ELECTRICAL SHOCK SAFETY CRITERIA

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ELECTRICAL SHOCK SAFETY CRITERIA

Proceedings of the First International Symposium on Electrical Shock Safety Criteria

EDITORS
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PREFACE

The first International Symposium on Electrical Shock Safety Criteria was held in Toronto, Canada, on September 7 through 9, 1983. It brought together leading experts from electrical utilities, universities and research laboratories from around the world, interested in problems associated with electrical shock and safety.

The main objective of the Symposium was to establish the state of the art in the field of electrical shock safety criteria as applied to electrical power utilities. To achieve this objective it was necessary not only to establish what is known, but also what is not known and where additional research effort should be directed. Wide ranging and free discussion of controversial topics was encouraged whenever possible. Consequently various speakers at times expressed conflicting opinions or drew different conclusions from the experimental results. Therefore readers should be aware that the viewpoints and results presented in the proceedings are those of the individual authors and are not necessarily shared by the editors.

The program for the three day symposium was arranged so that morning sessions were devoted to state of the art reviews of selected topics, while afternoon sessions consisted of panel discussion on topics raised in the morning sessions. Panel meetings and discussions following individual presentations were tape-recorded and except for some editing are given in full in these proceedings.

The proceedings are organized in three sections, each consisting of the morning review papers and afternoon panel discussions. Section 1 presents an in-depth analysis of the physiology of electrical shocks including such topics as body-weight scaling, electrocution equation, physiological effects of electrical current and factors affecting fibrillation threshold. Section 2 mostly deals with the analysis of body impedance under various conditions and with the techniques for measuring current distribution in the body. Section 3 is devoted to the discussion of safety criteria and related standards from the point of view of current practices in electrical utilities. A list of attendees and the Symposium program are included at the end of the proceedings.

The organizing committee of the Symposium consisted of S. Arnot, J.E. Bridges (Chairman), R.S. Baishiki, R.A. Del Bianco, J.H. Dunlap, G.L. Ford, P. Heroux, R. Kavet, I.A. Sherman (Secretary-Treasurer), M. Vainberg and M.C. Wills.

The editorial committee gratefully acknowledges special efforts of Prof. L. Geddes and Prof. G. Biegelmeier - panel meeting chairmen - for editing their respective panel discussions.

Finally, financial support and encouragement of the sponsors of the symposium - Ontario Hydro, The Electrical Power Research Institute and The Canadian Electrical Association are gratefully acknowledged.

Editorial Committee,

J.E. Bridges
G.L. Ford,
I.A. Sherman
M. Vainberg

Chapter 1

Physiology of Electrical Shocks

INTRODUCTORY REMARKS TO THE SYMPOSIUM ON ELECTRICAL SHOCK SAFETY CRITERIA

J. E. Bridges

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Several years ago it became apparent that important electrical safety developments which had evolved in Europe over the last decade were not widely known in other areas. Currently, electrical biological safety criteria developed in recent studies in Europe are no longer in agreement with criteria being used in many North American shock safety standards. In addition, the increasing level of transmission line short circuit currents, the expanding use of rights-of-way, and unresolved biomedical uncertainties have become causes for concern for proper and cost-effective transmission line and substation grounding design.

An example of this bioelectrical uncertainty is the magnitude-duration dependence of the minimum level of fibrillation current. As used often in North America, this relationship shows significantly higher threshold levels of current likely to cause fibrillation in some regions than for a similar relationship currently being considered for European electrical safety standards.

As the first step in addressing these issues, Ontario-Hydro, the Electric Power Research Institute (EPRI), and the Canadian Electrical Association agreed to sponsor a symposium or workshop with the participation of electrical safety research workers from both North America and Europe. The symposium could provide a unique opportunity for electric shock hazard experts to meet with utility engineers concerned with electrical safety.

An organizing committee was formed which included myself as chairman, S. Arnot of Ontario-Hydro as secretary, and as committee members: R. Kavet and J. Dunlap of EPRI, P. Heroux of Institut de Recherche d'Hydro Québec (IREQ), I. Sherman of the Institute of Biomedical Engineering of Canada, Mr. R. S. Baishiki of the Pacific Gas and Electric Company, and M. Y. Vainberg, G. L. Ford, and M. C. Wills of Ontario-Hydro, R. A. Del Bianco of CEA.

The organizing committee met in October of 1982 and after some debate, decided to hold a three-day conference which would consist of state-of-the-art reviews and panel discussions to identify topics for future investigation, especially as applied to the needs of the electrical power utilities. Every effort was made by means of letters, telephone calls, and personal contacts to invite all research workers in the United States, Canada, Europe, and the rest of the world who had direct experience in developing biological electrical shock safety criteria.

The committee further decided that the primary objective of the symposium would be to establish the state of the art in the field of electrical shock biological safety criteria as applied to electrical power utilities. A second objective would be to have utility experts meet with academic and industrial researchers to identify directions for future work. The symposium would focus accordingly on the following topics:

(1) Basic physiological effects of electrical shocks and the nature of cardiac fibrillation

(2) Electrical body impedance

(3) Magnitude-duration dependence of the minimum fibrillation current

(4) Body weight scaling

(5) Applicability of animal experiments with the establishment of safety criteria

(6) Utility/industry requirements for grounding practices and standards.

The response to the announcement of the symposium was very gratifying in terms of the quantity and quality of the papers submitted. Each of the three one-day sessions include both the invited tutorial papers as well as many of the submitted papers. The last hour and a half of each day is reserved for panel discussions. The program of the first day focuses on the electrical/physiological effects of shocks, the second day is devoted to impedance of the human body, and the third day deals with the implementation aspects and the future work required to resolve the issues identified.

In line with the objectives of our conference, we are mainly here to find out what we know, what we don't know, and what we need to know. It is not the objective of this conference to pass judgments on any shock criteria, electrical equipment, or existing standards. I wish to assure those who manufacture or use electrical equipment that it is not the intent of this symposium to recommend new standards or recommend changes in existing standards. It is our hope, however, that those who are concerned with such developments will use the information that is presented here as appropriate. With this in mind, the chairmen of each session as well as those in charge of the panel discussions are charged with the responsibility of establishing the state of the art and identifying those areas where additional work might be required. In the end, we are really here to identify the issues and not to resolve them.

The various presentations may, at times, introduce different qualitative conclusions or quantitative data. This is in keeping with our objective to determine the state of the art. A consequence of this policy is that the viewpoints and data in any given paper reflect largely those of the author or authors. Such views may or may not be shared by the Symposium Committee or other attendees of the Symposium. Furthermore, readers of these Symposium Proceedings should be aware that the context of the discussions are directed to the shock problems of electric power utilities. Extensions of the results presented here to other settings should be done with care, preferably after review of the entire proceedings and study of some of the more appropriate references mentioned in the papers.

Missing from the Symposium attendees is Charles Dalziel; he regretfully indicated he would not be able to attend. His direct participation will be greatly missed since his research work provided the background for many of the papers and safety criteria presented here.

Many of you have come a long way, have made considerable efforts to prepare papers, serve as program chairmen, or have taken time from your busy schedules. Offsetting these inconveniences are the possible benefits of improving electrical safety. Some 1,000 persons a year die of accidental electrocution in the United States. A sizable fraction of this number experienced the fatal shock in industrial settings. Fundamental to any improvement in electrical safety are the electrical shock biological safety criteria. If these are in error or too vague, it becomes doubly difficult to make significant progress to reduce the number of shock deaths.

Before proceeding directly to the papers, allow me to thank the sponsors of the program, Ontario-Hydro, the Electric Power Research Institute, and the Canadian Electrical Association, and to welcome and thank the participants of this conference for presenting papers and serving as session chairmen or panelists. I must acknowledge the support given to this conference by IEC Working Group 64, and especially the efforts of Drs. Biegelmeier and Hauf in helping formulate a meaningful program. I must also mention the efforts of the host organization Ontario-Hydro and Mr. Mark Vainberg of that group, who has borne the brunt of making the arrangements, mailing the announcements, and eventually publishing the proceedings.

J. E. Bridges
Chairman

PHYSIOLOGICAL EFFECTS OF ELECTRIC CURRENTS ON LIVING ORGANISMS, MORE PARTICULARLY HUMANS

DR. J. CABANES

Physician on the Medical Committee - Electricité and Gaz de France

Chairman of the Medical Studies Group of U.N.I.P.E.D.E

ABSTRACT

When an electric current passes through a living organism it dissipates a certain quantity of energy that can have two effects :

- a temporary modification of the physiology of an organ or the whole organism, in the form of an inhibition or an excitation,
- a thermal effect, the severity of which is defined by Joule's law.

The first process is responsible for three clinical situations:

- inhibition, an acute and temporary phenomenon commonly known as an "electric shock",
- arrest of breathing,
- and above all, arrest of circulation, usually connected with ventricular fibrillation which is the essential cause of initial deaths.

These phenomena need a relatively small amount of current, only appear beyond a threshold and vary with the physiological state of the victim and the physical parameters of the accident.

In order to meet the requirements of safety experts it is important for physiologists and physicians to try to define as precisely as possible the limits of these thresholds.

In practice, however, only a statistical approach is possible, and it must take into account the physiological conditions of the subject and various parameters defining the electrical accident:

- voltage, magnitude and duration of the current,
- frequency, and form of the electric signal
- point of application of the shock, current pathway and resistance of the organism.

The second process is responsible for burns, and their location, extent and consequences depend on the current pathway and the parameters of the Joule equation: voltage, magnitude and duration of the current.

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When an electric current passes through an organ or a living organism it releases a certain quantity of energy, the size of which depends above all on the physical characteristics of the current applied, the resistance of the circuit in which the living organism is contained and the duration of the current. As in any conducting body, the dissipation of this energy will produce a thermal effect. But what is peculiar to living tissues is that the passage of this current will lead to a temporary physiological modification of the organ or the organism concerned which can take the form of an inhibition or an excitation. These modifications are connected with the passage of the electricity and, like many other physiological phenomena, obey various rules:

- they have a threshold, ie there must be sufficient energy to cause the excitation or inhibition,
- they are often, but not always, reversible,
- finally, their severity depends on various factors:
  - first, the physiological state of the organ or the organism,
  - but also the physical characteristics of the current, ie its voltage, magnitude, duration, frequency, if it is alternating current, and the waveform of the electric signal,
  - finally, this effect also depends on the way in which the current is applied: point of contact, current pathway and resistance of the tissues traversed.

The first process, ie release of heat, is responsible for electrothermal burns, ie, real electrical burns which are connected with the passage of the current.

The severity of these burns is directly dependent on Joule's equation, ie the magnitude, the voltage and the duration of the current.

The passage of the current through structures deep inside the organism explains why these burns are not only superficial at the points of contact, but also affect all the deep tissues along the current pathway.

The second process is responsible for three situations which are peculiar to electrical accidents :

- inhibition, which is an acute and temporary phenomenon and which, in clinical language, it is customary to call "electric shock",

- arrest of breathing, which may be due either to prolonged contraction of the respiratory muscles or to inhibition of the upper breathing control centres,

- last, but not least, arrest of circulation, which is most usually connected with ventricular fibrillation, which, in turn, is the most frequent cause of initial deaths observed in electrical accident victims.

We shall attempt, in this general survey of the physiological effects of electric currents, to meet the requirements of safety experts by defining the thresholds for these different effects of electric current as precisely as possible. It seems important to us, however, to point out from the start that only a statistical approach appears valid, and for dangerous currents a sufficient safety margin must always be provided to take into account the major role played by the physiological state of the organism subjected to the electric current.

PERCEPTION THRESHOLD OF ELECTRIC CURRENT

The study of the perception threshold for the passage of electric current is an excellent way to approach the study of electrophysiology, for this first threshold forms a very good example to illustrate the difficulty in defining a threshold in any other way than by a statistical method.

It is usual to define the perception threshold as the minimum value of the current which, when originating from two metal electrodes and passing from hand to hand, causes a sensation for the person through whom it passes (a feeling of tingling, heat and shock). Actually this perception threshold varies widely from one subject to another, and though we can say that a mean value is approximately 1.1 mA, some subjects can feel the passage of a much lower current of the order of 0.5 mA, while others do not feel it until it reaches values of the order of 2 mA.

Figure 1, taken from DALZIEL, gives the results obtained from experiments on 167 men, plotted in semi-logarithmic coordinates.

Sex is another variable, and as shown in Figure 1, women have a decidedly lower threshold of perception than men.

Many other variables also come into play, particularly the contact area, the conditions of contact (pressure, temperature, humidity). Finally, it is usual to define the perception threshold by passing a current from one hand to the other, ie using the sensitivity of the skin of the palm of the hand, but there are other organs which are much more sensitive than the skin.

The most sensitive organ is without question the retina, since, as BRINDLEY has shown, 20 microamperes applied to the eyeball causes a phosphene-type sensation. The tongue is also a sensitive organ, its threshold of perception is around 45 microamperes according to DALZIEL.

MUSCULAR CONTRACTION - LET-GO CURRENT

The second example of the difficulty in defining a threshold can be given by the study of the threshold of muscular contraction and of let-go current.

The let-go current threshold can be defined as the maximum value of the current for which a person holding an electrode in each hand can still let them go.

Beyond a certain magnitude, electric currents, particularly alternating currents, can excite nerves and muscles, and when 50-60 cycle current is concerned, the muscular contraction becomes a veritable tetanus as the excitations given at each period of the current are added together. This muscular contraction can then hold the subject to the live conductor, for the flexor muscles are more powerful than the extensor muscles.

