ELECTRICITY-PHYSIOLOGICAL EFFECTS

Dominique Folliot

The study of the hazards, electrophysiology and prevention of electrical accidents requires an understanding of several technical and medical concepts.

The following definitions of electrobiological terms are taken from chapter 891 of the International Electrotechnical Vocabulary (Electrobiology) (International Electrotechnical Commission) (IEC) (1979).

An *electrical shock* is the physiopathological effect resulting from the direct or indirect passage of an external electrical current through the body. It includes direct and indirect contacts and both unipolar and bipolar currents.

Individuals-living or deceased-having suffered electrical shocks are said to have suffered *electrification*; the term *electrocution* should be reserved for cases in which death ensues. *Lightning strikes* are fatal electrical shocks resulting from lightning (Gourbiere et al. 1994).

International statistics on electrical accidents have been compiled by the International Labour Office (ILO), the European Union (EU), the *Union internationale des producteurs et distributeurs d'énergie électrique* (UNIPEDE), the International Social Security Association (ISSA) and the TC64 Committee of the International Electrotechnical Commission. Interpretation of these statistics is hampered by variations in data collection techniques, insurance policies and definitions of fatal accidents from country to country. Nevertheless, the following estimates of the rate of electrocution are possible (table 40.1).

Table 40.1 Estimates of the rate of electrocution - 1988

	Electrocutions per million inhabitants	**Total deaths**
United States*	2.9	714
France	2.0	115
Germany	1.6	99
Austria	0.9	11
Japan	0.9	112
Sweden	0.6	13

* According to the National Fire Protection Association (Massachusetts, US) these US statistics are more reflective of extensive data collection and legal reporting requirements than of a more dangerous environment. US statistics include deaths from exposure to public utility transmission systems and electrocutions caused by consumer products. In 1988, 290 deaths were caused by consumer products (1.2 deaths per million inhabitants). In 1993, the rate of death by electrocution from all causes dropped to 550 (2.1 deaths per million inhabitants); 38% were consumer product-related (0.8 deaths per million inhabitants).

The number of electrocutions is slowly decreasing, both in absolute terms and, even more strikingly, as a function of the total consumption of electricity. Approximately half of electrical accidents are occupational in origin, with the other half occurring at home and during leisure activities. In France, the average number of fatalities between 1968 and 1991 was 151 deaths per year, according to the *Institut national de la sante et de la recherche medicale* (INSERM).

Physical and Physiopathological Basis of Electrification

Electrical specialists divide electrical contacts into two groups: direct contacts, involving contact with live components, and indirect contacts, involving grounded contacts. Each of these requires fundamentally different preventive measures.

From a medical point of view, the current's path through the body is the key prognostic and therapeutic determinant. For example, bipolar contact of a child's mouth with an extension cord plug causes extremely serious burns to the mouth-but not death if the child is well insulated from the ground.

In occupational settings, where high voltages are common, arcing between an active component carrying a high voltage and workers who approach too closely is also possible. Specific work situations can also affect the consequences of electrical accidents: for example, workers may fall or act inappropriately when surprised by an otherwise relatively harmless electrical shock.

Electrical accidents may be caused by the entire range of voltages present in workplaces. Every industrial sector has its own set of conditions capable of causing direct, indirect, unipolar, bipolar, arcing, or induced contact, and, ultimately, accidents. While it is of course beyond the scope of this article to describe all human activities which involve electricity, it is useful to remind the reader of the following major types of electrical work, which have been the object of international preventive guidelines described in the chapter on prevention:

1. activities involving work on live wires (the application of extremely rigorous protocols has succeeded in reducing the number of electrifications during this type of work)
2. activities involving work on unpowered wires, and
3. activities performed in the vicinity of live wires (these activities require the most attention, as they are often performed by personnel who are not electricians).

Physiopathology

All the variables of Joule's law of direct current-

$$W = V \times I \times t = RI^2t$$

(the heat produced by an electric current is proportional to the resistance and the square of the current)-are closely interrelated. In the case of alternating current, the effect of frequency must also be taken into account (Folliot 1982).

Living organisms are electrical conductors. Electrification occurs when there is a potential difference between two points in the organism. It is important to emphasize that the danger of electrical accidents arises not from mere contact with a live conductor, but rather from simultaneous contact with a live conductor and another body at a different potential.

