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Human Thresholds of Electric Shock at Power Transmission Frequencies

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Reliable quantitative data about electric shock to humans at power transmission frequencies are available for three physiological responses to electrical stimulation: perception, uncontrollable muscular contraction, and death. Some humans can perceive less than 0.5 ma of 50 to 60 Hertz current, depending upon the type of hand contact made with an electrically energized circuit. Most adult male workers should be able to release 9 ma of 50 to 60 Hz current. A safety threshold of 5 ma, recommended for the general population including children, is based upon the conclusion that current in excess of release threshold should be regarded as hazardous and potentially lethal. Relevant threshold conditions include body size, current pathway, contact duration, and total resistance. Voltages calculated from reliable experimental data on effective currents and expected resistances are lower than voltages generally recommended to be safe.

THE most commonly available frequency of 60 hertz (1 Hz = 1 cycle/sec) in the United States, or 50 Hz in Europe, was selected for commercial electrical power transmission, partly for the biological reason that such a frequency was the lowest alternating current frequency which still gave the visual illusion of a continuous lighting current. Unfortunately, the extra-low-frequency (ELF) band below 100 Hz represents the most hazardous band of frequencies in the whole range from zero (direct current) to radio frequencies. The thresholds for stimulation of nerve,[1-3] skeletal muscle,[4] and cardiac muscle[3,5,6] have all been found experimentally to be minimal near the prevailing alternating current frequencies of 50 and 60 Hz.

The realistic evaluation of what constitutes a safe human threshold for electrical stimulation at extra-low-frequencies requires quantitative data on the minimal amount of electric current at these frequencies which is just strong enough to produce a measurable physiological response. Presently, such information is available for three responses which are important for electrical safety considerations: (1) perception of electric current flow, (2) uncontrollable muscular contraction, and (3) death. Adequate quantitative data for other responses to electrical stimulation (such as pain, unconsciousness, or burns) are not available, and so these effects are not considered further.

Because of physiological variation and the nature of probability, threshold levels are usually defined in terms of a certain percentage (viz, 50% or 99.5%) of a population in which a particular response to threshold stimulation is likely to be present or absent. No threshold can be said to apply to all individuals. Atypical idiosyncratic reactions, such as death from fright after contact with uncharged electrical circuits, are excluded from the following considerations.

Perception Thresholds

An almost limitless number of sensation thresholds could be defined depending upon the location selected on the body and the nature of the contacts made. The tongue, for instance, can detect an average of 43μa of direct current, and some individuals can detect 4μa with the tongue.[7] Cuts or even needle punctures on hands or fingers significantly decrease the current required perception, and currents almost too small to measure then often cause pronounced pain.

For practical purposes, the perception threshold at 60 Hz for a man or woman (or

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child) with healthy skin is defined as that root-mean-square (rms) current magnitude at which the presence of an increasing current in a hand-to-hand or hand-to-foot pathway begins to be detectable. Different threshold values are obtained, however, depending upon the nature (area?) of the hand contact.

Grip Contact.—When an electrode in the form of a metal cylinder was gripped firmly in one hand, the average perception threshold at 50 to 60 Hz for adult men was found by several investigators[5-11] to be close to 1.0 ma. The minimum 60-Hz current values perceived by adult men using a grip contact[7,9] were between 0.4 and 0.5 ma.

Tapping Contact.—When the perception threshold was determined by a finger-tapping contact on a flat electrode at a tapping rate of one or two times per second, the average values[2,9,10,12] were closer to 0.3 ma and the minimum current perceived by tapping was 0.2 ma for both men and women.[9] Average adult male perception thresholds of 0.2 to 0.3 ma were also produced[13,14] by intermittent 0.6-second stimulation with an alternating current of 50 Hz to fingers immersed in saline. Linemen were reported[15] to be able to detect 0.10 to 0.15 ma in the form of an arc (a very small "contact" with a high charge density) from a high voltage tower. The 60-Hz alternating current perceived by only 1% of the male population has thus been estimated to be 0.49 ma for grip contacts and 0.13 ma for touching and tapping contacts.[12]

Sex and Age Differences.—On the basis of the results obtained by Thompson[9] on 28 women and 42 men, Dalziel[10] suggested that the perception threshold current for women was lower than that of men by two thirds. Thompson[9] believed children to be capable of perceiving "still smaller currents," but neither he nor anyone else has presented any data on perception thresholds of children. Experimental data[2] on adult men tabulated according to age suggest that subjects younger than 30 years had only slightly lower perception thresholds than those over 30.

