

R 69-12439

5.

ELECTRIC CURRENT

Effect of Electric Currents on Cells and Tissues

In the presence of electrical currents, the body behaves like an electro-chemical system. On the other hand, due to anatomical reasons such as the presence of membranes, it generates potential differences between different parts of the body. Therefore, when one considers the possibility of electrical currents acting upon the body, the end result will be the integration of the intrinsic currents plus the externally applied currents.

Physiological systems are assumed to be, from an electrical point of view, a combination of resistors and capacitors (35, 36). When a steady direct current is passed through tissue, the tissue behaves like a simple electrolytic resistance path. Considering organic tissue to be an electrolytic system, the laws of electrolytic conduction can be applied. Suppose a field E exists between two electrodes in an electrolyte. All charges, q , in the solution will experience a force ($f = qE$) causing them to move along the field lines of force. The terminal velocity is equal, specifically, to the product of force f , and the mobility, u , defined as the velocity of the particle when force is acting on it. The total current i , flowing through the electrolyte is equal to the number of charges, N , times their velocity, u :

$$i = Nfu \tag{1}$$

The number of charges will be equal to twice the number of dissociated atoms and the anion and cation will have different mobilities, u_a and u_c , respectively. The number of dissociated molecules in a solution of concentration C can be expressed as δC , so that the current will be:

$$i = q\delta CE(u_a + u_c) \tag{2}$$

where i = current

q = charge

E = field strength

δC = number of dissociated molecules

The conductivity of the solution is defined as the ratio of current to potential difference; potential difference V is related to the field by a relation of the type $E = \frac{V}{d}$ where d is the distance between electrodes, V = potential difference, and E = field strength. In case the electrodes of force are close together so that d is much smaller than the plate size, the lines of force are on the average just d in length. For such a case the conductance (G) of the model electrolytic cell is:

$$G = \frac{1}{R} = \frac{q\delta C}{d} (u_a + u_c) \quad (3)$$

where G = conductance = $\frac{1}{\text{Resistance}}$

The conductivity ρ of the solution in the model cell would be the conductance per unit area normal to the direction of current flow, for unit distance of plate separation, or

$$\rho = q\delta C (u_a + u_c) \quad (4)$$

Since the tissues may be considered as suspensions of cells in the extracellular fluid, the theory of electrical resistivity of suspensions enables one to predict with some accuracy the resistivity of tissues. In general, the cytoplasmic resistivity of cells varies from 30 to 3000 ohm cm, 300 ohm cm being the best representative figure for most mammalian cells. The membrane resistivity varies from 100 to 100,000 ohms cm^2 , with most cells falling in the range of 1000 to 10,000 ohm cm^2 .

In considering alternating currents passing through biological systems, the concept of impedance must be included. For direct currents, impedance and resistance are merely the same, but for A.C. current, impedance is a complex function of resistance and capacitive reactance (see Equation 8). There appears to be no inductive factor present.

Extensive data are available on the electrical characteristics of biological materials (36). Dielectric constant and specific resistance of mammalian tissues are recorded in Figure 1-2 of *Microwaves* (No. 1). If an alternating potential, V , is applied to a tissue having a conductance, G , the transfer of electrical energy into heat, H , due to the electrical current, i , is given by the equation

$$H = V^2 \cdot F = i^2/G \quad (5)$$

(Joule's law). Similarly, if a small volume ΔV is exposed to a field strength E (in Volt/cm) it develops heat at the rate of

$$H = E^2 \kappa \cdot \Delta V = (j^2/\kappa) \Delta V \text{ watts} \quad (6)$$

where κ is the specific conductance (conductivity) in mho/cm and j is the current density. In the case of a more complex system, where various types of material are exposed to the total available potential, more complex relationships result, which express the heat developed in each type of material as function of its geometry and conductivity κ and also dielectric constant ϵ . (The dielectric constant ϵ is equal to $1/(3.6\pi)$ times the capacitance of a cm-cube, if the capacitance is expressed in units of $\mu\mu$ Farad.) In principle, it is possible to completely characterize the distribution of heat sources from a knowledge of the geometry and electrical properties ϵ and κ .

From Equation (5), it is obvious that the electrical conductance determines predominantly the exchange from electric to heat energy. This constant

characterizes directly the interaction of the electrical charges, which are forced by the electrical field through the material of interest with its molecular structure. The dielectric constant, ϵ , on the other hand, only indirectly participates in the over-all distribution of the heat sources. It characterizes to what extent current can pass as "displacement current" through the material, that is, as a current whose flow does not yield heat. Kirchoff's law states that the vector sum of real and displacement currents must remain constant through any series arrangement of different layers of matter. Hence, if the displacement current is large, that is when ϵ is large, the resistive current and heat development will be small, and in turn, for small ϵ or high κ , heating will be more pronounced in general.

Several different types of materials are arranged in series in the case when high frequency currents pass from one electrode through skin, subcutaneous fat layer, muscular tissue, etc., and eventually back to the other electrode. The current i delivered from the generator to the total tissue complex is expressed by Ohm's law (V potential)

$$i = V/Z \quad (7)$$

if Z is the over-all impedance of the configuration. Its value is identical with the sum of the individual impedances

$$Z = Z(\text{skin}) + Z(\text{fat}) + Z(\text{muscle}) + \dots$$

of each layer. Each impedance in turn is determined by

$$Z = d / \left[A(\kappa + j\omega\epsilon\epsilon_r) \right] \quad (8)$$

where d = tissue layer thickness, A = cross section of tissue passed by current, κ = conductivity in mho/cm, $\omega = 2\pi \cdot$ frequency, ϵ = dielectric constant, $\epsilon_r = 1/(36\pi \cdot 10^{11})$ in farads/cm and $j = \sqrt{-1}$. Hence, heat development in each layer can be obtained, in principle, from a knowledge of the electrical properties of each layer, its thickness, effective cross section, and the generator potential or current by use of the Equations (5 and 6). The ratio of heat development in various layers, obtained in this manner, permits one to predict how much heat is developed in the "deep tissues". (See also Microwaves No. 1.)

Effects of Electricity on Humans

In considering the effects of electricity on a human system, several factors previously mentioned should be taken into account (4, 18, 20, 22, 37).