The tissues and organs along the current path may undergo functional motor excitation, in some cases irreversible, or may suffer temporary or permanent injury, generally as a result of burns. The extent of these injuries is a function of the energy released or the quantity of electricity passing through them. The transit time of the electric current is therefore critical in determining the degree of injury. (For example, electric eels and rays produce extremely unpleasant discharges, capable of inducing a loss of consciousness. However, despite a voltage of 600V, a current of approximately 1A and a subject resistance of approximately 600 ohms, these fish are incapable of inducing a lethal shock, since the discharge duration is too brief, of the order of tens of microseconds.) Thus, at high voltages (>1,000V), death is often due to the extent of the burns. At lower voltages, death is a function of the amount of electricity ($Q=I \times t$), reaching the heart, determined by the type, location and area of the contact points.

The following sections discuss the mechanism of death due to electrical accidents, the most effective immediate therapies and the factors determining the severity of injury-namely, resistance, intensity, voltage, frequency and wave-form.

Causes of Death in Electrical Accidents in Industry

In rare cases, asphyxia may be the cause of death. This may result from prolonged tetanus of the diaphragm, inhibition of the respiratory centres in cases of contact with the head, or very high current densities, for example as a result of lightning strikes (Gourbiere et al. 1994). If care can be provided within three minutes, the victim may be revived with a few puffs of mouth-to-mouth resuscitation.

On the other hand, peripheral circulatory collapse secondary to ventricular fibrillation remains the main cause of death. This invariably develops in the absence of cardiac massage applied simultaneously with mouth-to-mouth resuscitation. These interventions, which should be taught to all electricians, should be maintained until the arrival of emergency medical aid, which almost always takes more than three minutes. A great many electropathologists and engineers around the world have studied the causes of ventricular fibrillation, in order to design better passive or active protective measures (International Electrotechnical Commission 1987; 1994). Random desynchronization of the myocardium requires a sustained electric current of a specific frequency, intensity and transit time. Most importantly, the electrical signal must arrive at the myocardium during the so-called *vulnerable phase of the cardiac cycle*, corresponding to the start of the T-wave of the electrocardiogram.

The International Electrotechnical Commission (1987; 1994) has produced curves describing the effect of current intensity and transit time on the probability (expressed as percentages) of fibrillation and the hand-foot current path in a 70-kg male in good health. These tools are appropriate for industrial currents in the frequency range of 15 to 100 Hz, with higher frequencies currently under study. For transit times of less than 10 ms, the area under the electrical signal curve is a reasonable approximation of the electrical energy.

Role of Various Electrical Parameters

Each of the electrical parameters (current, voltage, resistance, time, frequency) and wave-form are important determinants of injury, both in their own right and by virtue of their interaction.

Current thresholds have been established for alternating current, as well as for other conditions defined above. The current intensity during electrification is unknown, since it is a function of tissue resistance at the moment of contact $(I = V/R)$, but is generally perceptible at levels of approximately 1 mA. Relatively low currents can cause muscular contractions that may prevent a victim from letting go of an energized object. The threshold of this current is a function of condensity, contact area, contact pressure and individual variations. Virtually all men and almost all women and children can let go at currents up to 6 mA. At 10 mA it has been observed that 98.5% of men and 60% of women and 7.5% of children can let go. Only 7.5% of men and no women or children can let go at 20mA. No one can let go at 30mA and greater.

Currents of approximately 25 mA may cause tetanus of the diaphragm, the most powerful respiratory muscle. If contact is maintained for three minutes, cardiac arrest may also ensue.

Ventricular fibrillation becomes a danger at levels of approximately 45 mA, with a probability in adults of 5% after a 5-second contact. During heart surgery, admittedly a special condition, a current of 20 to 100×10^{-6} A applied directly to the myocardium is sufficient to induce fibrillation. This myocardial sensitivity is the reason for strict standards applied to electromedical devices.

All other things (V, R, frequency) being equal, current thresholds also depend on the wave-form, animal species, weight, current direction in the heart, ratio of the current transit time to the cardiac cycle, point in the cardiac cycle at which the current arrives, and individual factors.