Figure 2, also taken from DALZIEL, shows the individual variations of the threshhold of let-go current, measured on 134 men.

In this case too, there are wide individual variations, and though the statistical mean value is 16 mA, some subjects are already "stuck" to the conductor with currents of less than 10 mA, while others can free themselves with currents of more than 20 mA.

Finally, the threshold is much lower for women, the mean value being 10.5 mA.

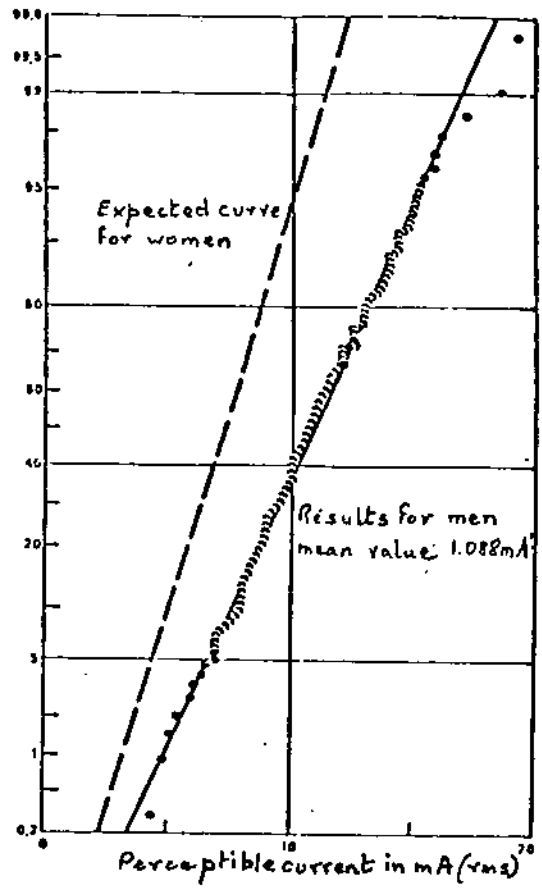


Fig. 1 - Threshold of perception of current, according to DALZIEL

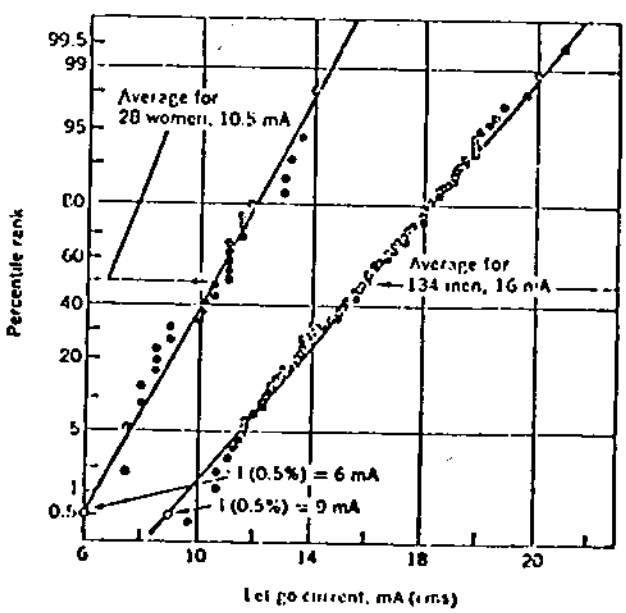


Fig. 2 - Threshold of let-go current current according to DALZIEL

ARREST OF BREATHING

Arrest of breathing can be caused by two different physiopathological processes :

- When the current passes through the thorax, ie when the current pathway is, as is most frequently the case, from an upper limb to a lower limb, or from an upper limb to an upper limb, prolonged contraction can affect the respiratory, intercostal, pectoral and diaphragm muscles. The minimum intensity necessary for this prolonged contraction of the respiratory muscles is of the order of 20 to 30 mA for a limb-to-limb current pathway.

This prolonged contraction of the respiratory muscles leads to asphyxia with cyanosis which rapidly develops into loss of consciousness and then to arrest of circulation and death, unless the subject is freed from the current and help is given. An important fact, however, is that breathing usually resumes as soon as the current is cut or after some respiratory assistance is given.

- In other cases, arrest of breathing is the consequence of inhibition of the breathing control centres in the brain.

This arrest of breathing through effects on the control centres occurs more rarely and requires two conditions:

- a point of contact on the brain,
- a higher current, but the exact current necessary to cause central arrest of breathing is not known precisely for humans.

In cases where arrest of breathing has a central origin, the resumption of breathing is often more difficult, and it has been shown by experiments that the higher the magnitude of the applied current is, the longer it takes for breathing to resume.

It is important to remember that in both cases arrest of breathing is reversible if respiratory assistance is provided sufficiently early, ie before arrest of circulation commences and especially before cerebral injury occurs, which may be the consequence of anoxia if the duration is more than 3 to 4 minutes. Spontaneous resumption of breathing and rapid success of resuscitation efforts seem to be the usual outcome of arrest of breathing through prolonged muscular contraction. Later successes requiring longer resuscitation assistance depend on the second physiopathological process.

VENTRICULAR FIBRILLATION

When an electric current of certain magnitude passes through the thorax the operation of the cardiac muscle may be disturbed in different ways : cardiac failure, simple arrest, ventricular fibrillation. The most serious and certainly the most frequent is ventricular fibrillation which is characterized by asynchronous contraction of the fibres of the myocardium.

Perfect synchronization of the auricular and then the ventricular contractions is provided by a special tissue: the nodal tissue which has very different physiological properties from those of the rest of the myocardium.

The excitation starts from the sino-atrial node and spreads into the two auricles to ensure their synchronous contraction. It is then taken up by the auricular/ventricular node at the top of the interventricular wall and very rapidly spreads

through the bundle of HIS, its branches and ramifications, into the two ventricles, for one of the physiological properties of the nodal tissue is rapid conduction. In this way the contraction of both ventricles is perfectly synchronized.

In ventricular fibrillation all this delicate process is replaced by asynchronous contractions of each of the muscle fibres, which leads to arrest of the circulation with anoxic consequences rapidly affecting the sensitive tissues: above all the brain, but also the other organs, in particular the heart. This explains why, if fibrillation, which cannot be spontaneously reduced in humans, is not quickly reduced, irreversible cerebral damage can occur and the functioning of the myocardium can be disturbed, which will make belated defibrillation difficult, if not impossible.

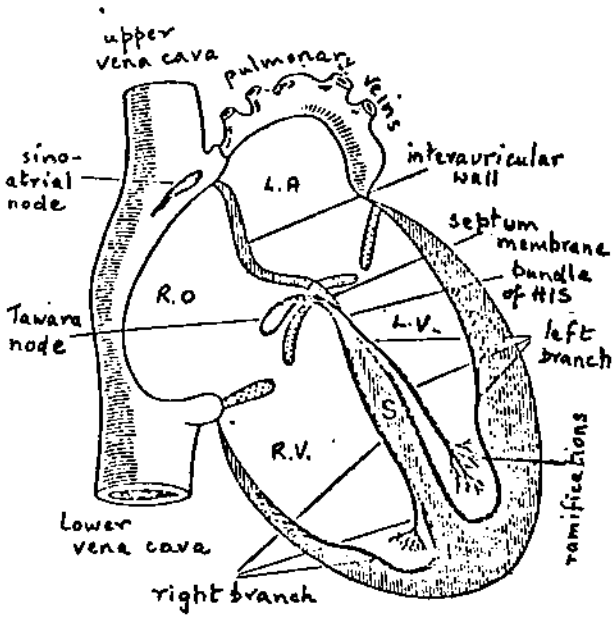


Fig. 3 -

The current intensity needed to make the heart fibrillate when a current passes from an upper limb to lower limbs cannot, of course, be measured on humans, as the intensity limits for feeling or let-go current can be. The value of this threshold can be determined only by studying electrical accidents with particularly well known physical characteristics and above all by extrapolating to humans the results of experiments on animals that have been carried out for a number of years.

Some authors have in fact noted that there is a certain proportionality between the fibrillation threshold and the body weight of the animal studied. On this basis it is possible to locate the threshold rather approximately between 70 and 100 mA for an adult human (Fig. 4).

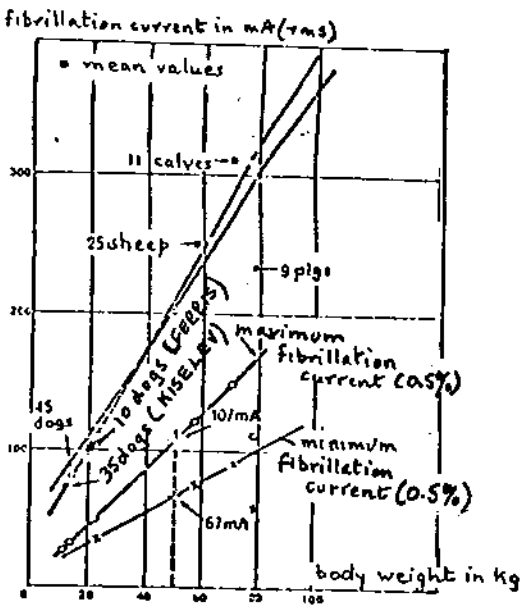


Fig. 4 - Fibrillation threshold depending on the weight of the organism (according to DALZIEL)

In reality, it is much more complex, because the fibrillation threshold varies rather widely depending on the physiological conditions of the subject on the one hand and the physical parameters of the accident on the other, ie the current pathway, the resistance of the organism, the voltage, the characteristics of the contact and finally the duration of the current.

THE CURRENT PATHWAY

This is the first of the factors likely to modify the fibrillation threshold, as the quantity of current traversing the heart varies widely depending on the path followed.

Working Group 4 of Committee 64 of the International Electrotechnical Commission recently established a "heart current" factor which forms an approximate estimate of the density of the current passing through the heart for various current pathways, taking the typical pathway, ie left-hand-to-both-feet, as reference point.

These factors are given in the following table:

CURRENT PATH	HEART CURRENT FACTOR
left hand to left foot or right foot or both feet - both hands to both feet	1.0
left hand to right hand	0.4
right hand right foot or left foot or both feet	0.8
back to right hand	0.3
back to left hand	0.7
chest to right hand	1.3
chest to left hand	1.5
seat to left hand, to right hand or to both hands	0.7

THE IMPEDANCE OF THE HUMAN BODY

The impedance of the human body is another important parameter because, according to Ohm's law, the magnitude of the current passing through the body is inversely proportional to that impedance. The total body impedance is made up of the sum of three impedances: the skin impedances at the two contact points and the internal impedance. The latter has above all a resistive component, is relatively constant and can be estimated at 500 Ohms. The skin impedance, on the other hand, is much more variable depending on the qualities of the skin, particularly its thickness, and the characteristics of the contact: area, pressure, humidity. This skin

impedance varies in time, since at the moment the current is applied, the skin capacities are not loaded and the total body impedance is therefore reduced to the internal impedance. Finally, the skin impedance varies with the voltage applied: for voltages of more than 100 V, the skin impedance decreases rapidly and becomes negligible when the skin is perforated by the electric current.

Figure 5 shows the variations of total body impedances for the current pathway upper-limb-to-upper-limb or upper-limb-to-lower-limbs and touch voltages up to 700 V.

I shall not deal any further with this question which will be discussed at greater length by Professor BIEGELMEIER.

Depending on the voltage, the current magnitude and the impedance, a fibrillation zone can therefore be defined. Fibrillation is possible in a range from 70-80 mA to about 4 amps. Beyond that, the current actually acts as both a fibrillating and a defibrillating agent at the same time.

Figure 6 shows that in this zone an area can be defined where fibrillation is possible depending on the body resistance. The two curves defining this zone have been plotted for a low resistance of the order of 1000 Ohms and for a high resistance of the order of 100 000 Ohms. The dangerous zones can be clearly seen in this figure. They range from 70 to 2000 V in the case of low impedance, and from 500 to 2000 V in the case of high impedance.

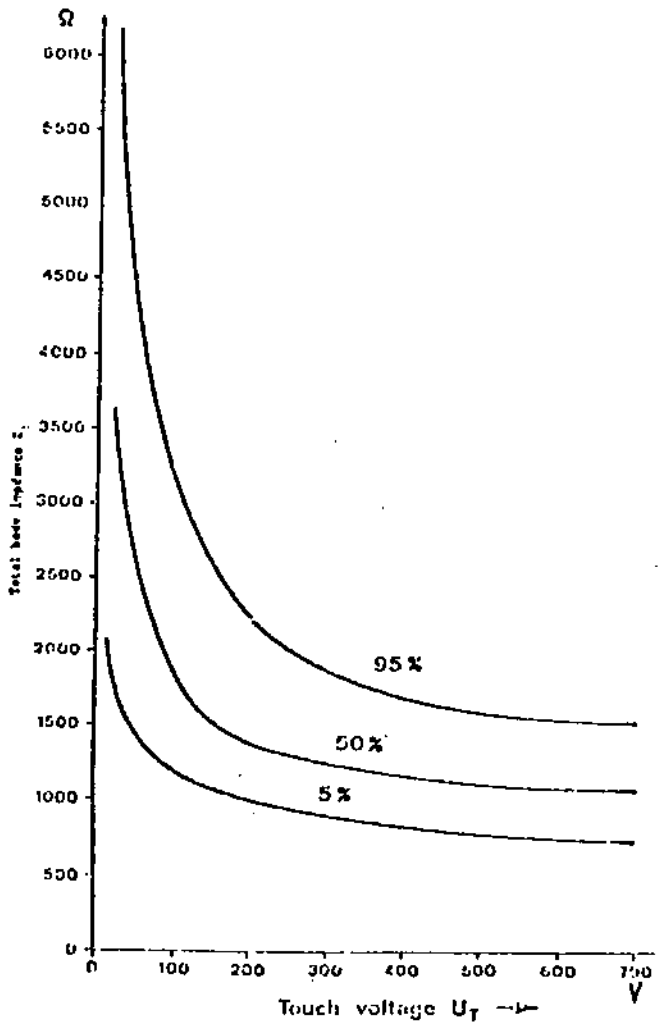


Fig. 5 - Range of total body impedances valid for live human beings for the current pathway hand-hand or hand-foot, for touch voltages up to 700 V.