- Skin and body contact resistance
- The voltage of the circuit
- The amount of current flowing through the body
- The type of circuit, direct or alternating, and the frequency.

Skin and Body Contact Resistance

Resistance of the skin will depend upon many factors (16), namely: size, shape, and nature of the contacting electrodes; individual differences of skin structure and thickness in different areas of the same body; presence or absence of sweat or external moisture contact; and frequency of current. The resistance of skin resides mainly in the epidermis, the thin outer layer of the skin. The epidermis is a layer of stratum corneum and contains no blood capillaries or nerve endings. The scaly, horny layer acts as a poor dielectric, which offers a high impedance (resistance) to the flow of current.

The resistance of the epidermis varies widely on different individuals and also between wide limits on a given individual (17). It is normally lowest on the palms of the hands, the soles of the feet, the central area of the face, the axillae, a belt around the abdomen, and the crotches of the elbows and knees. It is interesting to note that in passing from the palmar side of a finger to the dorsal side, the skin resistance increases in a strip about one-eighth inch wide by a factor of six or sevenfold.

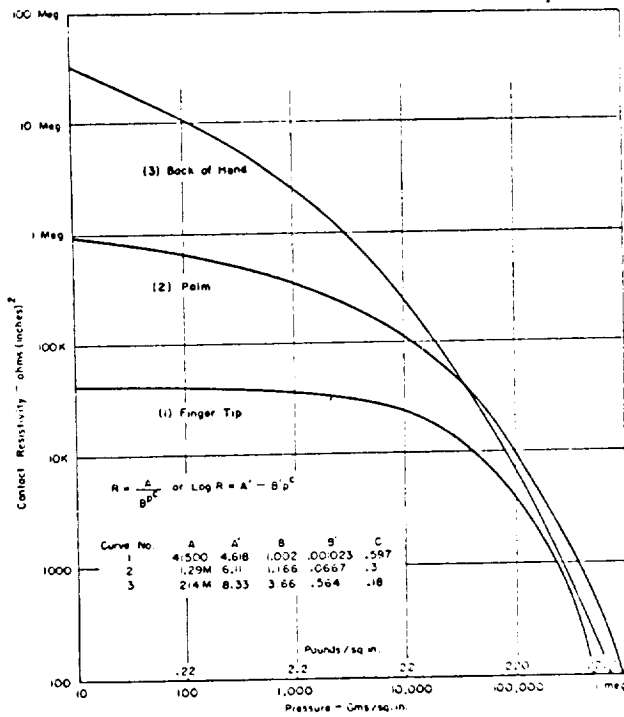
The protection offered by the epidermis is lowered by moisture (it may drop to 1/100th or less of its dry value), by the application of electrode paste (some of these contain finely ground sand particles which pierce the thin epidermis), by heat (blisters), by abrasions, by cuts, by the voltages of the circuit, or by any means that affect the continuity of the epidermis. Thin, moist skin surface may offer 400 ohms resistance or less. Dry skin may present 5000 ohms, and thick, calloused skin, several 100,000 to a million ohms. Once current penetrates epidermis by burning, resistance drops rapidly.

The effect of the level of applied voltage on the resistance of the human body is marked. Many body resistance values reported in medical literature are made at a few volts, or at less than a volt. Under these conditions the values reported are meaningless as far as electric shocks are concerned. There is a critical voltage at which the skin breaks down and its protection is lost. For example, on a fresh cadaver the hand to foot resistance at 50 volts, 60 Hz A.C. was 10,000 ohms; at 500 volts it was 1200 ohms, and at 1000 volts - 1100 ohms (17).

Skin to electrode contacts are very sensitive to pressure, frequency and other factors. Figure 5-1a presents preliminary data on the relationship between pressure and resistivity for the contact of dry human skin to metal. These curves require statistical evaluation for spread of data to be encountered in accidental situations.

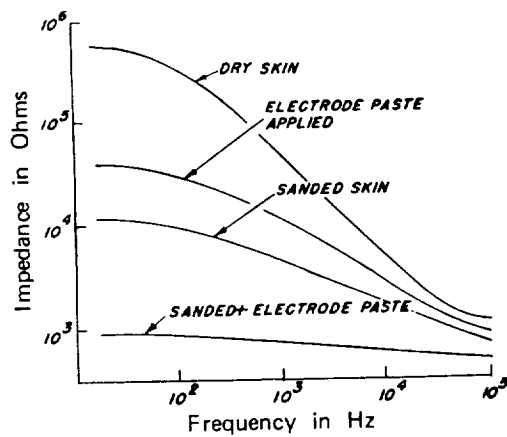
An example of the variation of skin impedance with frequency and marked sensitivity to skin-electrode contact is shown in Figure 5-1b (36). Empirical curves of this type will vary with electrode type, current, and duration of exposure, and should not be used for prediction of accidental conditions. Electrodes of the type recorded in Figure 5-1b are used for electromyographic study of muscle potentials. A flattening of the impedance curve for dry skin at both the high and low frequencies is interpreted as an asymptotic resistive component of the internal tissue structure of the muscle (5). The curve may

Figure 5-1
Variables Controlling Skin to Electrode Contact



a. Relation Between Pressure and Resistivity for the Contact of Dry Human Skin to Metal.

(After Morse⁽³¹⁾)



b. An Example of the Variation of Skin Impedance with Frequency and Condition of Electrode-Skin Contact.

Copper-disc electrodes 3/4 in. in diameter were used. (See text)

(After Stacey⁽³⁶⁾ Adapted from Burns⁽⁵⁾)

be divided into three major segments and the equivalent circuit, estimated. Complexities of the structure of the subdermal components interfere with exact modeling of the system. Measurements made on electrode separation show no large variation after the separation of two electrodes (3/4-inch diameter) exceeded one-half inch. The effect of electrode size was noticeable by a small increase in impedance with a decrease in electrode size. The diameter-to-spacing ratio is most important in determination of impedance of any one electrode in a linear array of electrodes along the skin.