The voltage involved in accidents is generally known. In cases of direct contact, ventricular fibrillation and the severity of burns are directly proportional to voltage, since

$$V = RI \quad \text{and} \quad W = V \times I \times t$$

Burns arising from high-voltage electric shock are associated with many complications, only some of which are predictable. Accordingly accident victims must be cared for by knowledgeable specialists. Heat release occurs primarily in the muscles and neurovascular bundles. Plasma leakage following tissue damage causes shock, in some cases rapid and intense. For a given surface area, electrothermic burns-burns caused by an electrical current-are always more severe than other types of burn. Electrothermic burns are both external and internal and, although this may not be initially apparent, can induce vascular damage with serious secondary effects. These include internal stenoses and thrombi which, by virtue of the necrosis they induce, often necessitate amputation.

Tissue destruction is also responsible for the release of chromoproteins such as myoglobin. Such release is also observed in victims of crush injuries, although the extent of release is remarkable in victims of high-voltage burns. Myoglobin precipitation in renal tubules, secondary to acidosis brought on by anoxia and hyperkalaemia, is thought to be the cause of anuria. This theory, experimentally confirmed but not universally accepted, is the basis for recommendations for immediate alkalization therapy. Intravenous alkalization, which also corrects hypovolaemia and acidosis secondary to cell death, is the recommended practice.

In the case of indirect contacts, the contact voltage (V) and conventional voltage limit must also be taken into account.

The contact voltage is the voltage to which a person is subjected on simultaneously touching two conductors between which a voltage differential exists due to defective insulation. The intensity of the resultant current flow depends on the resistances of the human body and the external circuit. This current should not be allowed to rise above safe levels, which is to say that it must conform to safe time-current curves. The highest contact voltage that can be tolerated indefinitely without inducing electropathological effects is termed the *conventional voltage limit* or, more intuitively, the *safety voltage.*

The actual value of the resistance during electrical accidents is unknown. Variations in in-series resistances-for example, clothes and shoes-explain much of the variation observed in the effects of ostensibly similar electrical accidents, but exert little influence on the outcome of accidents involving bipolar contacts and high-voltage electrifications. In cases involving alternating current, the effect of capacitive and inductive phenomena must be added to the standard calculation based on voltage and current (R=V/I).

The resistance of the human body is the sum of the skin resistance *(R)* at the two points of contact and the body's internal resistance *(R)*. Skin resistance varies with environmental factors and, as noted by Biegelmeir (International Electrotechnical Commission 1987; 1994), is partially a function of the contact voltage. Other factors such as pressure, contact area, the state of the skin at the point of contact, and individual factors also influence resistance. It is thus unrealistic to attempt to base preventive measures on estimates of skin resistance. Prevention should instead be based on the adaptation of equipment and procedures to humans, rather than the reverse. In order to simplify matters, the IEC has defined four types of environment-dry, humid, wet and immersion-and has defined parameters useful for the planning of prevention activities in each case.

The frequency of the electrical signal responsible for electrical accidents is generally known. In Europe, it is almost always 50 Hz and in the Americas, it is generally 60 Hz. In rare cases involving railways in countries such as Germany, Austria and Switzerland, it may be $16^{2/3}$ Hz, a frequency which theoretically represents a greater risk of tetanization and of ventricular fibrillation. It should be recalled that fibrillation is not a muscle reaction but is caused by repetitive stimulation, with a maximum sensitivity at approximately 10 Hz. This explains why, for a given voltage, extremely low-frequency alternating current is considered to be three to five times more dangerous than direct current with regard to effects other than burns.

The thresholds described previously are directly proportional to the frequency of the current. Thus, at 10 kHz, the detection threshold is ten times higher. The IEC is studying revised fibrillation hazard curves for frequencies above 1,000 Hz (International Electrotechnical Commission 1994).

Above a certain frequency, the physical laws governing penetration of current into the body change completely. Thermal effects related to the amount of energy released become the main effect, as capacitive and inductive phenomena start to predominate.

The wave-form of the electrical signal responsible for an electrical accident is usually known. It may be an important determinant of injury in accidents involving contact with capacitors or semiconductors.

Clinical Study of Electric Shock

Classically, electrifications have been divided into low- (50 to 1,000 V) and high- (>1,000 V) voltage incidents.

Low voltage is a familiar, indeed omnipresent, hazard, and shocks due to it are encountered in domestic, leisure, agricultural and hospital settings as well as in industry.