DURATION OF THE ELECTRIC CURRENT

This is also another very important factor and a lot of experiments have dealt with the variations of the fibrillation threshold as a function of time. FERRIS was the first to show that fibrillation needed a higher current magnitude, the shorter the duration of the current. In 1959 KOUWENHOVEN carried out a detailed study of the minimum magnitude of the current that can trigger fibrillation as a function of the current duration for durations from one half-period of 60 Hz current (ie 8.3 milliseconds) to 5 seconds. DALZIEL was the first to use a statistical approach and to try to extrapolate the experimental results to humans, and then DALZIEL and LEE who took into account the results of many other experiments.

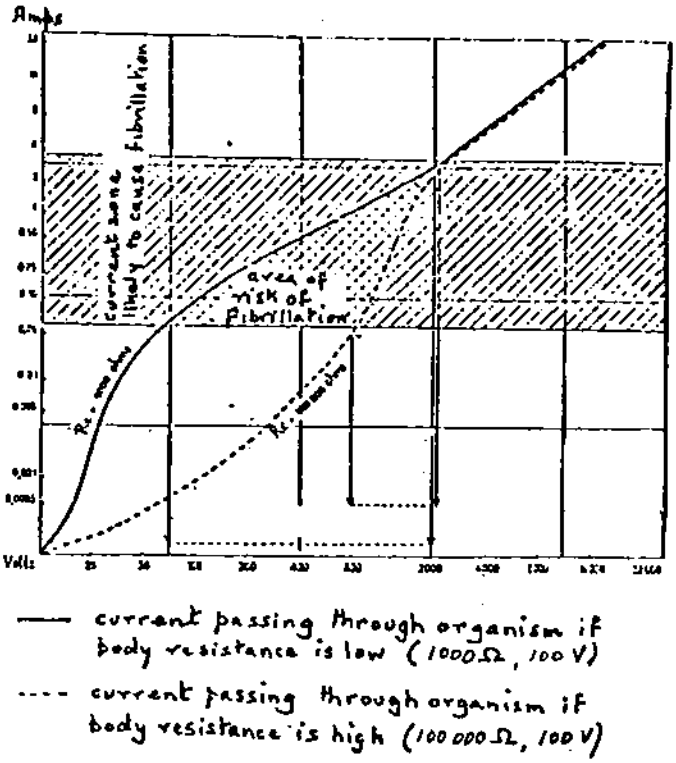
They showed that if the current and its duration were compared on a logarithmic scale, there was an approximately linear dependence between these two relations with the slope of $-1/2$. The relation between the fibrillating current magnitude and its duration can therefore be defined with the mathematic relation $I = K/\sqrt{T}$ for durations of current passage from 0.3 milliseconds to 5 seconds, with I in milliamperes, T in seconds, and K being a constant with a value of 116 for adult humans.

Other experimental research has been carried out more recently on the subject. In several publications, including one with LEE, BIEGELMEIER has been able to show, in the course of a review of all the experimental results that the curve representing the fibrillation threshold as a function of the current duration has a Z shape with 2 plateaus: a high one for short durations, the other clearly lower for longer durations. These two plateaus can be combined by a curve corresponding to durations near to that of half a cardiac cycle.

The highest plateau corresponding to short shocks represents the fibrillation threshold determined when the electric shock coincides with the partial refractory phase, ie the beginning of the repolarization of the ventricular myocardium, which corresponds to the T wave on the electrocardiogram. In fact, the myocardium fibre passes in the electrical sense through three successive phases :

- At rest the fibre is polarized : ie external positive charges balance internal negative charges, creating a potential difference between the cells of the order of 70 mV. During this period the muscle fibre can very easily be excited

Fig. 6 - Fibrillation zone depending on current magnitude, voltage and body resistance.



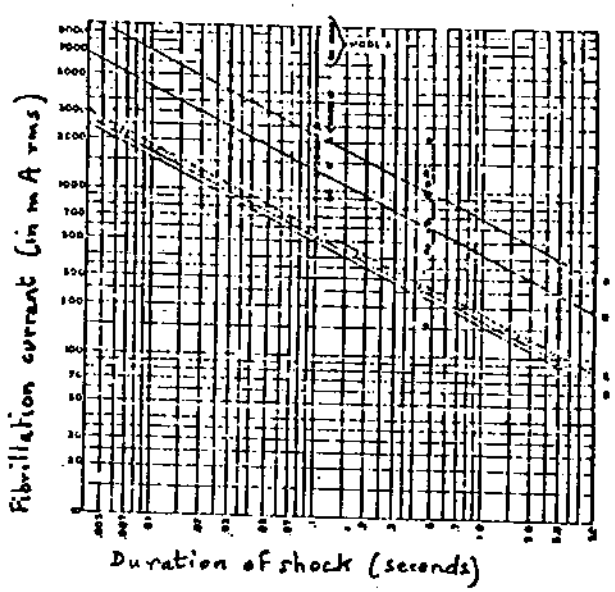


Figure 7

- The excitation takes the form of depolarization with inversion of the charges (B). During this period the fibre cannot be excited. The electric depolarization wave, which coincides with the complex chemical phenomena affecting primarily the sodium and potassium ions, spreads along the fibre at a rate close to 1 m/sec (C).

- Finally a progressive repolarization sets in which, especially in its initial

phase, creates a state of great heterogeneity in the excitability of the myocardium, certain fibres still depolarized being non-excitable, others, in the course of repolarization, being partially excitable, and others, finally repolarized, being totally excitable.

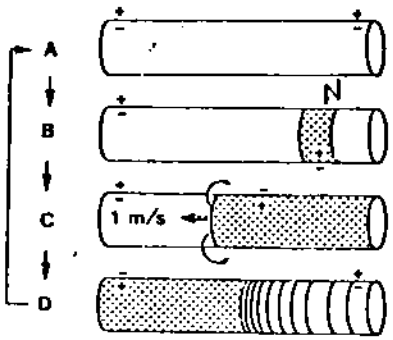


Fig. 8 - polarization/depolarization cycle of the myocardium fibre (according to ANTONI).

It is during this period that an electric shock with sufficient intensity can, because of this heterogeneity, trigger fibrillation by causing excitation of the excitable myocardium fibres. The ventricular fibrillation maintains itself by a very particular mechanism, that of reintroduction. In normal, ie synchronous, contraction of all the myo- all the myocardium fibres, the excitation wave stops of its own accord because very quickly the depolarization creates a state that repels any new excitation. In fibrillation, on the contrary, the asynchronism of the contraction of the various fibres of the myocardium means that the excitation wave will always find a possible pathway in the fibres at rest and therefore excitable, which, considering the propagation speed of the excitation wave will lead to the maintenance of the fibrillation by a circular excitation mechanism.

I shall not go further into this phenomenon as it will be dealt with in greater detail by Professor ANTONI.

The lowest plateau, corresponding to shocks of long duration, has a much lower value than the first threshold. The explanation of this great difference lies in the fact that a long electric shock will always affect the possible excitation period of the cardiac muscle. A current without enough intensity to trigger fibrillation will therefore be able to cause premature contraction of the myocardium, ie an extrasystole.

These extrasystoles have two important physiological properties :

- The first is that when a series of extrasystoles occurs, they are reproduced at progressively shorter intervals.

- The second is that this abnormal contraction reduces considerably the fibrillation threshold. In fact the excitability of the ventricles in the case of extrasystoles is much more heterogeneous than during a normal myocardial contraction.

The passage of an electric current for a long enough period will therefore lead to a series of extrasystoles that are progressively closer, and to a considerable lowering of the fibrillation threshold.

Here again I will leave it to Professor ANTONI to explain this very important electrophysiological phenomenon to you more precisely.

All these electrophysiological considerations of the various thresholds have been summed up in a table compiled by Working Group 4 of Committee 64 of the IEC.

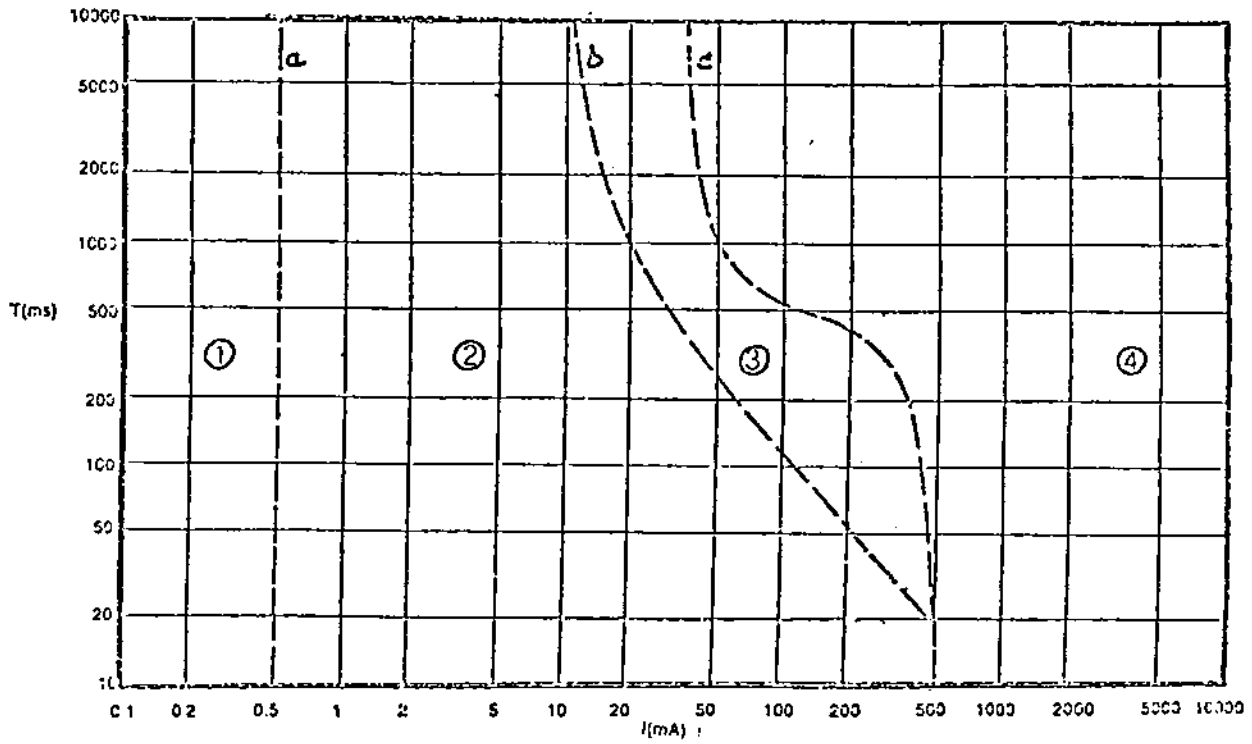


Fig. 9 - Physiological effects of currents depending on current duration and magnitude, valid for alternating currents of 50 - 60 Hz, on adult subjects and, with respect to fibrillation, for the left-hand-to-both-feet current pathway.

Figure 9 shows three curves, a, b and c, marking the limits of 4 zones:

- in the first zone no reaction appears until the perception threshold (curve a)
- in zone 2 no physiological effect occurs until the let-go threshold (curve b)
- in zone 3 certain troubles can appear which increase with the magnitude and duration of the current. They include the propagation of the excitation in the heart (including auricular fibrillation), reversible cardiac arrest without fibrillation, and finally muscular contractions which can lead to breathing difficulties.
- in zone 4 ventricular fibrillation is possible. In this zone we can also find arrest of breathing, cardiac arrest without fibrillation and burns which are more serious the greater the current magnitude and duration.

INFLUENCE OF THE NATURE OF THE CURRENT

So far we have considered electric currents with industrial frequency of 50-60 Hz and, above all, limb-to-limb current pathways.

The frequency of the current is another important parameter which can greatly modify the various thresholds previously considered. As a first example, the perception threshold increases rapidly with the current frequency, passing on average from 1 mA for 50-60 Hz to 2 mA for 1000 Hz, and 10 mA for 10 000 Hz. The same applies to the let-go current threshold which increases rapidly with the frequency as shown in Figure 10, taken from publication 479 of the IEC.