The measurement of body resistance is highly inexact. Since contact skin area and moisture contact are so highly variable, ranges of 20 to 1 or more for supposedly similar contacts are the rule. The best approach one can take is to pin-point the minimum resistance value for a given condition, and even this approach is far from satisfactory. Some of these are shown in Table 5-2. In the interpretation of this table and Table 5-3, it should be

Table 5-2
 Rough Approximation of Typical Lowest Resistances
 of Individual Elements of Human Circuits
 (See text for details before applying data)

(After Lee⁽²⁶⁾ from the data of Kouwenhoven and Milnor⁽²³⁾
 and Dalziel⁽⁹⁾ and Morse⁽³¹⁾)

RESISTANCE OHMS	HANDS OR FEET		SURFACE ONLY		MISCL. SURFACE OR BULK
	AREA SQ. INS.	DRY	AREA SQ. INS.	WET	RUBBER GLOVES RUBBER HEELS, SOLES DRY WOOD
20 M					
10 M					
M					DRY CONCRETE ABOVE GRADE 20 SQ. INS.
100 K		FINGER TOUCH			DRY CONCRETE ON GRADE 20 SQ. INS.
10 K		HAND-WIRE FINGER-THUMB GRASP	5 FINGER TOUCH		LEATHER SOLE, DRY, INCL. FOOT.
5 K		3 HAND HOLDING PLIERS 5 PALM TOUCH	1 HAND-WIRE 2 FINGER-THUMB		LEATHER SOLE, DAMP, INCL. FOOT.
1000		15 HAND AROUND 1-1/2" PIPE	5 HAND-PLIERS 30 PALM		WET CONCRETE ON GRADE 20 SQ. INS.
100		30 2 HANDS 1-1/2" PIPE	15 HAND - 1-1/2" PIPE 30 HAND-IMMERSED 60 FOOT-IMMERSED		BODY INTERNAL (EXCL. SKIN)

realized that the skin is punctured when the voltage exceeds 1000 to 2000 volts. This unfortunate circumstance removes a large portion of the total circuit resistance and allows the current to increase many fold. Graphically, this means that the horizontal resistance line is "stepped" at about 2000 volts from the total circuit resistance to the total circuit resistance less the skin resistance. At about this same voltage, or when the current is allowed to reach a few amperes, sparking or arcing may occur across the edges of the soles of shoes, again allowing increase of current. At this level of current, the shock is beyond the fibrillation zone, and serious tissue burning is involved, with the current magnitude limited by only the internal body resistance.

It is obvious that the larger or wetter the contact area, the lower the resistance. Ideally, to find the total resistance to current flow, one can add all the elements of resistance in the path, such as hand-to-wire, body, foot, and floor, or hand, body, hand, since all of these elements are in series. In reality, the variables are so complex as to reduce accuracy of this approach to very much approximation. More detailed data are available on the determination of ground-fault magnitude and human safety from fault-return path impedance (25).

The duration of the contact is of importance when considering electrical injuries. Time of exposure has a direct relationship with the degree of permanent damage observed. Resistance of the skin also decreases during the passage of the current and total body resistance decreases if contact is made with an electric circuit for any length of time. It may decrease within one minute from 260,000 to 380 ohms (16). In animal experiments, it was found that the current increased 5 to 10 percent if the animal was kept in the circuit for any length of time.

Tissue resistance per cc varies; muscle presents 1500 ohms per cc; brain, 2000 ohms per cc; bone, 900 ohms per cc or more; fat (free of muscle), several thousand ohms per cc (17). Total body resistance is a difficult measurement and depends most strongly on the size, location, and distance between electrodes. In electrocuted criminals, it was found to be 218 ohm (16). In these cases, an AC current was passed from the forehead to the feet in four shocks. The strength of the first and third shocks was 2,300 volts and each lasted seven seconds; the strength of the second and fourth shocks was 550 volts for fifty-two seconds. Much higher values are found with less perfect contacts.

If the contact resistance can be eliminated, a tissue resistance of about 100 ohms per cc can be assumed (17). Obviously, the parts of the body where contact is made are of vital importance. One can envision the electric current as spreading radially from the point of entrance to be collected again at the exit point; therefore, the greatest density current can be found at the entrance and exit points. For general purpose, the minimum value of body resistance for hand to foot path is considered to be 500 ohms (17). Most of this resistance resides in the limbs where a large proportion of the total cross section is taken up by the bones. In the trunk, the tissues and organs are considered to act as a conducting gel bathed in saline, and the current spreads out in a fusiform pattern between the points of entrance and exit. In estimating the resistance offered to the flow of current by an electric shock, the resistance of the trunk is considered to be negligible compared to that of the limbs. There is a diurnal variation in an individual's resistance which often confuses experimental data (34).

The anatomical location of vital organs relative to the current path is of great importance (4). In general, current passing through left side of thorax presents greater dangers of ventricular fibrillation and asystole. The cranium presents an excellent shield for the brain since bones are poor conductors. Electrical energy will pass around the cranium in extracranial soft tissues if given the opportunity; and in a longitudinal course (for example, head to ipsilateral upper extremity), scalp and cranium may be severely burned focally with apparently minimal penetration of brain by electricity.

In more transverse courses involving the head (especially where entrance and exit are of opposite sides of the skull) or where the cranial resistance is overcome, more direct cerebral effects occur. Most commonly this results in paralysis of medullary respiratory centers. Spinal cord may also be implicated, commonly in cervical region, by course of electricity from one upper extremity to another.

As seen below, the effects of electric currents are related to the amounts of current which flow and not specifically to the voltages applied. It is fortunate that in most electrical accidents, the contact of the body with the source of voltage is not perfect, and the contact resistance cuts down the amount of current flowing. Paradoxically, it has been shown that a moist skin with low resistance may divert a current to cause only skin burns when it otherwise may have entered the body to damage vital organs (16).

Voltage

The voltage of the circuit is usually the only accurately known factor in electrical shock accidents. The resistance that is offered by the human body depends upon so many parameters that it is difficult to form an estimate of the energy involved in the shock. If, however, the voltage is high enough to break down the contact resistance, and the current path through the individual is from hand to foot, or hand to hand, it is possible to estimate the value of the current on the basis of the resistances of the man's body.