In reviewing the range of low-voltage electric shocks, from the most trivial to the most serious, we must start with uncomplicated electrical shock. In these cases, victims are able to remove themselves from harm on their own, retain consciousness and maintain normal ventilation. Cardiac effects are limited to simple sinus tachycardia with or without minor electrocardiographic abnormalities. Despite the relatively minor consequences of such accidents, electrocardiography remains an appropriate medical and medico-legal precaution. Technical investigation of these potentially serious incidents is indicated as a complement to clinical examination (Gilet and Choquet 1990).

Victims of shock involving somewhat stronger and longer-lasting electrical contact shocks may suffer from perturbations or loss of consciousness, but completely recover more or less rapidly; treatment accelerates recovery. Examination generally reveals neuromuscular hypertonias, hyper-reflective ventilation problems and congestion, the last of which is often secondary to oropharyngeal obstruction. Cardiovascular disorders are secondary to hypoxia or anoxia, or may take the form of tachycardia, hypertension and, in some cases, even infarction. Patients with these conditions require hospital care.

The occasional victims who lose consciousness within a few seconds of contact appear pale or cyanotic, stop breathing, have barely perceptible pulses and exhibit mydriasis indicative of acute cerebral injury. Although usually due to ventricular fibrillation, the precise pathogenesis of this apparent death is, however, irrelevant. The important point is the rapid commencement of well-defined therapy, since it has been known for some time that this clinical state never leads to actual death. The prognosis in these cases of electric shock-from which total recovery is possible- depends on the rapidity and quality of first aid. Statistically, this is most likely to be administered by non-medical personnel, and the training of all electricians in the basic interventions likely to ensure survival is therefore indicated.

In cases of apparent death, emergency treatment must take priority. In other cases, however, attention must be paid to multiple traumas resulting from violent tetanus, falls or the projection of the victim through the air. Once the immediate life-threatening danger has been resolved, trauma and burns, including those caused by low-voltage contacts, should be attended to.

Accidents involving high voltages result in significant burns as well as the effects described for low-voltage accidents. The conversion of electrical energy to heat occurs both internally and externally. In a study of electrical accidents in France made by the medical department of the power utility, EDF-GDF, almost 80% of the victims suffered burns. These can be classified into four groups:

1. arc burns, usually involving exposed skin and complicated in some cases by burns from burning clothing
2. multiple, extensive and deep electrothermic burns, caused by high-voltage contacts
3. classical burns, caused by burning clothing and the projection of burning matter, and
4. mixed burns, caused by arcing, burning and current flow.

Follow-up and complementary examinations are performed as required, depending on the particulars of the accident. The strategy used to establish a prognosis or for medico-legal purposes is of course determined by the nature of observed or expected complications. In high-voltage electrifications (Folliot 1982) and lightning strikes (Gourbiere et al. 1994), enzymology and the analysis of chromoproteins and blood clotting parameters are obligatory.

The course of recovery from electrical trauma may well be compromised by early or late complications, especially those involving the cardiovascular, nervous and renal systems. These complications in their own right are sufficient reason to hospitalize victims of high-voltage electrifications. Some complications may leave functional or cosmetic sequelae.

If the current path is such that significant current reaches the heart, cardiovascular complications will be present. The most frequently observed and most benign of these are functional disorders, in the presence or absence of clinical correlates. Arrhythmias-sinus tachycardia, extrasystole, flutter and atrial fibrillation (in that order)-are the most common electrocardiographic abnormalities, and may leave permanent sequelae. Conduction disorders are rarer, and are difficult to relate to electrical accidents in the absence of a previous electrocardiogram.

More serious disorders such as cardiac failure, valve injury and myocardial burns have also been reported, but are rare, even in victims of high-voltage accidents. Clear-cut cases of angina and even infarction have also been reported.

Peripheral vascular injury may be observed in the week following high-voltage electrification. Several pathogenic mechanisms have been proposed: arterial spasm, the action of electrical current on the media and muscular layers of the vessels and modification of the blood clotting parameters.

A wide variety of neurological complications is possible. The earliest to appear is stroke, regardless of whether the victim initially experienced loss of consciousness. The physiopathology of these complications involves cranial trauma (whose presence should be ascertained), the direct effect of current on the head, or the modification of cerebral blood flow and the induction of a delayed cerebral oedema. In addition, medullary and secondary peripheral complications may be caused by trauma or the direct action of electric current.