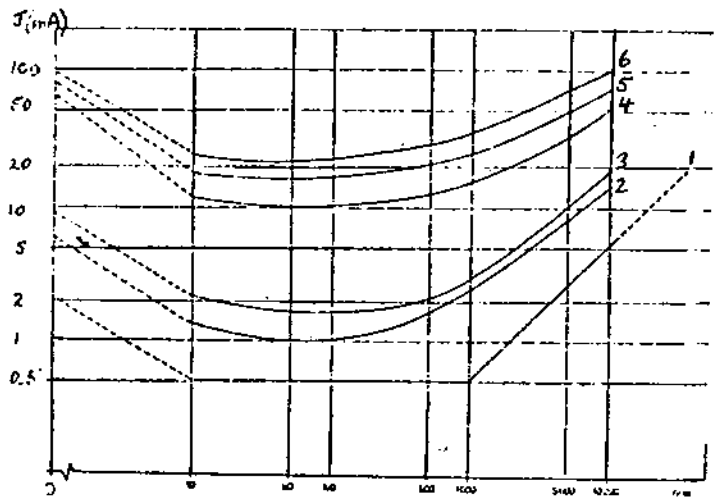


Fig. 10 - Curves of perception and let-go thresholds depending on frequency; the mean is given by curves 2 and 5 respectively

Curve 1: Conventional limit for current values normally not giving rise to any reaction.
Based on a publication of the Association for the Advancement of Medical Instrumentation (AAMI) of July 1971.

Curve 2: Threshold of perception for 50% of persons tested, i.e. remainder felt nothing.

Curve 3: Threshold of perception for 99.5% of persons tested, i.e. remainder felt nothing.

Curve 4: Let-go current for 99.5% of the persons tested, i.e. 0.5% could not let go.

Curve 5: Let-go current for 50% of the persons tested, i.e. 50% could not let go.

Curve 6: Let-go current for 0.5% of the persons tested, i.e. 99.5% could not let go.

In the case of direct current the thresholds are rather different from those defined for alternating current. The threshold of perception which depends greatly on touch conditions, duration of current flow and the characteristics of the individual, is of the order of 2 mA for a hand-to-hand pathway. But this threshold is more difficult to determine, for only the establishment and interruption of the current are felt in the case of direct current.

With direct current there is no "let-go" up to 300 mA, because up to that figure only the establishment and interruption of the current cause muscular contraction. Beyond 300 mA there may be muscular contraction when the current flow is long enough.

With regard to the fibrillation threshold, several important facts must be remembered :

First, for direct current the threshold of ventricular fibrillation is about twice as high for falling current as for rising current,

Ventricular fibrillation is quite exceptional for a hand-to-hand pathway.

For durations of less than 200 ms the fibrillation threshold is approximately the same as the r.m.s. value of the alternating current.

For shocks lasting longer than one cardiac cycle, the fibrillation threshold with direct current is between 3 and 4 times higher than with alternating current.

Working Group 4 of Committee 64 of the IEC has summed up these facts about thresholds with direct current in Figure 11.

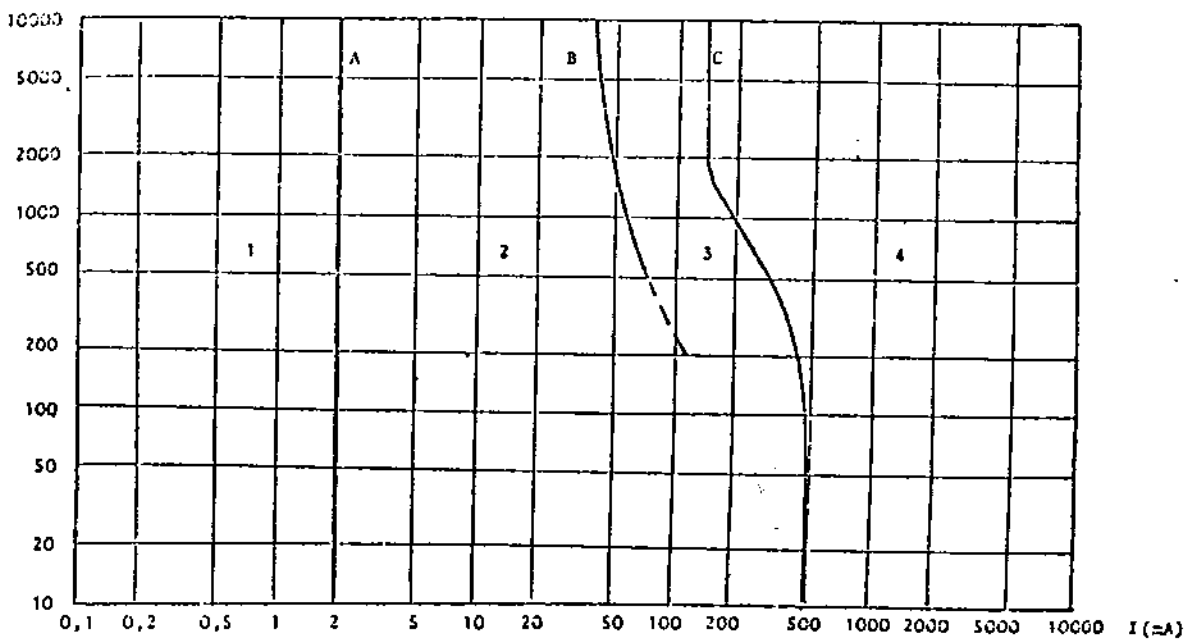


Fig. 11 - Time/current zones for direct currents. Curve C applies with a rising longitudinal current for adults.

As in the case of alternating current 4 zones are defined :

Zone 1 - Usually no reaction effect
Zone 2 - Usually no pathophysiologically dangerous effect
Zone 3 - Usually no damage to organs. Reversible disturbance in the formation and propagation of impulses in the heart, increasing with current magnitude and with time.
Zone 4 - Probability of ventricular fibrillation. Other pathophysiological effects, such as burns, may occur, increasing with current magnitude and duration.

The form of the electric signal is another important parameter. Figure 12 is also taken from the IEC Working Group and shows the values of the various forms of current respectively: discharge of a capacitor, alternating current and rectangularly pulsed current with equivalent physiological effectiveness.

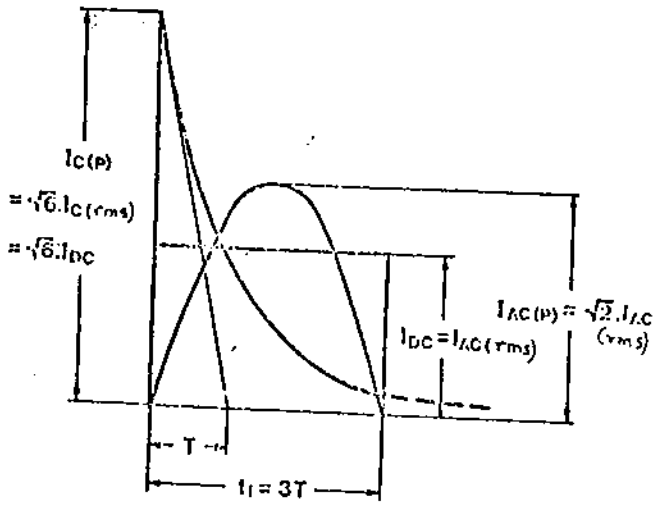


Fig. 12 - Role of the waveform of the electric signal

Finally, the contact location of the electric current is another very important parameter. We have already mentioned the differences connected with the current pathway. When the electric current is applied in the vicinity of the heart or even touching it, the fibrillation threshold drops considerably and reaches values that are no longer measured in mA but in μA These are therefore extremely low currents and this explains the importance that must be attached to the quality and the safety standards of medical instruments. Frequently equipment for checking breathing and heart beat, electrocardiograms, and electrical instruments for endoscopy or surgery are used in combination. The multiplicity of such instruments creates a constant risk, especially as they include electrodes placed close to the heart. The maximum risk is found in certain cardiac explorations using endocavity probes for measuring pressure, chemical constants and recording electrocardiograph tracks.

BURNS FROM ELECTRICITY

The second major risk connected with electricity is burning. Burns are actually the most frequent injuries caused by electric current, both in the home and in industry, and as an example, in the medical statistics of Electricite de France (EDF) for the last 20 years, their rate of occurrence is more than 80%.

Burns caused by electricity result from various physiopathological processes :

- some are due to the intense radiation of the electric arc : these are called arc burns
- others are due to the flow of current : these are electrothermal burns
- both processes can be combined : they are then called mixed burns
- finally, in industry in particular, electricity may be the origin of other types of burns, such as those caused by splashing of boiling oil or heated metals.

Arc Burns

These burns are due to the intense heat released by the electric arc. They are the most frequent burns since they represent 75% of burns in the Electricité de France statistics. They affect mainly the uncovered parts of the body (hands and face). The majority are small burns due to low voltage accidents.

Sometimes these burns may be much more extensive, when the accidents involve high voltage, and in this case the burns may be aggravated because clothing catches fire. Arc burns display a special topography when they affect the eyes : They may affect the eyelid and the cornea, if the eye was close to the arc. They can also affect the retina, because of the focussing of the lens, and can be the cause of visual after-effects.

Electrothermal burns

Electrothermal burns are due to the flow of current through the body. The severity of these burns is governed by Joule's law : $W = RI^2t$, and is therefore proportional to the resistance, current magnitude and duration. If we write the Joule equation $W = UIT$, we show the importance of the voltage. It is in fact the accidents due to high voltages which cause the most serious burns.

Electrothermal burns are more rare than arc burns (only 13% in the EDF statistics). They are located predominantly in the upper limbs, in particular the hands, but also the head. Electrothermal burns have several special characteristics:

- The first concerns the fact that these burns are not located only at the points of contact, but they also extend in depth along the whole current pathway.

- The second concerns their evolution. Kidney damage of the type where urine is suppressed seems more frequent in burns due to electricity than in other burns. This is explained by the importance of acidosis and hypovolemia in victims of electrical burns, and perhaps also, but less than might be expected, by the precipitation in the kidney tubules of chromoproteins released from the muscle mass destroyed by the current flow.

Mixed Burns

Mixed burns are the most rare. In the EDF statistics they figure as 9%. They combine the two processes, arc and Joule effect. They are more likely to be located in the upper limbs, and are more often the result of electrical accidents involving high voltages, than are other burns.

From these physiopathological considerations we realize the urgent need for rehydration and restoration of the acid-base balance of victims of electrical accidents who suffer burns.

Those were the main physiopathological considerations regarding electrical accidents.

SUMMARY AND CONCLUSIONS

To sum up, it seems desirable to draw some practical conclusions regarding the victims of electrical accidents :

1) The first aspect is that of the urgency of treating casualties who appear dead, since the people giving first aid, who are usually workmates or those around the victim of the accident, have only three or four minutes to start efforts for aiding breathing and circulation, before serious damage occurs to organs sensitive to anoxia, in particular the brain. This means that instruction in first-aid treatment should be widely given among staff of electric utilities and the general public, so that resuscitation techniques are known and can be

correctly applied by as many people as possible. In the case of staff of electric utilities in particular, the length of time taken to bring a victim down from a tower or pole may make it necessary to give first-aid at the top and continue during the descent.

2) Before starting resuscitation it is, of course, necessary to release the victim who may have remained in contact with the live conductor, either by switching off the electric equipment, or by removing the victim from the conductor, using insulated materials in order to prevent further accidents.

3) Where the victim is in a state of apparent death, we have found that three processes might be the cause : simple shock, arrest of breathing with resultant arrest of circulation.

- In cases where the subject has simply suffered a shock, but is breathing normally and has normal circulation, it is sufficient to place the victim in a lateral safety position. The victim should be watched until more professional help arrives and as far as possible a few days' hospitalization should be provided.

- In the case of a simple arrest of breathing, artificial breathing must be commenced as quickly as possible, preferably using the oral method which has the advantage of being more effective, easily controlled and possible to use in difficult circumstances like those of a victim at the top of a support.

- When there is arrest of circulation as well as arrest of breathing, indicated by paleness, impossibility of detecting heartbeats and peripheral pulse, and dilatation of the pupils, cardio-pulmonary resuscitation would be needed with both mouth-to-mouth resuscitation and external cardiac massage, until the arrival of help or until the victim reaches a hospital.

In the last two cases it is advisable to provide hospitalization. This will enable resuscitation to be continued using more elaborate methods, in particular electric defibrillation if necessary. This hospitalization will also make it possible to observe the victim for a few days and to make some additional examinations.

4) In the case of victims of electrical accidents who have suffered burns, transport to hospital, if possible a hospital specialized in the treatment of burns, seems a necessity. However, in cases where the transport would take a long time, it is important to start rehydration and restoration of the acid-base balance, which could be done either by a first-aid team at the site of the accident or in a hospital service close by, which would then provide transport to the specialized burns service, which is often the only service able to provide the surgery, observation and nursing care needed for major electrical burns.

DISCUSSIONS

LEE: I would like to congratulate my friend Dr. Cabanes for an excellent and very clear presentation. I want to add two points to some remarks he made. This is on the section dealing with the arrest of respiration. We are here as the guests of the Canadians and I think it is important to record that some very early and important work on arrest of respiration was done in this country in the 1930's. One classic paper by a Canadian Safety Engineer, published in a very reputable medical journal, the Journal of Hygiene in the 1930s recorded a case of prolonged arrest of respiration for 8 hours following a high voltage accident through the head. This person was recovered after 8 hours of artificial respiration. There was no external cardiac massage at that time. Following this there was some experimental work done in the physiology laboratories again in Canada, in which they sought to explain how this could happen, and again those papers (1÷3) gave a physiological explanation as to how this should have occurred. I make this point for two reasons. One because we are the guests of the Canadians and I think its important to recognize their early work in this field, and important work, and the second reason is that these were very experienced and intelligent men and the people that followed for many years drew the wrong conclusions from this work. But this is not a matter to discuss now, it's something we can raise at the panel discussion this evening. But it's very instructive to see how intelligent men with careful and carefully presented work drew the wrong conclusions and this might help us to see that we don't fall into the same trap when we come on to our newer matters today. Thank you.