In air at sea level, it requires a potential difference of about 35 KV (crest) for a power source to spark a distance of one inch (17). Therefore, there is only a slight chance that electricity will jump to a man unless he is careless and gets too close to the live circuit. There is, however, the possibility that he may touch a power source and, as he pulls or falls away, an electric arc may be formed between his body and the circuit.

Voltage parameters are divided into two groups, low and high, with 1,000 volts as the borderline (16). The external pathology is much more extensive when a person is exposed to high voltages than when a current at 100 to 200 volts passes through his body. The electric arc which usually leaps from the conductor to the body in high tension currents has a temperature of 2,500 to 3,000°C and melts even bone. The victim is often thrown away from the conductors due to the severe contraction of the muscles. Specific effects of high voltage shocks are related to contact sites and other variables (4). Figure 5-7c presents tentative lethal voltages for ventricular fibrillation as a function of duration of current under accidental wet contacts.

Amperage

The intensity (amperage) of an electric current is the relationship between its tension (voltage) and the resistance of the conductors - in the case of electric shock, the human body. The amperage, therefore, gives a more accurate account of the action of the current in the body than the voltage. In its passage through the body, electrical currents encounter the high resistance of the skin, which is surpassed only by that of the bone. Compared to the skin, the resistance of the internal organs can be neglected. Figure 5-3 shows the interrelations between resistance, 60 Hz voltage, current, and zones for the

various degrees of shock. A resistance of 100,000 ohms, which is about normal dry hand-to-hand touch value, gives a just-perceptible shock of 1.2 ma from a 120 volt system. The sensation produced by an electric shock depends, to a large extent, on the current density at the points of contact with the circuit. If the current density at the point of contact is low, there is no sensation of a shock. It is the value and frequency of the current, its duration, and its pathway through the body that is mainly responsible for the injuries received. If there are no vital organs in its path (two points on same leg or arm, or between the two feet), the injuries are usually limited to burns in those areas. With higher voltages and the same resistance, the currents quickly mount from perceptible to paralytic to fibrillating.

The data of Figure 5-3 are estimates of physiological thresholds taken from several studies (9, 23, 26). They are based on: current flow from arm to arm or arm to leg; one hundred fifty lb subjects - heavier subjects have lighter threshold currents in direct proportion to weight; and fibrillation current for 5 second shock duration.

At the right side of Figure 5-3, the 10 ampere line indicates burning due to overheating and boiling of water. This is the major danger in high voltage shocks. The skin is almost always punctured by the heavy current; 500 ohms is generally the applicable body resistance. Under this condition, voltages above about 2300 are burn-hazardous and are generally less likely to be fatal than voltages from 120 to 2300 v. The danger in the high voltage area is in possible burning damage of vital organs, rather than fibrillation, and statistically is not as dangerous as that of the lower voltage area (26). The range of amperage effects is seen in Table 5-4.

A general estimate of the current value may be made when the victim's reaction to a 60 Hz AC electric shock, his injuries, the current pathway through the body, the shock duration, and the voltage are known (17, 23). A man may be "frozen" to a circuit or he may be thrown away, depending upon whether his flexor muscles, or his extensor muscles, are first stimulated by the shock. If his flexor muscles are paralyzed and he cannot release his hold on the circuit, the amount of current flowing through the muscles of his hand is usually between 12 and 30 milliamperes. When the victim is unconscious but breathing, and has a pulse, the current was probably between 30 and 100 milliamperes. If the shock is at low voltage and the victim is unconscious, not breathing, and pulseless, his heart is probably in ventricular fibrillation, and the current range lies between 60 milliamperes and 4 amperes. If the victim is unconscious, not breathing, but has a pulse, the current through his trunk probably exceeded 10 amperes.

If the current flow through the brain is sufficient, unconsciousness occurs. With currents of 300 to 1200 milliamperes (70 to 150 volts applied across the head through good contact electrodes lasting for 0.1 to 0.5 seconds, such as used in electric shock therapy) unconsciousness is immediate and is followed by convulsive seizures. Coma, stupor, or confusional states are not unusual following electroshock. The current used in therapeutic electroshock is about 200-1600 milliamperes, 50-60 Hz AC at 70-130 volts for 0.1-0.5 seconds. Clinical reports state the duration of the confusional period as ranging from seconds up to several hours and even days (2, 16). After

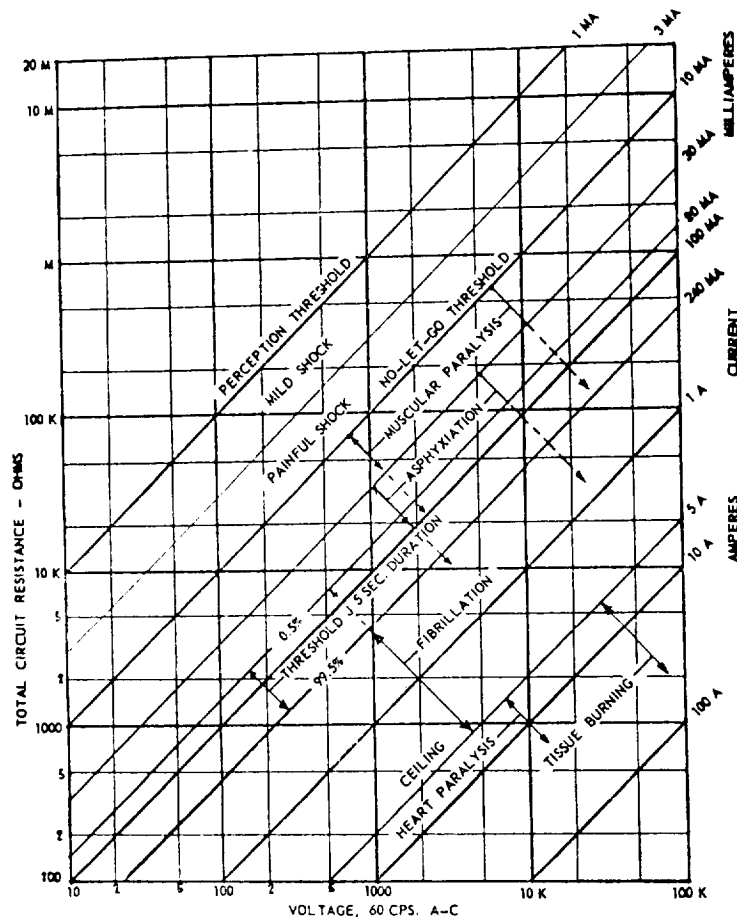


Figure 5-3

Range of Physiological Effects of 60 Hz AC on 150-lb Human

(After Lee⁽²⁶⁾ from the data of Kouwenhoven and Milnor⁽²³⁾
 Daiziel⁽⁹⁾, and Morse⁽³¹⁾)

