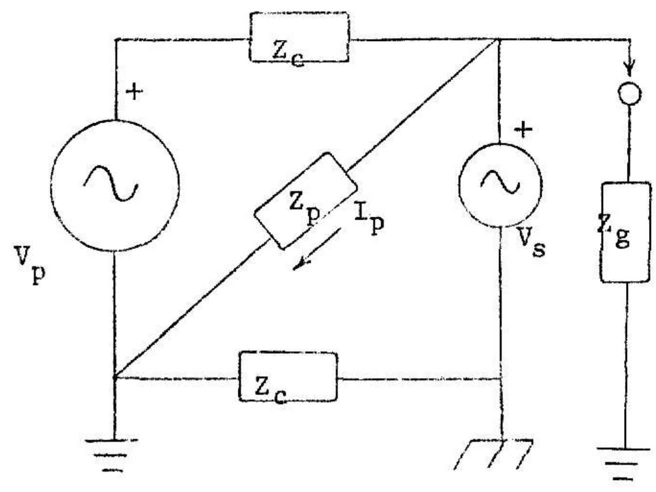
Fig. 8 A Typical Instrument Power Transformer

CASE I



Path From Chassis to Ground

CASE II



Path from Case to Ground

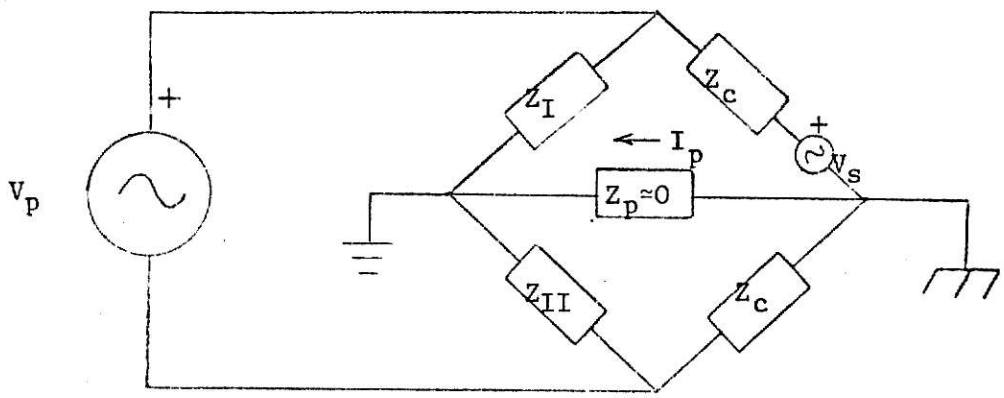
Fig. 9 Shock Paths in a Grounded Power System divider which channels most of the fault current harmlessly through Z_g to ground. Further, if the resistance of the body is assumed to be 500 ohms under worst case conditions (10), the current through the patient would be reduced to less than 0.2% of its original value. If, on the other hand, Z_g is high due to improper grounding most of the fault current would pass through the patient creating a potentially lethal shock condition. This demonstrates most emphatically the importance of maintaining good ground continuity.

In Case II (Fig. 9) the model represents a short circuit from the "hot" conductor of the secondary of the instrument transformer to the case of the instrument. The patient is shown to be in contact with the case and a ground point. If the case is not properly grounded the entire fault current passes through the patient. Again the importance of proper grounding is apparent.

4.2 Shock Paths Involving Isolated Power Systems

In the isolated power system there is no direct connection of the power lines and earth ground. Because of this the shock paths which are commonly encountered with an isolated system are different than those which are found in grounded systems. The possible shock paths for an isolated power system are shown in Fig. 10. In Case I the patient becomes part of an electrical shock path between the chassis or the patient ground lead, and an earth ground. Under these conditions the patient impedance becomes the center conductor in a bridge network which consists of impedances from line one to ground, Z_I, from line two to ground, Z_{II}, and the impedances from the primary winding of the instrument transformer to