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CABANES: (interpreted) Dr. Cabanes thanks Prof. Lee for his comments.

TARCHALSKI: Dr. Cabanes indicates that prolonged contraction of the respiratory muscles leading to asphyxia occurs at 20 to 30 milliamps. My question is, what evidence is available to support such a statement? The truthfulness of the statement would lead one to conclude there is a 20 to 30 milliamp level which is the first danger to life before ventricular fibrillation.

CABANES: (interpreted) This level of current would have to be maintained for a while for the chest to be paralyzed and secondary to this you could have a cessation of blood circulation which could lead to death. But this condition would have to be maintained for a while in order for this level of current to be lethal.

TARCHALSKI: That was not my question. My question is what evidence is there to support this statement, not the mechanics of it.

CABANES: Some experiments on dogs have shown that a current above 80 mA flowing from rear leg to front leg can induce asphyxia ending with death if the duration is longer than few minutes. However, I agree that the basis for this is not very firm but it is a reasonable inference and the basis for arrest of respiration through the central nervous system is even less well defined. As you said, there is certainly no basis, no data, to support firmly this particular threshold, so it must be viewed as a reasonable guess. Apparently Mr. Jelenick in Austria has been defending this point for a number of years and this question has been under discussion over there.

BIEGELMEIER: I personally do not believe very much in this respiration business because we have evidence now from animal experiments in Australia. They are using 50 Hz impulses with 1 millisecond duration to tetanize animals for branding. They attach electrodes to the mouth and tail of a cow, calf or other animals, and apply very strong impulses (in the order of 100 milliamperes) so the cattle are tetanized so that they can brand. They state explicitly that during this tetanization of the muscles, the animals continue to breathe. This is a contradiction to the asphyxia theory. Furthermore, we have one case of an accident where we could determine very accurately the current which was flowing through the person. It was a high voltage accident and the person was submitted to 40 milliamperes, 50 Hz ac for half an hour, and he continued to breathe. He just lost consciousness, but did not die. I think the threshold of asphyxia if it exists is much higher; of course the high voltage accident Dr. Cabanes told us about, where the centre of respiration was tetanized, is another business. I think we should discuss this problem further.

GEDDES: I think the discussion that has just developed calls attention to perhaps the most important thing when we're talking about current levels to produce a given effect. Our speaker mentioned one of the important things that we should all consider, that is the current path. So I would make a plea to all of us to specify the type of current, the duration of its application and the pathway through the body. With those three things, we can start to understand what the physiological responses were.

WILSON: Dr. Cabanes, do you have any information on the frequency of occurrence of serious injuries and fatalities among linemen in Électricité de France?

CABANES: (interpreted) In the last yearly statistics we have had 710 electrical accidents and 15 of them were fatal. That's in five years. In the case of the accidents where there is an apparent death of the subject these victims can be divided into three groups. The first third will reanimate spontaneously without outside help. A second group can only be reanimated with outside assistance and a third group can not be reanimated at all. As an illustration, I would like to describe an exceptional case in which a subject was put in cardiac and respiratory arrest as a result of electrocution. This person was immediately given mouth-to-mouth resuscitation and cardiac massage and there was a lapse of 45 minutes between the accident and his entry in the hospital. However, even with this relatively long lag, the resuscitation was completed although the subject was under fibrillation at the time of his admission to hospital.

WILSON: One simple question to Dr. Cabanes, how many linemen are there in Électricité de France?

CABANES: (interpreted) I don't know. These statistics are apparently valid for the whole of Électricité de France's 120 000 employees. Of course linemen have a greater exposure.

HEROUX: I'd like to ask Dr. Cabanes if he would explain the mechanism of acid based metabolism disturbance in electrocuted subjects and also if the use of mannitol is a normal procedure when an electrocuted subject enters hospital.

CABANES: (interpreted) The acid base metabolism disturbance tends to be heavier in cases of deep burns produced the current flow through the body during an electrical shock. I have no experience with the use of mannitol.

THE ELECTROPHYSIOLOGICAL BASIS FOR THE VENTRICULAR FIBRILLATION THRESHOLD AND FACTORS THAT AFFECT IT

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ABSTRACT

Ventricular fibrillation may result from electrical shock. This state of random chaotic depolarization of myofibrils is in sharp contrast to the orderly depolarization of normal myocardium. Laboratory techniques have been developed to quantitate the vulnerability of myocardium to electrically induced fibrillation. The most commonly used approach employs brief trains of stimuli during the relative refraction period of the cardiac cycle. Various physiologic and pharmacologic interventions such as ischemia, autonomic tone, endogenous compounds such as catecholamines and cardiac drugs have been found to have significant effects on these laboratory measurements. Laboratory assessment of fibrillation threshold has in turn coorelated well with clinical observations in man.

KEY WORDS

Ventricular fibrillation, ventricular fibrillation threshold, sudden death, myocardial ischemia.

INTRODUCTION

One of the most hazardous effects of electrical shock is the induction of ventricular fibrillation. The assessment of shock hazard is improved by an understanding of the basic mechanisms of ventricular fibrillation, and those physiologic and pharmacologic factors affecting its ease of induction. The purpose of this report is to review these mechanisms, describe the experimental methods used in the laboratory assessment of the vulnerability of myocardium to ventricular fibrillation, and summarize some of the factors affecting this level of vulnerability.

MECHANISMS

Ventricular fibrillation is the random chaotic depolarization of myofibrils. This state is in sharp contrast to the well ordered spread of depolarization through normal cardiac muscle. Two major theories have been put forward for the initiation and maintenance of this chaotic activity (Surawicz, 1971; Zipes, 1975). The first is reentry, an electrophysiologic mechanism underlying many common cardiac arrhythmias. In its most simple form, reentry involves a continuous circular wavefront of activation around an anatomic obstacle. Normally an activation

wavefront would spread simultaneously around both sides of such an obstacle. However, if unilateral block should occur on one side, "reentry" may occur due to the retrograde penetration of activation from the other side. If this wave of activation persists in a circular fashion around either an anatomic (or functional) obstacle, a sustained, abnormal cardiac rhythm results. This mechanism is responsible for many cardiac arrhythmias such as AV nodal reentry, ventricular tachycardia and the tachycardia of the Wolff-Parkinson-White Syndrome.

Another possible explanation for ventricular fibrillation is the repetitive depolarization of multiple foci of automatic activity. Ventricular muscle, as opposed to the specialized conduction tissue of the heart, has limited capacity for spontaneous repetitive depolarization. By some as yet unknown mechanism, multiple areas of ventricular myocardium might be induced to undergo rapid spontaneous depolarization resulting in the sort of chaotic disorganized patterns characteristic of ventricular fibrillation.

Though neither of these mechanisms have been entirely validated or refuted the preponderance of evidence at the present time favors reentry as the basic mechanism for the initiation and maintenance of ventricular fibrillation. Ventricular fibrillation, once induced, tends to be self-sustaining. The larger the portion of myocardium involved the more likely fibrillation will be sustained. If small portions of myocardium are separated from a larger fibrillating mass, fibrillation will cease. Although spontaneous resolution of ventricular fibrillation may be seen in lower animals it becomes progressively more rare as hearts become larger. (Zipes, 1975)

THE INDUCTION OF VENTRICULAR FIBRILLATION

The most common setting for ventricular fibrillation is probably that of myocardial ischemia and infarction, or diffuse myocardial disease due to long-standing coronary atherosclerosis. These ventricles, due to multiple areas of altered conduction and refractoriness, have increased susceptibility to fibrillation. Specific initiating factors in the clinical setting include tachycardia and ventricular ectopic beats. As the heart rate increases, there is increasing dysynchrony of activation of the ventricles since time differences in conduction and refractoriness are magnified with each succeeding beat. This principle also applies to single premature beats which occur at a point in the cardiac cycle when various portions of the myocardium are in markedly different states of refractoriness following the preceding depolarization (so called vulnerable period). This phenomenon, the "R on T," is frequently seen in the setting of acute myocardial infarction when premature beats are common and ventricular fibrillation threshold is substantially lowered. Finally, in the setting of profound myocardial ischemia, spontaneous ventricular fibrillation may occur without evidence of initiating ectopic activity (Moore and Spear, 1975).

Severe electric shock may also produce ventricular fibrillation. The passage of current through the heart may result in a change in the automaticity of the heart cells, transform nonspontaneously depolarizating cells to depolarizing ones or affect local membrane currents (Surawicz, 1971). This sensitivity of the heart to electrical currents has been used by investigators seeking an index of vulnerability of the heart to fibrillation.

EXPERIMENTAL ASSESSMENT OF VENTRICULAR FIBRILLATION THRESHOLD

The level of ventricular vulnerability to fibrillation may be measured using laboratory techniques. The most common laboratory approach has been to measure the amount of electrical current necessary to produce ventricular fibrillation

when applied during the most vulnerable part of the cardiac cycle (Moore and Spear, 1975). Immediately following depolarization of the myocardial cell, a period of absolute refractoriness to stimulation begins. This is followed by a period of relative refractoriness in which depolarization can occur but requires an increased strength of stimulation for induction. Towards the end of the relative refractory period, there is a period of increased vulnerability to electrical stimulation, particularly anodal stimulation, described as the "anodal dip" or vulnerable period. This is in turn followed by a period of diastolic repose in which the myocardium is more resistant to induced fibrillation. Experimental techniques have taken advantage of this sequence of events by applying electrical stimuli to the myocardium during the phase of maximum vulnerability. The initial approach was to use single brief electrical stimuli which were "scanned" through the relative refractory period at varying coupling intervals from the preceding beat. After each scan, the current was increased in intensity and the scanning repeated until fibrillation occurred. In order to increase the ease and speed of theshold determination, a second method using trains of stimuli was developed. A single train of stimuli thus replaced a complete scan of the relative refractory period using single stimuli (Fig 1). The train was initiated during the absolute refractory period and produced depolarization of the ventricles at the point in the relative refractory period at which the myocardium was maximally susceptible, the anodal dip. Each subsequent train was increased in intensity until fibrillation occurred. The principles underlying both techniques were identical, the train technique simply being faster.

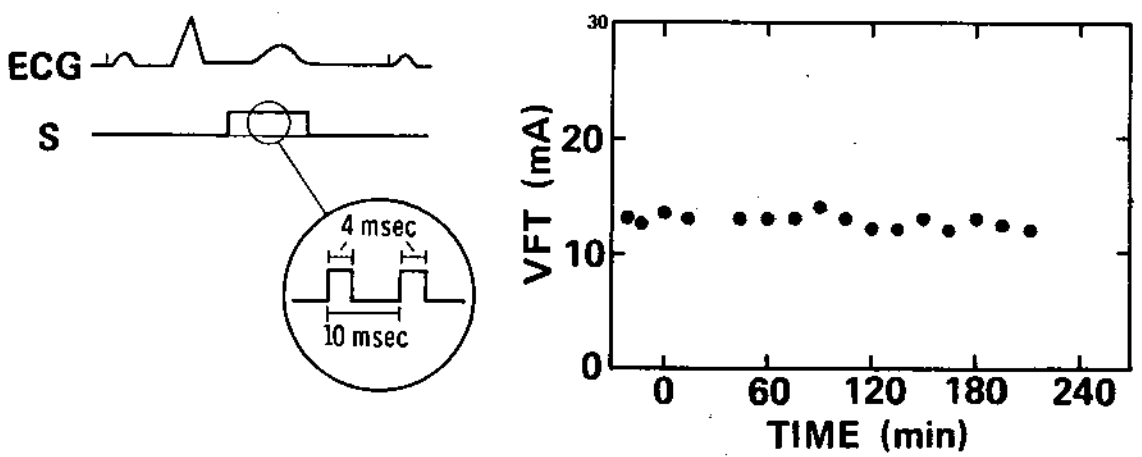

Fig. 1. The technique for determination of ventricular fibrillation threshhold (VFT) is illustrated in the left panel. Trains of 10 pulses, 4 msec. in duration and 10 msec. apart are initiated during the absolute refractory period of the ventricle. The stability of this animal model is illustrated in the right panel. In this control animal VFT remains stable to within 2 mA over a period of 3 hours.

The values reported for fibrillation threshold in normal animals using these techniques range from 5-50 mA. There is also a report of ventricular fibrillation threshold determination in man (Horowitz and colleagues, 1979). Using trains of stimuli at the time of cardiac surgery, ventricular fibrillation threshold was found to average 34 mA in the left ventricle of patients without atherosclerotic heart disease. Values were significantly lower if atherosclerotic disease was present in the left ventricle, averaging only 19 mA.

More recently, a third method for the assessment of vulnerability to fibrillation has been developed using a non-electrical approach (Clusin and colleagues, 1982).

The proximal left coronary artery of an experimental animal is ligated and the length of time necessary for the development of ventricular fibrillation is measured. This value, the time to ventricular fibrillation, can be used as an index of myocardial vulnerability. Serial determinations can be made with all 3 techniques by rapidly defibrillating the animal and allowing 15-20 minutes between each assessment for the myocardium to return to the control state.

The absolute value of fibrillation threshold is significantly influenced by certain experimental variables, such as train frequency, current increment and the number of trains delivered. Assessment of the effects of some of these variables has been performed (Winkle and colleagues, 1980). These findings stress the importance of meticulous experimental technique and the difficulty of comparing studies performed by different methods. Although the data from this study did not precisely define the mechanism of initiation of fibrillation using trains of electrical stimuli, they suggested an interaction existed between the stimuli and local time dependent factors such as local catecholamine release and diffusion.