Table 5-4

Range of Current Sensitivity of 150-lb Man at 60 Hz AC

(After Lee⁽²⁶⁾)

Imperceptible	0 - 1 ma
Perceptible, Mild	1 - 3 ma
Annoying, Painful	3 - 10 ma
Paralyzing, "no-let-go"	> 10 ma
Asphyxiation, Unconsciousness	> 30 ma
Fibrillation, Loss of Circulation	80/240 ma - 4a(5 sec.)
Heart Paralysis Threshold	4a approx.
Burning, Heat Damage	> 5a

three to five treatments, EEG alterations are persistent, increasing up to 6 and 12 treatments, reaching a plateau at that level. These changes are diffuse and disappear gradually in weeks after treatments cease, lingering in proportion to the number of treatments given (1).

Frequency Factors

The median threshold of sensation for direct current of over 100 adult men and women is 1.43 milliamperes as compared to 1.0 for 60 Hz AC (17). Other factors equal, alternating current is approximately three times more injurious than direct current (1) (see Table 5-5). Direct current under 220 volts seldom leads to death whereas even 25 volts alternating current may be dangerous (tetanization of respiratory muscles) if the body is well grounded.

Table 5-5
Comparative Effects of AC and DC Currents Given on the Thorax
(Modified from Aita⁽¹⁾)

Direct Current Voltage 110-800	Alternating Current Voltage 110-380, 50-60 cps	Effect
Under 80 milliamp.	Under 25 milliamp.	Slight contracture of respiratory muscles
80-300 milliamp.	25-80 milliamp.	Respiratory muscle spasm. ac: If duration over 30 sec., cardiac arrest followed by ventricular fibrillation. dc: Ventricular fibrillation only if precise course through heart.
	80 milliamp. to 3 amp.	ac: Ventricular fibrillation if over 1 sec.
300 milliamp. to 3 amp.	voltage 3000 and over; over 3 amps.	Respiratory muscle spasm. Cardiac arrest. Serious burns if over few seconds.

Sixty Hz is about the worst possible frequency as far as human safety is concerned. It appears that humans are about five times as sensitive to 60 to 400 Hz as to DC, but more studies are in progress on this point (17). At 10,000 Hz, however, sensitivity is about the same as for DC, and appears to decrease still farther as the frequency is increased, probably due to the skin effect keeping the bulk of the current on the skin, or at least just under the skin. Frequencies above 100,000 Hz do not produce the pricking sensation of low frequency shocks; instead the sensation is one of warmth or heat (17). There, are, however, few data available as to the trauma that may be produced by the continued passage of high frequency current through the body for long periods.

Table 5-6 outlines the relative effect of different frequencies in perception of shock and paralysis normalized to 60 Hz = 1.0.

Table 5-6
 Effect of Frequency (Hz) on Perception and Paralysis
 (fraction of 60 Hz effect)
 (After Lee⁽²⁶⁾)

<u>f(Hz)</u>	<u>effect</u>
0	0.2
10	0.9
60	1.0
300	0.8
1000	0.6
10,000	0.2
RF	0.01

The frequency sensitivity of "let-go" current is seen in Figure 5-10.

Death from electrical injuries is usually due to cardiac or respiratory arrest (4). In most instances, cardiac arrest results from ventricular fibrillation. Respiratory arrest may be due to direct effects of the current on the respiratory center, or secondary to hypoxia of the cells of the center due to inadequate perfusion as a result of the ventricular fibrillation.

Organ Damage by Electric Current

Organs vary greatly in sensitivity and pathological response to electric currents (16, 30). The following summary is far from comprehensive and is intended only as a reference source for planning for emergency procedures after operational accidents:

The Central Nervous System

Organic damage to the nervous system occurs in that portion of the brain or spinal cord where the current passes through. It is not specific and sometimes is similar to that found in other types of cerebral injuries (1, 10, 13, 24).

Post mortem studies indicate that electrical injuries to the nervous system can be summarized as follows:

- mild and severe cellular alterations, from swelling to liquification,
- rupture of the walls of the blood vessels, mainly of the internal elastic membrane,
- shrinkage, thinning, and breaking up of the cerebral parenchyma with the formation of tears, slits or fissures.

Following accidental electroshock, hypoxia and heat damage are likely the causes of permanent neurologic sequelae and pathological changes seen in the occasional patient (1). A diffuse and massive charge of electricity through the brain causes damage by generalized heating. In many instances, the electrical energy dissipates mostly at the scalp and cranium with a burn;

little if any electricity passing through the brain. Many of these patients surviving have no cerebral sequelae; some have a post-concussion syndrome; a small percentage incur burns deep enough to involve dura and brain at a local site; rarely epidural infection occurs.

Whether isolated cerebrovascular insults may be blamed on electricity is uncertain. Focal thrombosis and hemorrhage have been cited and the problem is much like that seen following direct craniocerebral trauma. One is left to presume that electricity may injure intracranial blood vessels.

Electricity may pass through the spinal cord transversely, obliquely or longitudinally, resulting in many different cord syndromes. Transient deficits are not unusual. Permanent defects may remain, of which syndromes from loss of anterior horn cells are common.

Peripheral nerves likewise may be transiently paralyzed or more permanently damaged by heat-effects from passage of current or by outright burns. Violent tetanic action, falls or blows may also contribute to vertebral and nerve injury.

The Skin

In the skin, with its high resistance, the most marked changes are produced (4, 29, 30). Current effects on the skin are twofold. First, in passing through the skin, the electric energy is transformed into heat which alters the structures along the path of the current. Second, free discharge causes the formation of electric sparks which leads to the formation of third degree burns.