CASE I



CASE II

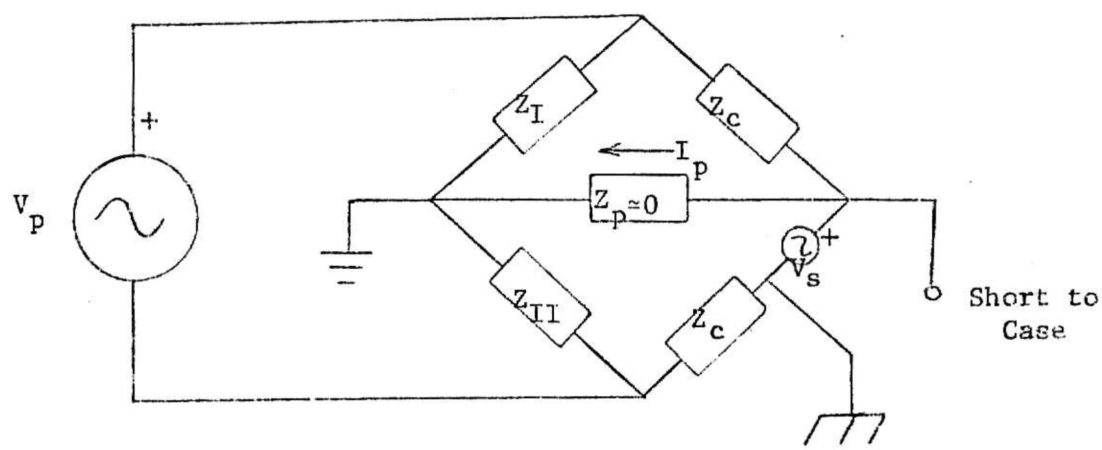


Fig. 10 Shock Paths in an Isolated Power System

the secondary winding. The physical origin of these impedances is shown in Fig. 11 in which the isolation transformer interwinding impedances, due to capacitances C_3 and C_4, are included in Z_I and Z_{II} respectively.

A Thevenin equivalent circuit at the terminals of Z_p provides for the determination of the potential shock hazard which exists for a given system. Equivalent circuits for two particular sets of system parameters are shown in Fig. 12. In these models Z_c has a magnitude of 2.65 Megohms which represents a leakage capacitance of 1000 μμf at a frequency of 60 Hz. The leakage impedances for line one and line two of the isolated system have both been given the value 5 Megohms. It is assumed that the windings of the instrument transformer can be represented by voltage sources with corresponding voltages determined by the line voltage and the turns ratio of the transformer. Also for the purpose of discussion it is assumed that the secondary voltage, V_s, is equal to the line voltage across the primary, V_p. Under these circumstances the two isolated cases of Fig. 10 give a maximum shock current, I_{ss}, according to the expression

$$I_{ss} = V_p/15.4 \text{ microamperes,}$$

while Case I in the grounded system (Fig. 9) gives no shock current. In contrast to this, the circuit of Case II of the grounded system (Fig. 9) can supply a shock current given by