FACTORS AFFECTING THE VULNERABILITY TO FIBRILLATION

Based on both clinical and experimental data, there appear to be several factors affecting the vulnerability of ventricular myocardium to the initiation of fibrillation. These include physical factors, physiologic and pathologic conditions, and a variety of drugs and endogenous compounds (Surawicz, 1971; Zipes, 1975; moore and Spear, 1975.) An understanding of these effects may be important in the assessment of risk of an individual to the induction of ventricular fibrillation by electrical currents.

Ischemia

Myocardial ischemia results in a profound depression of ventricular fibrillation threshold. This has been demonstrated in a number of experimental studies (Burgess and colleagues, 1971; Meesman and colleagues, 1976) and easily appreciated clinically. Many factors such as early premature extra beats, leakage currents, and pacemaker stimuli in the vulnerable period have been found to induce ventricular fibrillation in patients immediately following myocardial infarction when similar stimuli would have resulted in little or no effect on a normal individual. Ventricular fibrillation may also result from reperfusion of ischemic myocardium. Though known experimentally for some time, this has also been recently demonstrated clinically during procedures designed to reinstitute bloodflow to the heart by lysing clots acutely in the early stages of myocardial infarction. The time course of ventricular fibrillation theshold lowering has been studied in the experimental animal (Burgess and colleagues, 1971; Meesman and colleagues, 1976.) Lowering of threshold is greater in the ischemic ventricle and it begins to decrease shortly after occlusion, reaching a nadir at approximately 10 minutes. Most studies have found that threshold soon begins to return toward normal, reaching that level approximately 30 minutes after complete occlusion. Though not quantitated in man, similar changes probably occur and contribute to the very high early mortality of coronary occlusion.

Autonomic Influences

Based on experimental studies, it would appear that vagal or parasympathomimetic activity tends to promote an increased ventricular fibrillation threshold opposing the decreased fibrillation threshold resulting from sympathetic activity. This may be particularly true in the ischemic heart (Kent and colleagues, 1973; Kolman, Verrier and Lown, 1976). In one animal study, psychological stress during coronary occlusion resulted in significant ventricular arrhythmias (Corbalan, Verrier

and Lown, 1974). In addition to the effect of autonomic tone, circulating compounds having autonomic effects have also been demonstrated to influence fibrillation threshold. It would appear that the beneficial effect of vagal stimulation is mediated through acetylcholine release. Edrophonium, an acetylcholinesterase inhibitor, has been shown to increase fibrillation threshold (Harrison and colleagues, 1974). In a similar fashion, increased sympathetic tone resulting from circulating catecholamines may reduce fibrillation threshold and a number of drugs from the family of beta adrenergic blocking agents (Fig 2) have been found to increase fibrillation threshold (Anderson, Rodier and Green, 1983; Schnittger and colleagues, 1978).

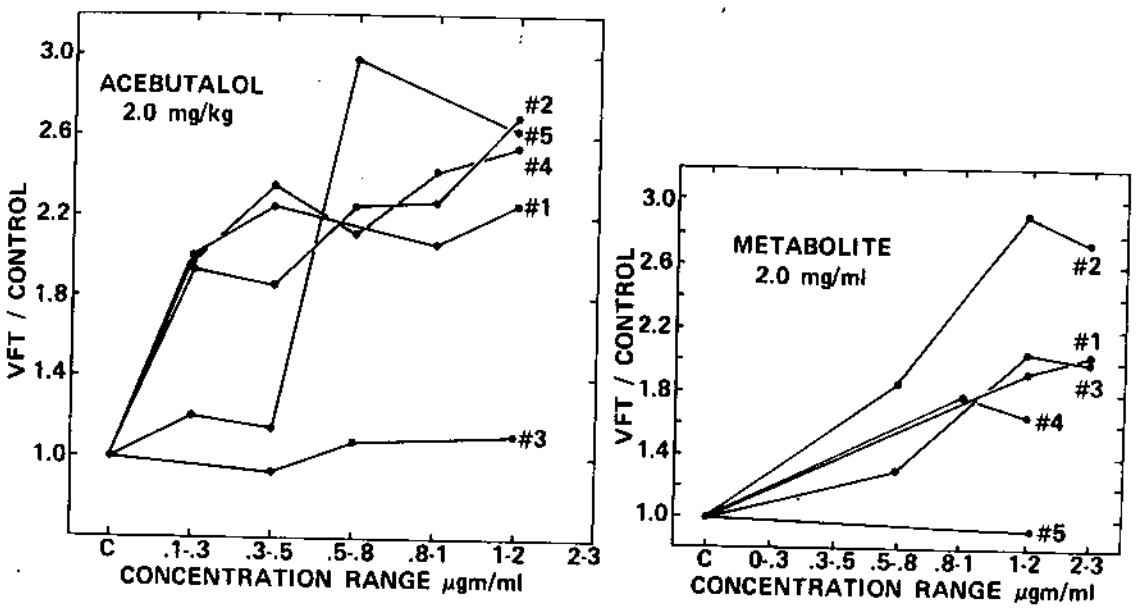

Fig. 2. Experimental models for the determination of ventricular fibrillation threshold are useful in the assessment of drugs and certain physiologic conditions. As illustrated here they are particularly useful in determining the relative potencies of 2 agents. A beta adrenergic blocking drug Acebutolol (left panel) is compared to its principal metabolite (right panel). These experiments demonstrate that the parent compound exerts significantly greater effect on fibrillation threshold (VFT) at equivalent plasma concentrations than the metabolite. # = experiment number

Exercise

Exercise in the absence of ischemic does not appear to affect fibrillation threshold However, the combination of myocardial ischemia and exercise resulted in a 25% decrease in VF threshold and development of spontaneous ventricular fibrillation in 5 out of 13 experimental animals (Dawson, Leon and Taylor, 1979).

Drugs

Despite the fact that alcohol depresses heart function and chronic overuse is associated with ventricular arrhythmias, the acute infusion of alcohol appears to result in an increase in ventricular fibrillation threshold (Kostis and colleagues, 1973).

Digitalis is a commonly used cardiac drug and has been shown to have complex effects on ventricular fibrillation threshold and a complex interaction with the autonomic nervous system (Moore and Spear, 1975). Both digitalis in the denervated heart and sympathetic stimulation decrease fibrillation threshold. However, the combination of the two, that is, digitalis in the presence of sympathetic stimulation results in an increase in fibrillation threshold.

As one would expect, a number of antiarrhythmic drugs have been found to increase ventricular fibrillation threshold. These include aprindine (Kroll and Lucchesi, 1975), lidocaine (Schnittger and colleagues, 1978; Spear, Moore and Gerstenblith, 1972), procainamide (Yoon and colleagues, 1974), encainide (Jaillon and colleagues, 1980), tocainide (Schnittger and colleagues, 1978), diltiazem (Clusin and colleagues, 1982). These studies demonstrate that a broad spectrum of antiarrhythmic drugs of several different pharmacologic types seems to affect ventricular fibrillation threshold in a similar protective fashion.

Ventricular fibrillation threshold testing has been a useful laboratory technique for exploring both the physiology and pharmacology of ventricular fibrillation. While specific correlation with ventricular vulnerability in man is lacking, data from ventricular fibrillation threshold studies have paralleled clinical observations. These techniques have proven useful in screening new compounds for antiarrhythmic potential and in identifying physiologic states associated with increased or decreased vulnerability. Therefore the incorporation of data generated from such studies may allow a more accurate assessment of the risk of environmental exposure to shock hazards.

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DISCUSSIONS

ANTONI:

1. There were quantitative figures on the dispersion of the refractory state in one of your slides. Could you please explain, how these were obtained?

2. You referred to a decrease of the fibrillation threshold accompanying an increase in the heart rate of a normal non-ischemic heart. This is in agreement with findings of our laboratory in which the variability of the action potential (AP) duration within myocardial preparations was reduced, when the heart rate was increased.

3. In studies at our laboratory on the isolated guinea pig heart, acidosis decreased the fibrillation threshold, whereas alkalosis increased it. We could explain this by the accompanying changes of the AP-duration, which was prolonged in acidosis and shortened in alkalosis (range of pH 6.4 - 8.0). What is the reason for the different behaviour in the whole animal?

GRIFFIN: In response to your first question these data were obtained in the laboratory of Dr. Neil Moore (University of Pennsylvania, USA) using a circular plaque having a recording electrode arranged around the periphery and a stimulating electrode in the center. The heart would be stimulated and the maximum difference in the time of recovery between the earliest and latest of the electrode sites plotted as a function of stimulus strength.

With respect to your second question the effect of acidosis on fibrillation is quite complex. In Moore's laboratory respiratory acidosis affected threshold only when accompanied by hypoxia. In other laboratories metabolic acidosis has been found to decrease threshold. It should also be stressed that the exact mechanism of fibrillation induction remains unknown, therefore, it is difficult to know the role changes in action potential duration might play. The dispersion in recovery may be produced in some other fashion.

PATHOPHYSIOLOGICAL BASIS OF VENTRICULAR FIBRILLATION

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ABSTRACT

Ventricular fibrillation is a primary disturbance of the excitatory processes in the heart, secondarily resulting in pumping failure and in break-down of the blood circulation. This paper presents evidence to the hypothesis that ventricular fibrillation, induced by electric shock, is due to the re-entry of excitatory waves.The development of this disturbance requires mainly 3 conditions: 1. interconnected pathways for conduction in the ventricles, 2. waves of excitation which are shorter than the pathways, and 3. unidirectional conduction due to transient unidirectional block of conduction. These conditions are met when the heart is stimulated during the early phase of its recovery from excitation (vulnerable period). A non-homogeneous state of excitability (e.g. induced by repetitive extrasystoles) favours the development of re-entry. Alternating current is more dangerous than direct current because it induces bursts of extrasystoles which easily pass over into ventricular fibrillation. In general, the susceptibility of the heart to undergo this dysrhythmia is closely related to the degree of non-homogeneity of excitability during the phase of repolarization. This is illustrated by various examples.

KEYWORDS

Ventricular fibrillation; ventricular flutter; circus movement; re-entry; vulnerable period; alternating current; direct current; threshold for fibrillation.

INTRODUCTION

Ventricular fibrillation is a severe disturbance of the cardiac function with its primary cause lying in the excitatory processes of the heart. In contrast to the pumping failure due to cardiac arrest in which any excitatory activity is absent, the break-down of blood circulation due to ventricular fibrillation results from the enhanced and highly irregular electrical activity.

In the electrocardiogram ventricular fibrillation appears as deflections of varying size and duration at frequencies between about 200 and 500/min (Fig. 1). If the disturbance persists for several minutes, the circulatory arrest may lead to irreversible cerebral damage and may render the chance to restore the cardiac function to normal more and more improbable.

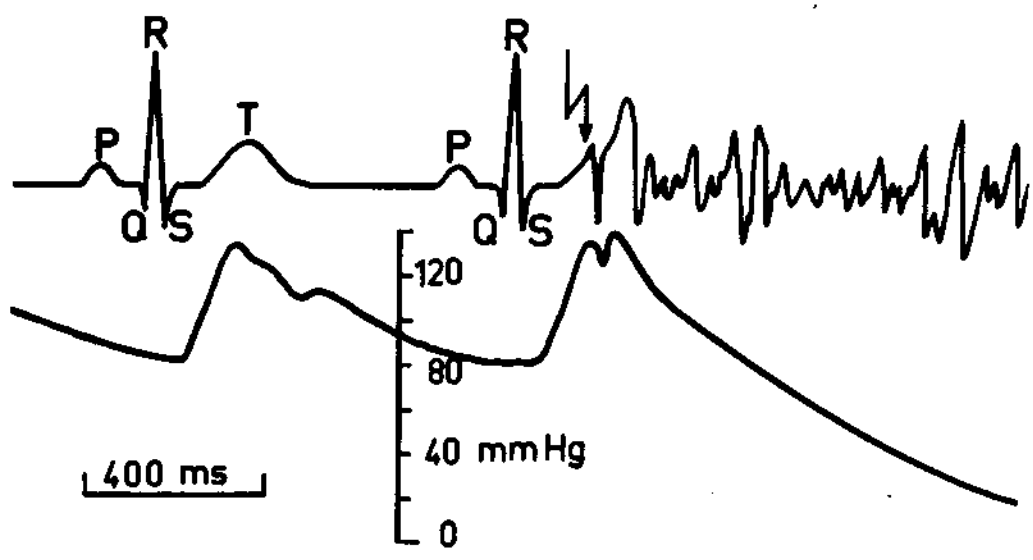

Fig. 1. Behaviour of the electrocardiogram (upper curve) and the blood pressure (lower curve) under normal conditions (left) and during the induction of ventricular fibrillation by an electric shock (right, arrow).

These facts are in agreement with the experience that, under appropriate conditions, ventricular fibrillation can be induced in an otherwise normal heart, but that the development and the persistence of the arrhythmia are strongly favoured if some kind of cardiac damage produces or enhances a non-homogeneous state of excitability in different regions of the ventricles.

On the other hand, the fibrillatory arrhythmia would by itself exert no deleterious influence , neither on the heart nor on other organs, as long as the circulation of blood is maintained (f.i. by a heart-lung-machine). Thus, fibrillation of the atria can persist for many years without impairing the cardiac function very much, provided that the contractile force of the ventricles remains sufficient.