Electrothermal burns have no consistent gross or microscopic characteristics by which they may be distinguished from other hyperthermal injuries (30). Arcing of the current may produce pitlike defects on the surface of hair or epidermis that are rarely, if ever, produced by other forms of heat. Metallic constituents of the external conductor may be deposited in or on the surface of an electrical burn, and their presence may help to establish the kind of an electrode with which the skin was in contact. In the case of alternating current such metallic deposits may be present at both sites of contact. With direct current the deposits will occur only at the site of contact with the negative electrode.

Contact with such a superheated conductor will cause severe and instantaneous burning even though no electricity flows through the skin. Rarely does a current of 110 volts produce a large electrothermal injury of the skin unless the contact is maintained for a considerable period of time. Fern-like markings of pink color are often seen after lightning strikes. The color intensifies post mortem. All severity of burns up to severe charring may be seen after lightning or high voltage arc strikes.

The Voluntary Muscles

In traversing the body, AC currents cause tetanic contractions of the entire musculature. Very often, the body of an electrocuted person is bent

in extreme extension or opisthotonos. The muscular spasm may be so intensive as to cause disruption of muscles, luxation of joints and, rarely, fractures of bones.

The Bones

In high tension accidents in which the current enters the body through the skull, lesions of the bone are common. In some cases the electric arc burns a deep hole in the bone, and the meninges and the brain, too, may be affected. In other cases of less severe types of accidents, the bone is often exposed by the destruction of the soft tissues. The high resistance of the bone, no doubt, gives rise to the formation of an intensive heat (16). When an arc jumps to several small places on a victim's arms or legs, deep sinuses and osteomyelitis may develop (17).

The Blood Vessels

The walls of blood vessels through which a current has passed long enough to cause necrotic change become brittle and friable. The inner endothelial lining of the vessel undergoes changes and parietal thrombi are attached to the intima. The great vulnerability of the vessels accounts for the severe hemorrhages as complications of electrical injuries (16).

The Eye

The changes observed on the eyes are usually late complications of electrical injuries. The so-called electric cataract has been described by several authors and occurs chiefly in lightning cases where the current enters the body through the head (16, 17).

The Heart

Ventricular fibrillation is affected by three factors: a sufficient current density, a low or medium voltage and duration of contact which may very well be short. Currents over 6 amperes (see Figures 5-3 and 5-7; Equations 9 and 10) have a different effect on the myocardium. They do not cause ventricular fibrillation, but cardiac standstill, mostly in systole. Blood pressure falls when these high currents are on, but heart usually resumes beating and reestablishes circulation when the current is turned off (23). Autopsies performed on electrocuted persons usually show no anatomic lesions of the heart (16).

Limits of Tolerance to Electric Currents

Figure 5-3 and Tables 5-4 to 5-6 give a rough estimate of critical thresholds for functional damage caused by electric currents. The following are more refined time-dependent thresholds which can be used for extrapolation in setting safety and design standards for unusual electrical equipment or conditions.

Short Shocks and Discharge Thresholds

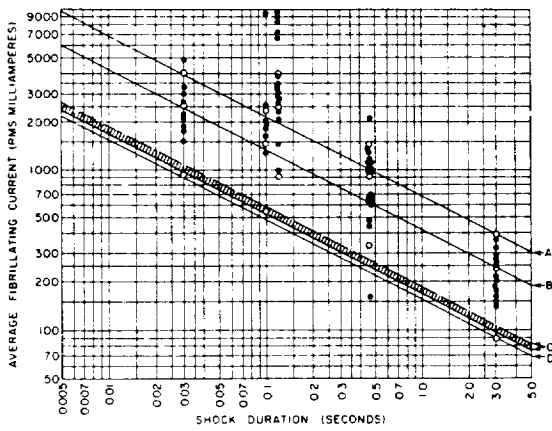
Tentative criteria for the hazard from short shocks and impulse discharges are presented in Figure 5-7 (10). The threshold of danger is taken as the minimum shock likely to produce ventricular fibrillation in a large group of normal men (10). One method of extrapolation from animal data is shown in Figure 5-7a. The data points represent results obtained from experiments on sheep using 60 Hz alternating current with shock durations from 0.03 to 3.0 seconds. Several animal species were used to establish the relationship of fibrillating current to body weight, and the cross-hatched areas designated by C represent the probable response for all 70 kilogram animals, including man.

It has been recently pointed out that for AC shocks of one to five seconds' duration, there probably is no significant difference between the threshold values at about 80 milliamps as all of these shocks cover an entire heart cycle (19, 33). Figure 5-7b shows a review of animal data from many investigators for 50 and 60 Hz AC as well as condenser discharges. With two exceptions, all tests with fatal shock lie above the 100 mAs (maximum amplitude) value, noted here as the upper boundary of the range ($Q = 100 \text{ mA} \cdot \text{sec}$). The points below the upper boundary represent curarized animals or tests performed under anomalous conditions (from Figure 5-7a) where each animal was given shocks of increasing current strength until ventricular fibrillation resulted, which was then stopped by electric de-fibrillation. After a brief period of recuperation, the animal was again subjected to shock and the resulting ventricular fibrillation was again stopped by electrical counter-shocks. Tests continued until ventricular fibrillation could no longer be stopped. Since some of these test data were disregarded in plotting the 0.5% fibrillation threshold line of Figure 5-7a, it seemed unwarranted to consider these values in establishing threshold ranges. The 0.5% line in Figure 5-7a (dashed line in Figure 5-7b) resulted from an attempt to establish the probable lower boundary at which lethal fibrillation can still occur. The slope of the straight dashed line of Figure 5-7b appears to be flat, since a large proportion of ventricular fibrillation cases observed with a current passage duration of $> 0.4 \text{ sec}$. are not taken into account. On the other hand, except for the cases mentioned above, all other animal test data found in the literature are compatible with the interpretation that the ventricular fibrillation current threshold is constant beyond 1 second.

Using lower current threshold for range III of Figure 5-7b and the body resistances obtained under the most unfavorable conditions for three different current paths (12), the voltage and time relation can be determined and plotted as Figure 5-7c. The resulting curves represent the boundaries of three current paths for the lethally dangerous voltage as a function of duration under accidental conditions of wet contact over a large area. If the most commonly encountered current path II is used as the criterion of the safe contact voltage, this curve above the 1-sec. duration shows good agreement with the German Electrical Engineering Society's safety voltage of 65 V_{eff} (33). The acceptance of these newer curves by any national or international standards group remains for the future.