$$I_{ss} = V_p/1.32 \text{ microamperes.}$$

Clearly, from these results, it is impossible to state absolutely that

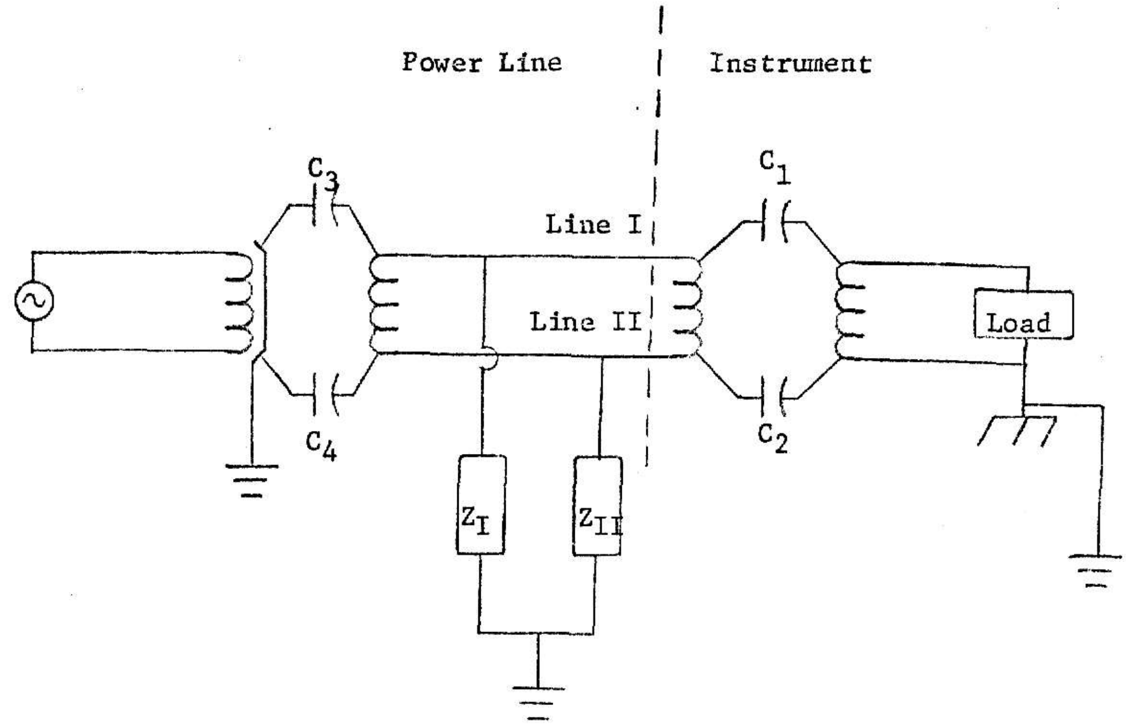
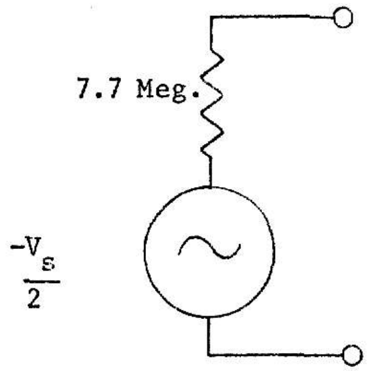


Fig. 11 Isolated Power System and Instrument Power Transformer Showing Transformer Leakage Capacitances

Isolated Equivalent Circuit



Grounded Equivalent Circuit (Case II)

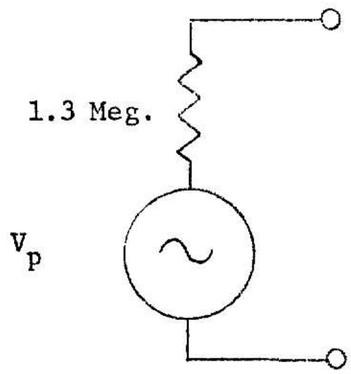


Fig. 12 Thevinin Equivalent Circuits for the Power Systems of Section 4.1

an isolated system is safer than a grounded one or vice versa. In order to determine the relative merit of these systems, expressions for leakage currents have been tabulated in Table II for several different system parameters. Since the circuits in Case I and Case II of the isolated system (Fig. 10) are symmetric about the shock path through Z_p, the shock currents for the two configurations have the same magnitudes but opposite polarities. As a result, only the expression for the maximum shock current in Case I has been included in Table II.

It has been shown that an isolated system is not necessarily safer than a non-isolated system and in the most general case the relative safety of any power system must be analyzed specifically using particular system parameters to assess the numerical values of expected leakages.

4.3 Shocks Involving Grounding Systems

There is another source of leakage current commonly found in the hospital environment which indirectly involves a grounded power supply system. Such a source is shown in Fig. 13. In this circuit a large current, I_f, flows in the earth ground wire due to a failure in an electrical appliance. Since the wire has a small but finite resistance, R_w, there will be a potential difference, $V_g = I_f R_w$, between the grounds of the two appliances. If the fault current is sufficiently large this ground to ground potential may be great enough (over 5 millivolts) to cause a lethal current to flow through the heart of an electrically susceptible patient.