Sensory disorders involve the eye and the audiovestibular or cochlear systems. It is important to examine the cornea, crystalline lens and fundus of the eye as soon as possible, and to follow up victims of arcing and direct head contact for delayed effects. Cataracts may develop after an intervening symptom-free period of several months. Vestibular disorders and hearing loss are primarily due to blast effects and, in victims of lightning strike transmitted over telephone lines, to electrical trauma (Gourbiere et al. 1994).

Improvements in mobile emergency practices have greatly reduced the frequency of renal complications, especially oligo-anuria, in victims of high-voltage electrifications. Early and careful rehydration and intravenous alkalinization is the treatment of choice in victims of serious burns. A few cases of albuminuria and persistent microscopic haematuria have been reported.

Clinical Portraits and Diagnostic Problems

The clinical portrait of electric shock is complicated by the variety of industrial applications of electricity and the increasing frequency and variety of medical applications of electricity. For a long time, however, electrical accidents were caused solely by lightning strikes (Gourbiere et al. 1994). Lightning strikes may involve quite remarkable quantities of electricity: one out of every three victims of lightning strikes dies. The effects of a lightning strike-burns and apparent death-are comparable to those resulting from industrial electricity and are attributable to electrical shock, the transformation of electrical energy into heat, blast effects and the electrical properties of lightning.

Lightning strikes are three times as prevalent in men as in women. This reflects patterns of work with differing risks for exposure to lightning.

Burns resulting from contact with grounded metallic surfaces of electric scalpels are the most common effects observed in victims of iatrogenic electrification. The magnitude of acceptable leakage currents in electromedical devices varies from one device to another. At the very least, manufacturers' specifications and usage recommendations should be followed.

To conclude this section, we would like to discuss the special case of electric shock involving pregnant women. This may cause the death of the woman, the foetus or both. In one remarkable case, a live foetus was successfully delivered by Caesarian section 15 minutes after its mother had died as a result of electrocution by a 220 V shock (Folliot 1982).

The pathophysiological mechanisms of abortion caused by electric shock requires further study. Is it caused by conduction disorders in the embryonic cardiac tube subjected to a voltage gradient, or by a tearing of the placenta secondary to vasoconstriction?

The occurrence of electrical accidents such as this happily rare one is yet another reason to require notification of all cases of injuries arising from electricity.

Positive and Medico-Legal Diagnosis

The circumstances under which electric shock occurs are generally sufficiently clear to allow unequivocal aetiological diagnosis. However, this is not invariably the case, even in industrial settings.

The diagnosis of circulatory failure following electric shock is extremely important, since it requires bystanders to commence immediate and basic first aid once the current has been shut off. Respiratory arrest in the absence of a pulse is an absolute indication for the commencement of cardiac massage and mouth-to-mouth resuscitation. Previously, these were only performed when mydriasis (dilation of the pupils), a diagnostic sign of acute cerebral injury, was present. Current practice is, however, to begin these interventions as soon as the pulse is no longer detectable.

Since loss of consciousness due to ventricular fibrillation may take a few seconds to develop, victims may be able to distance themselves from the equipment responsible for the accident. This may be of some medico-legal importance-for example, when an accident victim is found several metres from an electrical cabinet or other source of voltage with no traces of electrical injury.

It cannot be overemphasized that the absence of electrical burns does not exclude the possibility of electrocution. If autopsy of subjects found in electrical environments or near equipment capable of developing dangerous voltages reveals no visible Jelinek lesions and no apparent sign of death, electrocution should be considered.

If the body is found outdoors, a diagnosis of lightning strike is arrived at by the process of elimination. Signs of lightning strike should be searched for within a 50-metre radius of the body. The Museum of Electropathology of Vienna offers an arresting exhibition of such signs, including carbonized vegetation and vitrified sand. Metal objects worn by the victim may be melted.

Although suicide by electrical means remains thankfully rare in industry, death due to contributory negligence remains a sad reality. This is particularly true at non-standard sites, especially those involving the installation and operation of provisional electrical facilities under demanding conditions.

Electrical accidents should by all rights no longer occur, given the availability of effective preventive measures described in the article “Prevention and Standards”.