Any attempt to explain ventricular fibrillation in terms of its pathophysiological and its electrophysiological mechanisms has to consider some additional facts which are closely connected with this kind of disturbance and which may also serve as valuable tools in the clarification of the underlying mechanisms. For special questions the reader is referred to more detailed articles and reviews on this subject (Cranefield, 1978; Antoni, 1979, 1982; Janse and Kleber,1981).

FACTS THAT SHOULD BE EXPLAINED

There is the well known observation that ventricular fibrillation can be induced by a single electrical impulse of appropriate intensity if it coincides with the early phase of repolarization. This so-called vulnerable period corresponds to the initial part of the T wave in the ECG (Fig. 1). The minimal strength of current required to produce fibrillation (the threshold for fibrillation) is more or less higher than the threshold for inducing a single extrasystole. The difference between the two thresholds depends in part on purely physical conditions but to a greater extent on the intrinsic susceptibility of the heart to fibrillate.

Apart from the induction of fibrillation by electrical stimulation, a spontaneously generated extrasystole may also induce fibrillation or flutter when it coincides with the vulnerable period. This is the basis of the so-called 'R-on-T-phenomenon' in the ECG which is considered as a preliminary symptom of imminent fibrillation.

As a rule, the onset of fibrillation occurs abruptly, and its termination may take place in the same way. Sometimes there are also sudden changes in the frequency of fibrillation or transitions from flutter to fibrillation and vice versa. Influences that shorten the duration of the excitatory process (and consequently of the refractory period) are able to convert flutter to fibrillation, as has been shown with vagal stimulation or with application of acetylcholine in mammalian atria. This is a particularly interesting finding because vagal stimulation as well as the application of its transmitter are known to inhibit spontaneous automatic activity very much.

Big hearts,i.e. the hearts of large animals, are in general more susceptible to fibrillation than small ones, and similarly, a whole atrium can easily be induced to fibrillate, whereas an atrial trabecula will resist. However, there are also certain differences as to the species which are examined.

Eventually, an explanation of the fibrillatory mechanism has to take into account that the dysrhythmia can be terminated momentarily by a strong electric shock applied through the closed chest via large-sized electrodes. The strength required for this electrical defibrillation is usually considerably higher than the one that may induce the arrhythmia.

RE-ENTRY VERSUS AUTOMATICITY

As an explanation of the mechanisms underlying ventricular fibrillation two alernative concepts have been discussed for many years:
1. the hypothesis of ectopic automaticity (Engelmann, 1875; Rothberger and Winterberg, 1914; Scherf, 1947 etc.),
2. the hypothesis of circus movement due to re-entry (Mines, 1914; Lewis, 1918; Garrey, 1924; etc.).

The first hypothesis assumes that the fast and irregular activity of the fibrillating ventricles is induced by one or several ectopic pacemakers firing at high rates. The second hypothesis postulates a disturbance of the spread of excitation,in that the waves start to circulate within more or less extended regions of the heart.

It cannot be ruled out at this moment that both mechanisms may operate under certain conditions. However, most of the above mentioned phenomena accompanying the induction of fibrillation by electric current are only convincingly explained by the hypothesis of re-entry. This may be further substantiated by the following facts:

There are f.i. no signs of automaticity in intracellular recordings from myocardial preparations which are strongly stimulated during their early phase of recovery, nor does automatic activity usually start or stop abruptly. Moreover, the theory of focal automaticity can hardly explain the well established dependence of the cardiac susceptibility to fibrillation on the size of the heart. However, all of these phenomena are well understood on the basis of re-entry. This will be outlined subsequently in more detail. Most convincing evidence in favour of the re-entry hypothesis has recently come from multielectrode mapping performed on fibrillating atria or ventricles (Alessie,Bonke and Schopmann,1973; Janse and coworkers, 1980).

Instead of accumulating further arguments, the conditions may be considered which are required for re-entry to occur.

ESSENTIAL PREREQUISITES FOR RE-ENTRY

The basic condition for re-entry is given by the net-like structure of the cardiac tissue in its macroscopic as well as in its microscopic dimensions. This is schematiccaly illustrated in Fig. 2 which symbolizes an elementary section of the branched network of the cardiac muscle. Although this structure would in principle allow re-entry to take place, the disturbance does not occur because the spread of excitation proceeds in the way shown in the upper panel of Fig. 2. The wave enters the system, branches off and travels along all excitable pathways converting them into a refractory state. In the lower horizontal branch of the system the propagating waves encounter and exstinguish one another because none of them is able to enter the refractory zone of the other one. Afterwards (not illustrated in Fig. 2)the recovery from excitation occurs in the same sequence as the propagation took place.

From these considerations it becomes clear that re-entry is normally not possible because the waves of excitation are longer than the circus pathways, or in other words, because the state of refractoryness of any point lasts longer than the spread of excitation. Re-entry will therefore only become possible if the wave of excitation is shorter than the pathway. Such an effect can result from an abbreviation in the duration of the excitatory state or from a reduction of the velocity of propagation. It is known that various kinds of damage to the heart may induce those influences. Another condition which may also cause shortening of the wave of excitation is the stimulation during the early phase of recovery.

From Fig. 2 it may also be derived that shortening of the wave of excitation is not the only condition required for re-entry.Even if the wave of excitation would be very short, re-entry would not occur as long as the wave could spread in all directions.Another essential condition for the development of re-entry is thus a unidirectional block of conduction. Such a condition can occur when a premature excitation enters the system while it is still partial refractory from the preceding excitation.

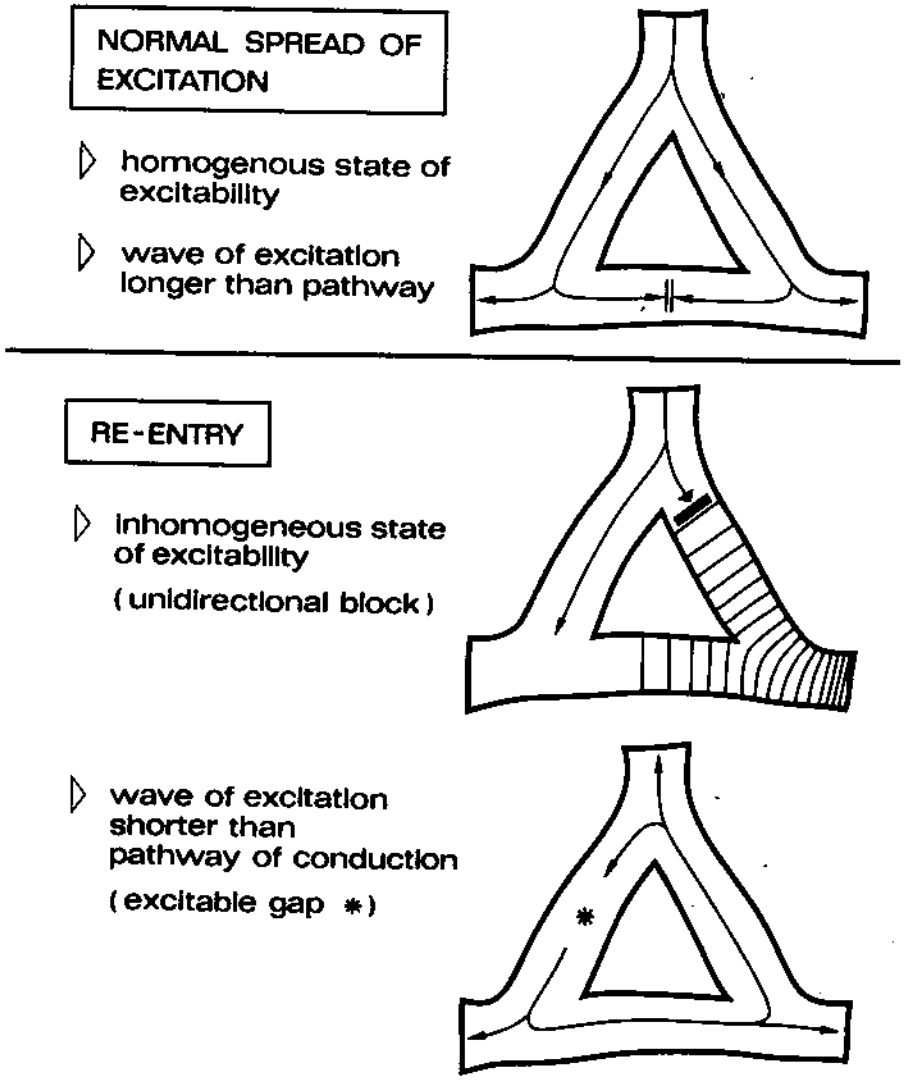

Fig. 2. Schematic representation of the network of cardiac tissue and of the conditions during normal spread of excitation and during the development of re-entry

The lower panel of Fig. 2 illustrates the development of re-entry due to a premature excitation : The premature (and consequently shortened) wave of excitation encounters one branch of the system still in a refractory state and can only spread along the other excitable pathway. Then the wave arrives at the originally blocked site from the opposite direction when this has recovered from its refractoryness and starts to re-enter the system in the antidromic direction. If the wave is short enough, it may continue to re-enter and to excite the ventricles repetitively at a high rate due to the subsidiary wavelets which leave the circus pathway.

The described conditions can occur in the heart when a premature excitation enters a region which is not yet fully recovered and in which a non-homogeneous state of excitability is present. The probability of re-entry (and of fibrillation) is the greater, the

earlier during recovery the premature beat occurs and the less homogeneous the excitatory state of the ventricles is.

MECHANISM OF THE VULNERABLE PERIOD

It has already been mentioned that ventricular fibrillation can be induced by a single stimulus of sufficient intensity coinciding with the early phase of recovery - the vulnerable period(Fig. 1). The previously outlined concept of the mechanism of re-entry includes also a satisfactory explanation of the vulnerable period. The most essential points are summarized in Fig. 3 .

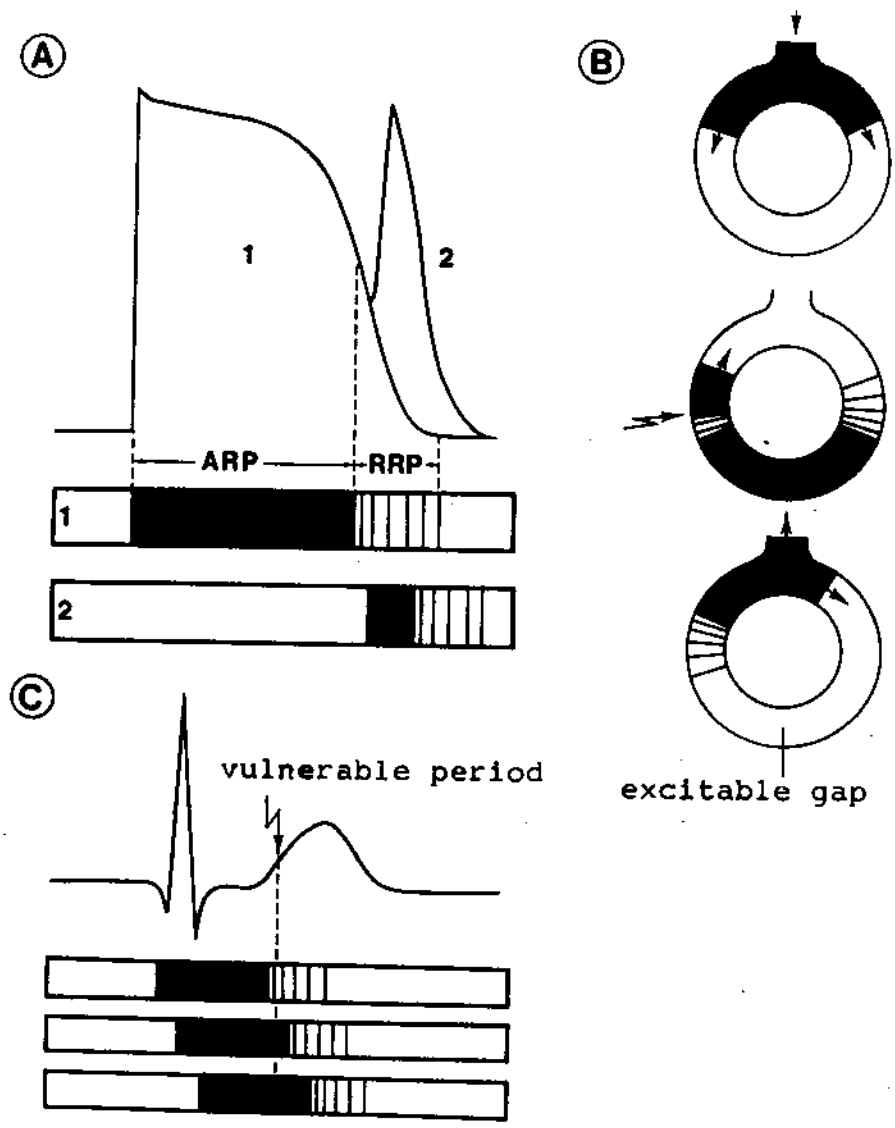

Fig. 3 .Schematic representations used to explain the vulnerable period. A)Single fibre action potentials during premature stimulation(2); ARP and RRP = absolute and relative refractory periods. B) Development of re-entry.C) Temporal relations between the vuln.period and the ECG. The symbols below the ECG tracing characterize different regions of the ventricles.

part(A)shows by means of intracellularly recorded action potentials that stimulation of the heart muscle during the early phase of recovery induces an excitatory process of short duration that entails a shortened wave of excitation. Moreover,it has been proved experimentally that a wave of excitation, elicited in this way, does only propagate in one direction (Fig. 3 B). This means that there is a unidirectional block of conduction in the orthodromic direction. Part(C) shows once again the temporal relationship between the vulnerable period and the ECG. The symbols below the ECG tracing illustrate the distribution of refractoryness in 3 different regions of the ventricles. In the region represented on the top, the stimulus (arrow) encounters conditions which are similar to those represented in part (B) of the figure. This means that the stimulus may induce re-entry in this region. At an earlier instant, the stimulus would have remained ineffective because of the absolute refractoryness of the tissue. At a later instant, the stimulus would have encountered conditions which are no longer favourable for re-entry. Only during the early phase of recovery,conditions are such that stimulation of appropriate strength can induce re-entry, and this explains the vulnerability of this phase.