Figure 5-7

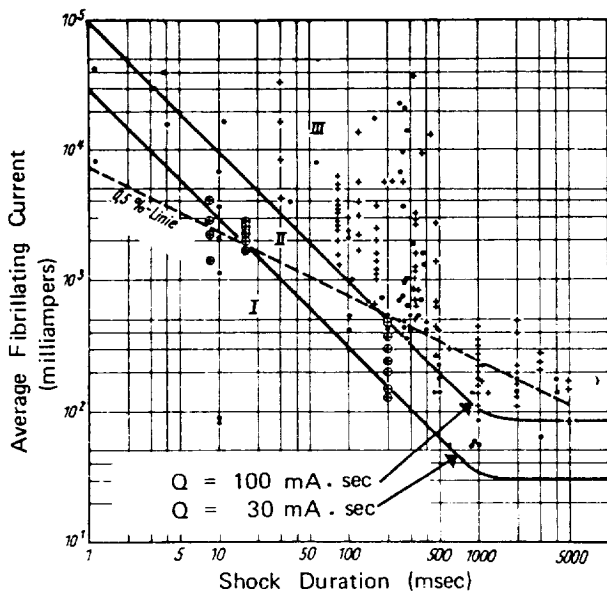
Ventricular Fibrillation Thresholds for Alternating Current



a. Typical Method of Extrapolation from Animal Data for 60 Hz AC

- Experimental points
- Calculated points
- A 99 1/2-per-cent line for 57.4-kg sheep
- B 50-per-cent line for 57.4-kg sheep
- C 1/2-per-cent line for all 70-kg animals including man
- D 1/2-per-cent line for 57.4-kg sheep

(After Dalziel⁽¹⁰⁾)

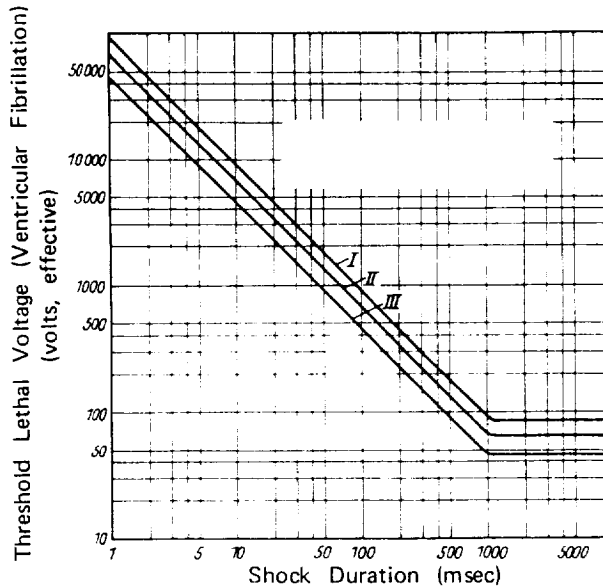


- + lethal ventricular fibrillation
- nonlethal
- ⊙ inexact data or animals with heart damage

b. Comparison of the Fibrillation Current Ranges with Animal Test Data Found in Literature for 50 and 60 Hz AC and Condenser Discharges

The dashed line represents the 0.5% line of Figure 5-7a(C)

(After Osypka⁽³³⁾)



- I current path Hand-trunk-hand (1300 ohms)
- II current path Hand-trunk-feet (970 ohms)
- III current path Hands-trunk-feet (650 ohms)

c. Lethal Voltages for Ventricular Fibrillation (100 mA·sec) as Function of Duration Under Unfavorable Accidental Conditions of Wet Contact Over Large Body Area (See text)

(After Osypka⁽³³⁾)

Figure 5-8 shows the relationship of theoretical initial current and time constant to the threshold for human accidents resulting from capacitor discharges (8). Short shocks, whose durations are a small fraction of a second, are particularly dangerous if they occur during the T-wave phase of the electrical heart cycle (17). A shock through hand to foot of about one ampere, and of a duration of 0.01 seconds occurring in the T phase, may put a human heart into ventricular fibrillation. The same shock, falling outside of the T phase, will have a transient effect on the heart. Atrial flutter or fibrillation is rare in electric shock cases (17). Small shocks just preceding the refractory phase of the heart cycle may cause atrial fibrillation (3).

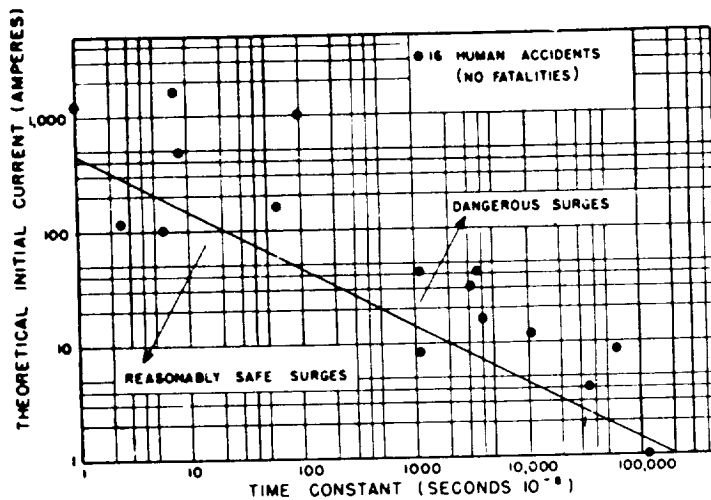


Figure 5-8

Proposed Criterion for Reasonably Safe Surge Currents and Points
Representing 16 Human Capacitor Surge Accidents.
(Based on 50-watt-second discharges)

(After Dalziel⁽⁸⁾)

Constant Current Thresholds

Figure 5-9 shows distribution curves for men and women for effects brought about by exposure to a 60 Hz current (14). The experimental points are defined as the maximal current the subjects are able to tolerate when holding a copper conductor in one hand and yet let go of the conductor by using muscles directly affected by that current, i. e., "let go" current and thresholds.