			$V_s = V_p$		$V_s \neq V_p$	
			$Z_I = Z_{II}$	$Z_I \neq Z_{II}$	$Z_I = Z_{II}$	$Z_I \neq Z_{II}$
ISOLATED SYSTEM		I_{ss}	$-\frac{V_s}{Z_c + Z_I}$	$\frac{-2V_s}{\frac{Z_c Z_I}{Z_{II}} + Z_c + 2Z_I}$	$\frac{-V_s}{Z_c + Z_I}$	$\frac{(Z_I - Z_{II})V_p - (Z_I + Z_{II})V_s}{Z_c(Z_I + Z_{II}) + 2Z_I Z_{II}}$
		Voc	$\frac{-V_s}{2}$	$-V_s \frac{Z_{II}}{Z_I + Z_{II}}$	$\frac{-V_s}{2}$	$V_p\left(\frac{1}{2} - \frac{Z_{II}}{Z_I + Z_{II}}\right) - \frac{V_s}{2}$
GROUNDED SYSTEM	CASE I	I_{ss}	-0-	-0-	$\frac{V_p - V_s}{Z_c}$	$\frac{V_p - V_s}{Z_c}$
		Voc	-0-	-0-	$\frac{V_p - V_s}{2}$	$\frac{V_p - V_s}{2}$
	CASE II	I_{ss}	$\frac{2V_s}{Z_c}$	$\frac{2V_s}{Z_c}$	$\frac{V_p + V_s}{Z_c}$	$\frac{V_p + V_s}{Z_c}$
		Voc	V_s	V_s	$\frac{V_p + V_s}{2}$	$\frac{V_p + V_s}{2}$

TABLE II. Maximum Leakage Currents for Power Systems

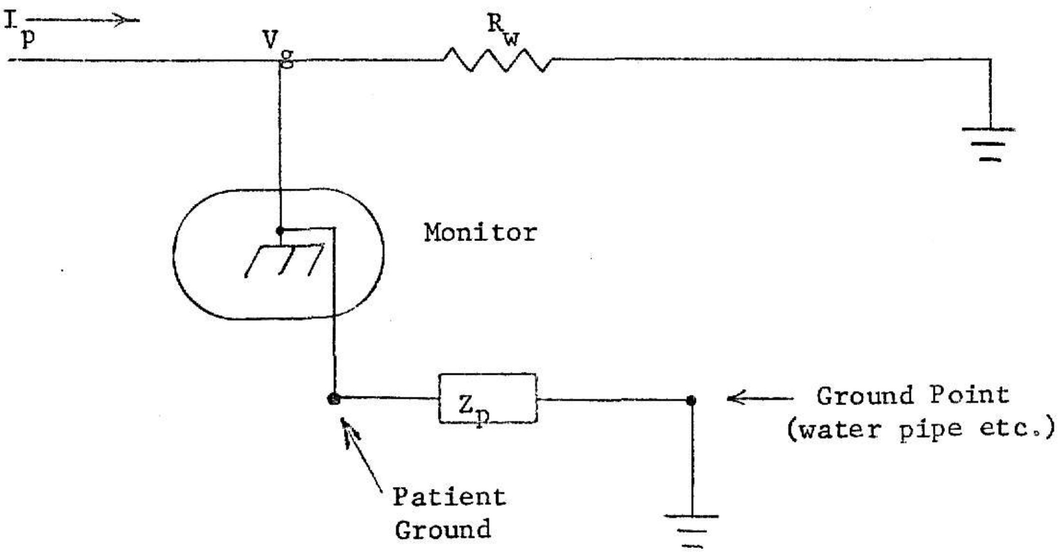


Fig. 13 A Ground to Ground Shock Path

V. SHOCK PREVENTION

Thus far, the sources of shock currents have been analyzed and the electrical properties of the body have been discussed. In this section several means of shock prevention will be discussed.