Release Thresholds

The release or "let go" threshold for a healthy man, woman, or child at 50 to 60 Hz is defined as the highest rms magnitude of a 50- to 60-Hz current flow in a hand-to-hand or hand-to-foot pathway during which an electrode held in a hand can be released by muscular control. Above this current value voluntary release is not possible, and such an experience is said to be very painful, frightening, and exhausting.

Men's Release Threshold.—The average self-inflicted 60-Hz current value[9] at which the arm muscles "would no longer respond to (the subject's) wish" was 8.35 ma for 42 men. Not surprisingly, this is lower than the release threshold later determined more objectively in a competitive atmosphere[16] in which the range of rms 60-Hz currents for 114 men at the "let-go" threshold was from 9.7 to 21.6 ma with an average at 15.5 ma. The nonpreferred hand averaged 0.5 ma less than the hand usually used. There was no difference in the let-go currents between wet and dry hands. The series for 60 Hz was later expanded[4,17] to total 134 men with a 50% let-go current of 15.87 ma rms (22.4-ma crest) and a 99.5% let-go current of 9.0 ma rms (12.7-ma crest). Other investigators[11,18,19] obtained similar data for men's release thresholds.

Women's Release Threshold.—The self-inflicted current value for 28 women at which muscle release was impossible was 5.15 ma.[9] The average 60-Hz let-go current for 28 women tested by Dalziel et al[4] was 10.5 ma rms (14.8-ma crest), and the release threshold for 99.5% of this population of women was at least 6.0 ma rms (8.4-ma crest). The women tested were sedentary types, and, although the women volunteered freely for the tests, "it proved impossible to develop enthusiasm or any degree of competition at high currents."[4]

Children's Release Threshold.—Such tests on children are even more difficult to perform and interpret. A boy nearly 11 years old had a 60-Hz let-go current of 9 ma rms,[17] while a well-developed 9-year-old boy weighing 28.1 kg (62 lb) had a 60-Hz let-go current of 7.6 ma.[16] Dalziel[17] also reported on slightly different tests made at the University of Wisconsin in which a 60-Hz current of 7 ma paralyzed the grip of a 5-year-old boy. No experimental data for let-go currents of children younger than five years

are available, but if release thresholds of children are proportional to forearm circumference and general strength as they are in adults,[20] then younger children may be expected to have smaller release thresholds.

Lethal Thresholds

The lethal threshold for healthy men, women, or children is defined as the smallest rms magnitude of a 50- to 60-Hz current which will directly cause death in a healthy individual. Indirect potentially lethal effects of electric shocks, such as falls or mechanical injury caused by muscular reactions to electric current, are excluded from the definition.

Electric current at 50 to 60 Hz may initiate death by producing ventricular fibrillation or cardiac arrest of the heart, or by preventing the oxygenation of the blood in the lungs by tetanization of thoracic musculature or inhibition of central nervous respiratory control. Both cardiac arrest and respiratory inhibition require electrical currents for their initiation which are larger than those required for ventricular fibrillation or thoracic tetanization, and so neither cardiac arrest nor respiratory inhibition will be considered further in the present context of minimum thresholds of electric current initiating death. Of course, both processes are important final manifestations of death by the mechanisms of ventricular fibrillation or thoracic tetanization, which require lesser amounts of current for their initiation. The heart and the muscles of respiration can all be in the path of currents which flow through the thorax along such common accident pathways as hand-to-hand, hand-to-foot, head-to-hand, and head-to-foot.

Ventricular Fibrillation.—Uncoordinated asynchronous contraction of heart muscle fibers producing no pumping action on the blood can be caused by a 50- to 60-Hz electric current flowing through the heart.[21-23] The threshold of current required to produce ventricular fibrillation in dogs is as low as 20μa during procedures in which current flow can be concentrated at the heart muscle by conductors either placed directly in or upon the heart or inserted into the heart chambers via the major blood vessels.[24] Less than 200μa of a 60-Hz current has caused ventricular fibrillation in humans under similar circumstances.[24] The lethal threshold for ventricular fibrillation is significantly lower during a few msec of the partial refractory period of the heart cycle.[5,6,24-26] However, most periods of contact during accidents with electric current are probably at least one second in duration, and, therefore, encompass at least one heart cycle, including the most sensitive portion.