Figure 5-10 is a plot of frequency in cycles per second versus let-go currents.

From these curves it can be concluded that a reasonably safe electric current for normal healthy adults is the let-go current which 99 1/2 percent of a large group can release by using muscles directly affected by that current.

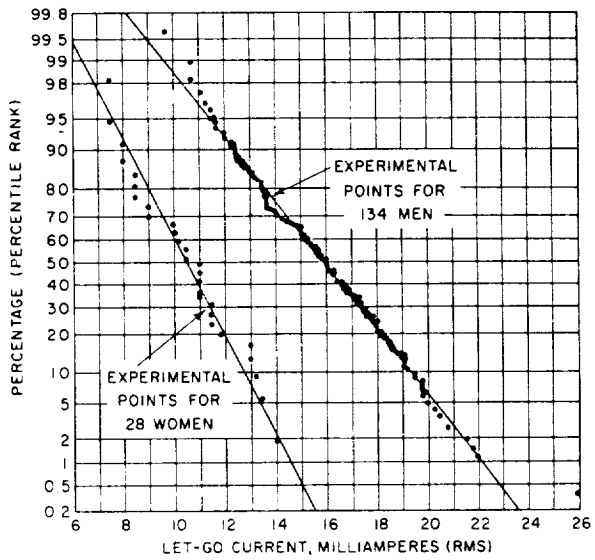


Figure 5-9

Distribution Curves for Men and Women of "Let-go" Current Thresholds at 60 Hz. (See text)

(After Dalziel⁽¹¹⁾)

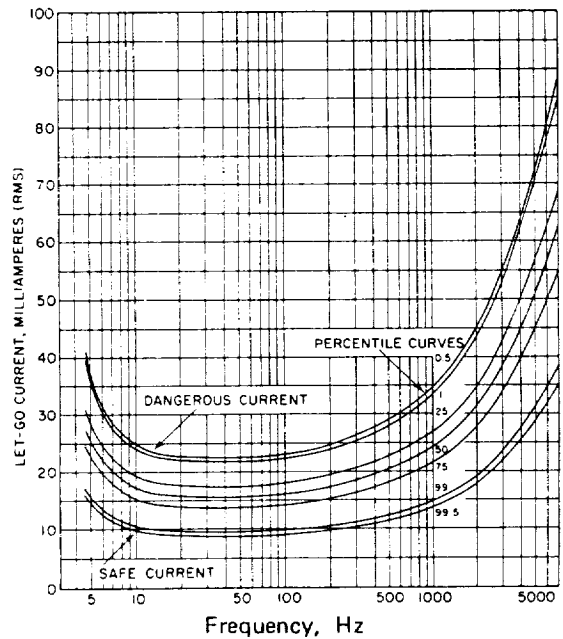


Figure 5-10

Sine-wave "Let-go" Current for Men Versus Frequency

(After Dalziel⁽¹¹⁾)

The reasonably safe 60 Hz AC current for most normal healthy adult men is about nine milliamperes; the reasonably safe 60 Hz current for most normal healthy adult women is about six milliamperes. Let-go currents are affected by frequency. Frequencies of 10-200 Hz appear to be the most dangerous. In interpreting these let-go curves it should be kept in mind that with currents exceeding the no-let-go threshold, the skin at the contacts tends to develop blisters quickly, which reduces the skin resistance, allowing the current to increase. So while the dry skin resistance (Figure 5-2) is applicable up to the "no-let-go" threshold, it should be modified to "wet skin" criteria after that threshold is passed.

The fibrillation threshold for constant current at 60 Hz given arm to leg is seen in Figure 5-3. The data indicating sensitivity to amperage and to shock duration are based on tests on guinea pigs, dogs, sheep, and calves. It was found that the weight relationship held quite well even between animals of different species, as well as for animals of the same species, but of different weights. There are two fibrillation lines, one at which 0.5% of the population is affected and one at which 99.5% is affected. Since there has, as yet, been developed no way to predetermine one's susceptibility, the 0.5% line must be assumed to be the applicable one. Likewise, the 5 second time is generally assumed although the great majority of shocks are of very short duration, muscular reaction throwing the victim free. Experimental data on times over 5 seconds are not available, so it is not known whether extrapolation is justifiable. It has been suggested that a rough evaluation of constant current thresholds may be determined by the equations (26):

$$0.5\% \text{ Probability Current} = \frac{W}{150} \times \frac{165}{\sqrt{t}} \text{ ma} \quad (9)$$

$$99.5\% \text{ Probability Current} = \frac{W}{150} \times \frac{165 \times 3}{\sqrt{t}} \text{ ma} \quad (10)$$

where w = weight, pounds

t = times, seconds (5 sec. max.)

For leg to leg shocks, multiply these currents by 10. Equations 9 and 10 must be used with the appropriate circumspection and knowledge that the human accident does not always fit the equation (17).

The frequency dependence of threshold fibrillating current is not as clearly defined as "let-go" current. It has been suggested that fibrillation threshold current at 0 and 10,000 Hz is 130% of 60 Hz value at and below 0.1 sec. The threshold of 500 ma at 0.1 sec. is conservative for longer times. Between 10 and 1000 Hz, the 60 Hz values should be assumed (26).

Currents of ten or more amperes, flowing from hand to foot, will hold the heart in asystole as long as the current continues to flow. When the circuit is broken the heart will often return to normal sinus rhythm. If, however, the shock was a long one, the heart may remain in standstill.

Safety and Emergency Practices

Safety practices involving electrical equipment have received recent review (6, 10, 26, 37). Electrical safety in hazardous atmospheric environments have also been recently summarized (7, 15, 28, 32).

The emergency treatment following electrical injury include prolonged cardiopulmonary resuscitation; cardiac massage; defibrillation; and hypothermia for severe hypoxia (1, 9, 20, 21, 23, 27). Cerebral edema may be managed by hypertonic urea intravenously or by hypothermia. Closed-chest defibrillation is accomplished by 5-7 amperes at 400-500 volts in 0.1-0.2 second shocks (300 joules or watt-seconds) from manubrium sterni to apex of heart, allowing approximately 1.5 amperes to flow through the heart. Safety precautions must be followed in this procedure (14).

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