5.1 The Effect of Electrodes and Electrode Placement on Shock Magnitudes

In evaluating power systems, the impedance of the patient and the conductors through which a shock current passed were assumed to be small enough (in comparison with the internal impedance of the shock source) that they could be approximated by short circuits. In actual fact this is rarely the case. The total patient impedance, which is represented by Z_P, is the sum of all the impedances of the body, the leads or conductors comprising the shock paths, and the impedance internal to the instrument responsible for the shock. Great reductions in shock hazards can be achieved by insuring that these impedances are as high as possible. There are two main categories to consider when assessing the shock current limiting qualities of an instrument system. The first of these is the type of electrodes in use, since different electrode configurations can produce vastly different effects for a given leakage current. Surface plate electrodes or subcutaneous pin electrodes are the safest because they present a high impedance to the shock source. Also, because they are on or near the surface of the body, a relatively high current on the order of a hundred milliamperes is needed to produce a current density in the heart which is sufficiently large to induce ventricular fibrillation(9). In some applications however, external electrodes are impractical as in the case of an electric pacemaking apparatus which requires direct electrical connection to the myocardium. In cases such as this when an electrical conductor is in close proximity to the heart, an extremely minute current on the order of 20μa may be sufficient to produce cardiac arrhythmias.(21) The use of intravenous catheters falls into this category and extreme caution must be exercised to prevent a shock condition from arising. The content of the catheter is the chief factor determining its effect in limiting a shock current. A saline filled catheter having an inside diameter of 0.5 mm and a length of one meter has an impedance of about 2.5 Megohms, while a catheter containing copper leads to a measuring device on its tip may have an impedance on the order of several kilohms or less thus causing a much greater current.(22)

5.2 The Effect of Electrode-Instrument Coupling on Shock Magnitude

The means by which patient leads are coupled to an electronic instrument can significantly affect the possibility of an electric shock. If for example, the patient ground or reference lead is connected directly to the chassis ground of an instrument, a shock path can exist as shown in Case I of the grounded power system described earlier. If, on the other hand, the patient leads are completely isolated from the instrument this path cannot exist. Differential amplifiers may be used to isolate the patient leads and at the same time reduce noise due to ambient electromagnetic fields from power lines or radio transmissions. These amplifiers are available with input impedances on the order of megohms, and can limit shock currents to values well below safe limits.

Optical (23), radio frequency (24), and transformer coupling (24) are also possibilities for isolation circuits but these methods involve modulating the patient's biological signal for transmission at a frequency which is high enough to carry all the necessary information contained in the original signal. In addition to their ability to isolate the patient leads from the monitoring equipment, these systems have the added advantage that the body is relatively insensitive to rather large leakage currents at the high frequencies used to transmit the biological signal. The disadvantages of these systems lie in their more sophisticated circuitry and higher cost.

5.3 The Effect of Grounding on Shock Magnitude

Even if the patient leads are totally isolated from the equipment to which they are coupled, the patient is still susceptible to electrical shocks unless all conductors in his immediate environment are at the same electrical potential. To insure that this is true, it is essential that all conductors within the patients reach are grounded to the same point by a conductor of low resistance (#12 A.W.G. stranded copper wire). (18) The point to which all grounding conductors are connected is called the patient grounding bus and was described earlier. It is also important that the chassis and case of all instruments and equipment in the patients environment be connected to ground since any current leakage through the patient due to a fault in a piece of equipment will then be divided between the ground conductor and the patient, thus greatly reducing the shock hazard.

5.4 The Relative Advantages of Isolated and Grounded Power Systems

The advantages of an isolated power system over a grounded one is the topic of much debate among authorities on the subject of hospital safety. From the previous discussion on power systems it was apparent that either system could produce a lethal shock current, if currents in excess of ten microamperes are to be considered unsafe. Because of the higher cost of an isolated system and because it offers no greater safety from microshocks (shock currents in the microampere range) than a grounded system, it is unnecessary to provide each electrically susceptible patient with his own individual isolated power supply, although this has been suggested by some authors.(19,25) Because the isolated system does provide protection from macroshocks (large shock currents) by virtue of its floating power lines, it is recommended that an isolated power system be installed for each ward. This would protect most patients with externally connected leads as well as hospital personnel. Patients who have internal electrical connections and are susceptible to very low levels of leakage currents are best protected by insuring that all necessary ground connections are properly maintained.