Under normal circumstances in which electrical contact is made with the surface of the body, currents of 50 to 100 ma flowing in the region of the heart for longer than one second are required to produce ventricular fibrillation in quadrupeds.[5,6,19,21] The threshold for production of ventricular fibrillation in dogs, sheep, and calves varies directly with body weight, and if these results on quadrupeds are extrapolated to humans, calculated minimum ventricular fibrillation threshold currents of 30 ma for 2-year-old children[18] and of 60 to 120 ma for adult humans[27] have been suggested.

The human threshold of current required to initiate ventricular fibrillation is considered by safety experts to be very important, because ventricular fibrillation is thought to be a common mechanism of death from electrical accidents. Once initiated, ventricular fibrillation in humans only very rarely reverts spontaneously to normal heart rhythm, even after contact with the energized conductor is broken, and death occurs in a few minutes. The special knowledge and ability required to maintain viability of victims of ventricular fibrillation and the equipment necessary to restore normal heart rhythm are not generally available for accidents outside hospitals, although efforts continue to be made to alleviate these circumstances. Thus 50- to 60-Hz currents greater than 30 ma through the thorax of a child, or 60 to 120 ma through the thorax of an adult, must certainly be considered above the lethal threshold.

Thoracic Tetanization.—Currents known to be smaller than those which produce ventricular fibrillation, however, are also capable of causing death to humans. In these cases death is the result of inability to breathe, caused by sustained currents which produce uncontrollable muscular contraction of the respiratory muscles of the thorax and

diaphragm. This occurs typically in a situation in which the victim cannot or does not let go of the conductor for several minutes. Current magnitudes in the upper ranges of adult let-go currents (typically 18 to 22 ma or more), flowing across the chest at 60 Hz, have produced cessation of breathing in adults experimentally.[27] Clinically, survivors of low-voltage accidents who sustained currents clearly above the let-go range but less than the ventricular fibrillation threshold for long periods of time showed signs of impending suffocation.[28]

Lee[29] suggests that this mechanism of death is infrequently diagnosed because the familiar postmortem findings in obstructive suffocation (small lung hemorrhages produced by strong negative pressure during powerful attempted inspiratory movements) are not present after electrical suffocation. However, it is generally agreed that death can be caused by tetanic contraction of the respiratory muscles for periods long enough to produce suffocation.[30-33]

Because under "worst case" conditions currents in the upper ranges of release currents may cause suffocation by tetanic contraction of the respiratory muscles, currents just in excess of the respective release thresholds must be regarded as the minimum lethal threshold for both adults and children.

Safety Recommendations

General Perception.—One practical motivation for establishing human perception thresholds has been the realization on the part of the manufacturers of electrical appliances that the general populace tends to become annoyed by any perception of electrical current flow.[9] Furthermore, unexpected perception of small amounts of electric current far too feeble to cause direct injury to the body may be hazardous if sudden reflex movements or loss of balance result. The 1% perception threshold of 0.13 ma and the 50% perception threshold of 0.34 to 0.36 ma for tapping and touching contacts have been taken into consideration by some authors[9,34] in recommending 0.2 ma as the maximum leakage current for appliances.

However, the minimum experimental values obtained with grip-type contacts, such as are used with portable appliances, have formed the basis for the European standard by the International Commission on Rules for Approval of Electrical Equipment, which states that leakage current not exceed 0.5 ma.[34] In the United States the January 1969 Draft USA Standard for Leakage Current for Appliances C101.1 also adopted 0.5 ma as the maximum leakage current for appliances,[35] a proposal based upon unpublished data obtained by Underwriters' Laboratories on currents required to produce reflex muscle reactions following random casual contacts.

General Safety.—Currents only slightly in excess of an individual's release current are said to be very painful, frightening, and exhausting. As discussed above, such current magnitudes should also be regarded as potentially lethal. The 99.5% release threshold for a 60-Hz current for adult men (21 to 46 years of age) has been generally accepted to be 9 ma rms.[4,17,27,28,32,36,37] Uninterrupted currents in excess of 9 ma should, therefore, be regarded as hazardous and potentially lethal to some adult men working at any occupation.