VI. PRACTICAL HOSPITAL SAFETY

It has been shown that electric shocks of very small magnitude can be delivered to a patient inadvertently by faulty equipment or wiring in the patient's environment, and that these small shocks can often cause death resulting from ventricular fibrillation. The mechanisms by which these shock currents are produced in the patient have been analyzed for both grounded and isolated power systems with the result that while isolated systems provide protection from macroshocks they do not provide guaranteed protection from microshocks, and hence do not constitute an acceptable solution to the problem of electrocution of the electrically susceptible patient. It was also shown that adequate grounding is of the utmost importance in providing protection from both macro- and microshock. In view of these findings one may conclude that the optimum route to patient electrical safety lies in a combination of locally isolated power and good grounding.

6.1 Modernization of Power Distribution Systems

If one takes as a worst case situation, the hospital whose intensive care unit is supplied by two or more branches of the hospital electrical system and which has two prong receptacles without provision for grounding one can make the following improvements to decrease the chance of an accidental electrocution. First, if financially feasible, an isolated power system should be installed to meet or exceed minimum standards as set down in the *National Electrical Code*.(18) A line isolation monitor (LIM) should be installed with the isolation transformer and should be checked and calibrated on a regular basis according to its manufacturers specifications. An LIM is a device which measures the impedance between the isolated power lines and earth ground (previously referred to as Z_I and Z_{II}). In the event that one or both of these impedances drops to a value lower than a predetermined threshold an alarm will sound indicating that a hazardous condition exists. If the isolated system is financially not feasible a grounded system may be substituted but it should be noted that the entire patient area must be supplied by one and only one branch of the hospital emergency system. The requirements for grounding are the same as those described previously in Section 3.5 and are the same for both grounded and isolated systems.

6.2 Regular Inspection and Maintenance of Electrical Equipment

In addition to the improvements made in the wiring of the electrically susceptible patient areas, special care must be taken to insure that all electrical equipment is functioning properly and is in good repair. The most common faults which occur in this category are breaks in the ground lead of an instrument between the third prong of the power plug and the chassis or case of the instrument.(26) The other most common defect in electronic equipment is reversal of the polarity of the conductors in the power cord when they are connected within the instrument. In some instances this may cause the case of the instrument to be at a dangerously high voltage with respect to ground.(27) Both of these faults are corrected by proper servicing of the instrument. In addition to this, instruments should be tested periodically for possible leakage currents which may be harmful to the patient. Methods for carrying out these tests have been presented by Denes Roveti(20), the National Fire Protection Association(27), and C. F. Starmer et al.(28)

VII. CONCLUSIONS

From this study of hospital electrical safety it is apparent that a comprehensive program including regular preventative maintenance and testing of equipment and education of hospital personnel to the dangers of electric shock is necessary to prevent loss of life due to accidental electrocution.

Specifically, leakage currents must be kept within limits specified previously. For electrically susceptible patients the maximum leakage allowable is 10μa while for other patients a 100μa leakage is the allowable maximum. These limits are certainly subject to the individuals involved and thus must be utilized only as guidelines.

Hospital personnel should be well educated to the dangers which are associated with the use of electronic instrumentation and electrical appliances in the vicinity of the patient and should visually inspect instrument power cords and plugs for physical damage before using them. Any irregularities in instrument operation should be viewed as a potential hazard and the instrument should be checked immediately for excessive leakage and ground continuity. If these simple precautions are taken the possibility of accidental electrocution in the hospital can be greatly reduced.