In the case of the general populace, however, the response of the smallest children determines the maximum safe current limit. A 4-year-old boy is reported[38] to have been killed by being unable to release 8 ma of uninterrupted 60-Hz current, and a 5-year-old boy is reported[17] to have been unable to release 7 ma of 60 Hz current during laboratory testing. Dalziel and Burch,[20] discussing electric fence safety, suggested 4 ma as a safe 60-Hz current for children. Dalziel[17] later calculated that 50% of the safe let-go threshold of 9 ma for adult males, or 4.5 ma rms (6.3-ma crest), would be a reasonably safe 60-Hz current for children.

A similar figure of 5 ma as the maximum uninterrupted 60-Hz current to which a child may be safely subjected was arrived at in a different manner in the report by Underwriters' Laboratories on electric fence safety.[18] Extrapolating by body weight from adult data on ventricular fibrillation thresholds, Whitaker[18] concluded that the "allowable current" of 30 ma for a 2-year-old child should be divided by a safety factor of approximately 6. This value of 5 ma has continued to be acceptable by Underwriters'

Laboratories,[36,39] as well as by the Canadian Standards Association,[40] as a safe current limit for the general populace.

Total Resistance.—The impedance which a body presents to the flow of current through it may be considered a noninductive resistance at alternating current frequencies of 50 and 60 Hz. The smaller the resistance the larger the current flow for a given voltage (Ohm's Law). Since current flow produces physiological responses, it is important to evaluate the magnitude of the resistance before concluding whether or not a particular voltage will be associated with a physiological response.

The total resistance includes contact resistances between electrical conductors and the skin at points of entrance and exit of current, the resistance of the skin itself, and the internal resistance of the body. In general, the total resistance decreases as the area of contact increases. It tends to be higher for direct current, perhaps because of electrode polarization, and falls as alternating current frequency increases.[41,42] It also drops during prolonged passage of a 60-Hz current.[43] This latter fall may be due to increased sweating, since the presence of water, electrolytes, or perspiration on the skin can diminish the total resistance greatly.[18] Fear and anxiety tend to increase sweating, especially on the palms of the hands, and this indirect effect is the only objective evidence that psychological factors such as anticipation or alertness may alter a physiological response to electric current.

The total resistance is 1,500 to 5,000 ohms between intact wet hands measured[8,44] specifically at a frequency of 50 or 60 Hz. However, the resistance of pathways through even very small cuts or needle punctures in the skin (or through moist mucous membranes) can be one tenth this amount. This lower resistance approximates the internal resistance of the body which, by minimizing the skin and contact resistances, has been measured[41-43] in adults to be between 120 and 300 ohms for 50 and 60 Hz of alternating current. In children the internal resistance for the same current pathway may be even smaller, since internal resistance is probably proportional to path length.

Relying upon intact skin as a protective mechanism to prevent injurious current flow, safety authorities have used 1,500 ohms[36,45] as a nominal minimal resistance likely to be encountered between dry (indoor) contacts at extremities, and they have suggested either 1,000 ohms[46,47] or 500 ohms[18] as the nominal minimal resistance between wet (outdoor) contacts at extremities. It is questionable, however, if safety standards should depend upon intact skin resistance as protection in field situations,[31] especially since minimum resistances of 120 to 300 ohms have been demonstrated in the laboratory.

Safe Voltages.—Since the current magnitude through the body determines the physiological response, a voltage may be considered safe only when the total resistance is maintained by natural or artificial barriers at a sufficiently high level to limit the current below the recommended threshold. Conversely, under conditions in which the total resistance is only a few hundred ohms, unsafe currents can be generated from a low impedance source by only a few volts.

Actual experimental measurements of 60-Hz let-go voltages on 26 adult men, in whom the average resistance was 1,130 ohms in a hand-to-foot pathway,[46] demonstrated the safe let-go voltage to be 10.2 v for 99.5% of a normal adult male population,[33,48] a value which is consistent with the accepted release threshold for adult men of 9 ma. Although similar experimental data are not available on safe voltages for the general population, the most reliable figures available for threshold currents and possible resistances indicate that even 1 or 2 v of extra-low-frequency current from a constant source may become dangerous in situations involving young children under circumstances of very low total resistance.

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