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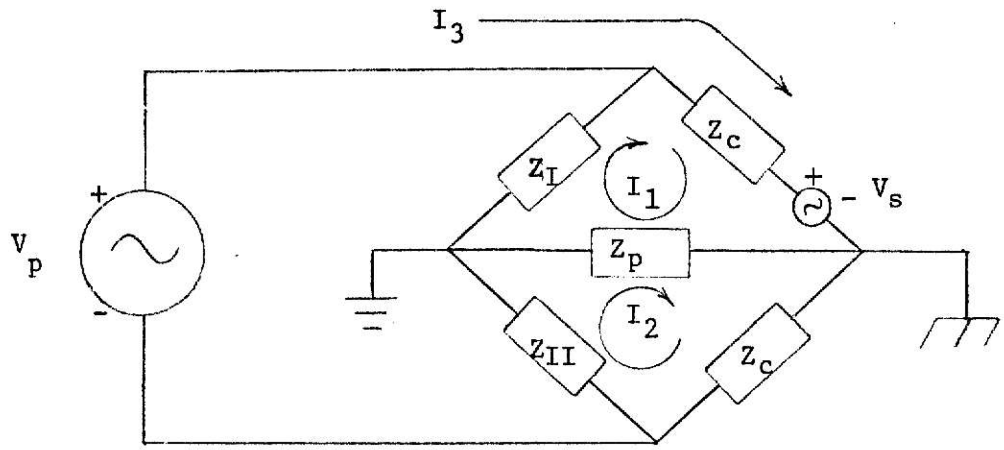
X. APPENDIX

Derivation of Leakage Current in an Isolated System

Consider the system of Fig. 11 as redrawn in schematic form in Fig. 10.



Applying Kirchoff's voltage law gives the following equation for the syste

$$V_p = (I_1 + I_3)\, Z_c + V_s + (I_3 + I_2)\, Z_c$$

$$0 = (I_1 + I_3)\, Z_c + V_s + (I_1 - I_2)\, Z_p + I_I Z_I$$

$$0 = (I_2 - I_1)\, Z_p + (I_2 + I_3)\, Z_c + I_2 Z_2$$

or in matrix form

$$\begin{bmatrix} Z_c + Z_p + Z_I & Z_c & -Z_p \\ Z_c & 2Z_c & Z_c \\ -Z_p & Z_c & Z_c + Z_p + Z_{II} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \doteq \begin{bmatrix} -V_s \\ V_p - V_s \\ 0 \end{bmatrix}$$

Cramers rule is used to solve for I_1 and I_2

$$I_1 = \frac{-Z_c Z_{II} V_2 - Z_c{}^2 V_p - 2Z_c Z_p V_p - Z_c Z_{II} V_p}{Z_c{}^2 Z_I + Z_c{}^2 Z_{II} + 2Z_I Z_c Z_p + 2Z_{II} Z_c Z_p + 2Z_c Z_I Z_{II}}$$

$$I_2 = \frac{-Z_c^2 V_p + Z_c Z_I (V_s - V_p) - 2Z_c Z_p V_p}{Z_c^2 Z_I + Z_c^2 Z_{II} + 2Z_I Z_c Z_p + 2Z_{II} Z_c Z_p + 2Z_c Z_I Z_{II}}$$

Then it is assumed that $Z_p << Z_I$, Z_{II} and Z_c. Thus, terms containing Z_p are insignificantly small and may be eliminated. This assumption gives the same current as would be obtained if Z_p were identically zero. The resulting current, I_{ss}, is the maximum expected shock current and is given by

$$I_{ss} = I_I - I_2 \Big|_{Z_p = 0}$$

$$I_{ss} = \frac{(Z_I - Z_{II})\, V_p - (Z_I + Z_{II})\, V_s}{Z_c(Z_1 + Z_2) + 2Z_1 Z_2}$$

By applying the principle of superposition and letting Z_p equal an infinite impedance the open circuit voltage across Z_p is found to be

$$Voc = V_p \left(\tfrac{1}{2} - \frac{Z_{II}}{Z_I + Z_{II}}\right) + \frac{V_s}{2}$$

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ELECTRICAL SAFETY IN THE HOSPITAL ENVIRONMENT

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ABSTRACT

Due to the expanded use of electronic monitoring apparatus and electrical appliances in modern health care facilities, electric shock has become a topic of major concern to all medical and hospital personnel.

In this paper the nature of hospital electrical hazards is discussed and recommendations are made for improving electrical safety. In addition, the physiological and electrical factors which contribute to causing a fatal electric shock are individually discussed and then related to the total shock system. Finally, an extensive bibliography of articles relevent to the study of hospital electrical safety is included to provide the reader with a convenient reference for further information.