VENTRICULAR FIBRILLATION INDUCED BY ALTERNATING CURRENT - SIGNIFICANCE OF EXTRASYSTOLES

It is a well known fact that electrical hazards with alternating current (ac) of 50-60 Hz are much more dangerous than those with direct current (dc). In animal experiments it could be shown that the probability of inducing ventricular fibrillation by ac does increase very much with the duration of current flow, whereas short pulses of ac ,comprising only one or few ac periods, are rather less dangerous than dc pulses of equal duration (Younossi and coworkers, 1973).

Figure 4 shows results concerning the ac threshold for ventricular fibrillation in the isolated perfused guinea pig heart(Weirich, Hohnloser and Antoni, 1983).The fibrillation threshold for ac of 5, 50 and 200 Hz is plotted against the duration of current flow. With ac of 50 Hz the threshold decreases from a value of about 80 mA at a duration of 100 ms (= 5 ac periods) to about 12 mA at 725 ms (= 36 ac periods). The other curves will be discussed subsequently. The considerable decrease of the fibrillation threshold with ac of 50 Hz can now be explained by the fact that at the longer duration there are bursts of extrasystoles which precede the onset of fibrillation and increase the susceptibility of the heart to fibrillate due to the state of non-homogeneous excitability which they create.

If the thresholds for fibrillation (determined with short dc pulses applied during the vulnerable period) of normally conducted excitations are compared with the thresholds for extrasystoles, the latter are lower by about 30 % (Sugimoto,Schaal and Wallace, 1967; Hauf and coworkers, 1973). This difference increases when several extrasystoles follow each other in close succession, as it happens when ac of sufficient strength is passing through the heart.

At the higher ac frequency of 200 Hz the threshold for fibrillation is shifted in parallel to higher values of current strength (Fig.4). This can be attributed to a decrease of the stimulatory efficacy of the ac due to the shortening of the ac half-wave duration at the higher frequency. If instead of sinusoidal ac, dc pulses of constant

duration are used at the corresponding frequencies, no change of the threshold for fibrillation can be detected (Weirich, Hohnloser and Antoni, 1983).

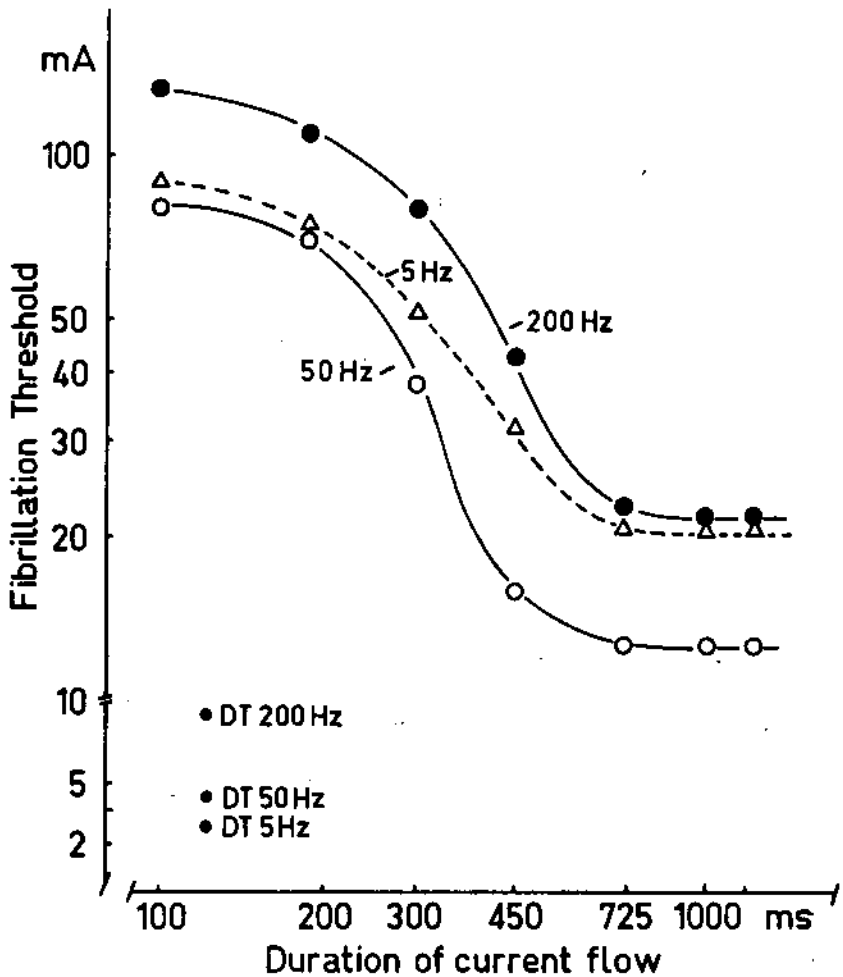

Fig. 4 .Relationship between fibrillation threshold and duration of current flow determined with sinusoidal ac of different frequencies (5 - 200 Hz)in the isolated perfused guinea pig heart.

At the lower ac frequency of 5 Hz the slope of the threshold for fibrillation is clearly less steep in Fig. 4. This can be explained in the following way : The comparatively small differences in the fibrillation thresholds of the two frequencies at the shorter durations of current flow are entirely attributed to the differences in the stimulatory efficacy. At the longer durations, the higher fibrillation threshold for ac of 5 Hz results from the fact that a smaller number of extrasystoles are induced by this current in the given time.

There are many other conditions in which the changes of the threshold for fibrillation for ac are closely related to the frequency of the extrasystoles that can be induced by the current. Thus, any influences that increase the duration of the refractory period will increase

the threshold for fibrillation. This has been shown with antiarrhythmic drugs and different other influences. On the other hand, it has to be taken into account that various kinds of damage to the heart that increase the state of non-homogeneity in its excitability will tend to decrease the threshold for fibrillation in a way that the stimulation with ac will require a smaller frequency of extrasystoles to induce the arrhythmia.

MECHANISM OF ELECTRICAL DEFIBRILLATION

The most effective method for suppressing ventricular fibrillation is the application of short-lasting,strong electric shocks to the fibrillating heart. The mechanism of action of this procedure can also be understood on the basis of the re-entry hypothesis : The strong electric pulse is appropriate to stimulate all excitable regions of the heart and convert them into an unexcitable (refractory) state.Thus, the re-entering waves of excitation are no longer able to proceed, since refractory tissue is encountered everywhere, and this will stop ventricular fibrillation momentarily. The broad application of the current is required to stimulate all excitable gaps in between the circulating waves. On the other hand, the electrical defibrillation can remain effective only as long as the heart is not yet damaged to a degree that would cause re-entry to occur again.

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DISCUSSIONS

HEROUX: In relation to the two rival theories of fibrillation, ectopic locus versus reentry. I would note that a coupled system of differential equations describing myocardial characteristics can, under certain conditions, make a transition to chaotic behaviour, as described by Leon Glass of McGill University. In a homogeneous medium, such a system has been demonstrated to generate spiral fronts of excitation. Would not this theory be a useful conceptual link between the rival theories, that is, reentry generates the ectopic locus, although stimulation does not originate in it?

ANTONI: I do not intend to disregard the advantage of mathematical models in obtaining a better understanding of complicated systems. However, one must be cautious, because those models can only work on the basis on which they are considered. As to the two alternative concepts of fibrillation, many observations point to an interrelationship just opposite to that you have mentioned. In most cases the fibrillating arrhythmia may be induced by focal activity (automaticity) and may then continue as reentry. If atrial fibrillation persists for many years, this can hardly be due to an ectopic focus but very likely to persistent circus movement.

BRIDGES: I notice the current thresholds given in your paper for an electrode on the heart are in the milliampere range. On the other hand, O.Z. Roy, Green and others have found for otherwise equivalent situations, microampere threshold levels. Can you explain the difference?

ANTONI: I am fairly sure that the differences you mentioned are not due to differences of the animal species or to any biological properties but are exclusively attributable to purely physical conditions. In our experimental setup, the relatively small contact areas between the electrodes (wires) and the heart cause a comparatively high resistance and are therefore responsible for the high current required for inducing fibrillation.

DOLAN: What was the current density or electric field in your cell membranes? Can you estimate it?

ANTONI: It was difficult to estimate the current density in our preparation because the electrodes were not plates but were wires with no well defined contact area.

REILLY: Two questions as follows: (1) In the presentation, a curve was shown relating stimulus duration to thresholds for both ventricular fibrillation, and for extrasystole, using two different electrode sizes. Can you explain why the larger electrode requires a larger threshold for extrasystole than with the smaller electrode, but the opposite effect is seen for ventricular fibrillation threshold. (2) A graph was presented showing the change of fibrillation threshold with frequency for unidirectional pulse trains, and for sinusoidal waveforms. As frequency was increased, thresholds increased for sinusoidal stimulation, but not for pulse train stimulation. Would Dr. Antoni please explain this difference? We note that dynamic models of excitable membranes predict that beyond a certain frequency, oscillating currents are less efficient than unidirectional currents, and that greater oscillatory current magnitudes are required as frequency is increased. Could membrane excitability properties account for the fibrillation threshold shift with frequency?

ANTONI:

(1) In order to stimulate the heart inducing an extrasystole it will be sufficient to depolarize one or a few myocardial cells to threshold. This will require a certain current density at the region of stimulation. If the size (contact area) of the electrodes is increased, current density is reduced and hence the stimulating efficacy of the current declines. In order to induce fibrillation it will not be sufficient to stimulate a few cells because the development of the arrhythmia requires stimulation of a certain mass of heart muscle in which a certain degree of non-homogeneity of the excitability does exist. Thus, increasing the size of the electrodes has two opposite effects on the threshold for fibrillation - a decrease of the stimulating efficacy of the current and simultaneously an improvement of the conditions required for re-entry. Obviously, the latter influence becomes stronger than the former one, when the electrodes are made larger.

(2) The differences in the fibrillation thresholds for trains of rectangular pulses and for sinusoidal ac at frequencies increasing from 50 to 500 Hz can solely be attributed to the change of the stimulating efficiency of the current without a change in membrane properties. With increasing ac frequency the duration of the ac half waves decreases, and this is obviously not compensated by the steeper slope of rising phases of the sinusoidal pulses. With the rectangular pulses, the duration was kept constant while increasing the frequency and thus no change in threshold might be expected.

THE CONDITIONS NECESSARY FOR THE ELECTRICAL INDUCTION OF VENTRICULAR FIBRILLATION

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ABSTRACT

Ventricular fibrillation is a lethal electrical dysrhythmia which results in a complete loss of blood pumping by the heart. It can be precipitated by a single or repetitive electrical shock. For a single stimulus to evoke fibrillation it must be suprathreshold and be delivered in the vulnerable period of the ventricular cycle which occurs during the T wave of the electrocardiogram. Repetitive stimuli above about 5/sec induce fibrillation by creating re-entrant excitation. Repetitive stimuli of a wide variety of waveforms can produce fibrillation, an important factor being frequency - the higher the frequency, the higher the current required.

The basic law of tissue stimulation, expressed by the strength-duration curve, underlies all cardiac stimulation, whether it be for pacing or for inducing fibrillation. The law states that the peak current required for excitation increases as the duration of the stimulus pulse is decreased. From this basic law there derives an energy-duration and a charge-duration curve. There is no single stimulus duration that can achieve stimulation with a minimum current, energy and charge.

In this paper, the fundamental law of tissue stimulation is applied to demonstrate how excitation and fibrillation of heart muscle are achieved.

KEYWORDS

Ventricular fibrillation; powerline hazard; re-entrant excitation; vulnerable period; high frequency hazard.

INTRODUCTION

A major hazard of powerline alternating current is ventricular fibrillation, a condition in which all of the fibers of the ventricles, the main pumping chambers of the heart, contract and relax asynchronously and rapidly. A complete loss of cardiac pumping and circulatory collapse ensue. If circulation is not supported by cardiopulmonary resuscitation (CPR), or defibrillation is not accomplished within about three minutes, irreversible brain damage starts to occur.

There are several situations in which ventricular fibrillation can be precipitated, all of which require that the ventricles receive an effective stimulus. It is the objective of this paper to present the criteria for such stimulation and show what kind of stimulation initiates ventricular fibrillation.

VENTRICULAR FIBRILLATION

Before discussing tissue stimulation, it is of value to understand how ventricular fibrillation can be precipitated and sustained. Ventricular fibrillation was first induced by Hoffa and Ludwig (1850) by the application of repetitive induction-coil shocks to the exposed ventricles of a dog heart. However, the mechanism underlying fibrillation and its maintenance were not demonstrated until Mines (1913) and Garrey (1914) demonstrated circus motion. They used rings of tissue cut from the atria of a ray (Mines) and the ventricle of a turtle (Garrey) and their studies led to the concept of re-entrant excitation.

The concept of re-entrant (circus-motion) excitation is illustrated in Fig. 1, in which a ring of myocardium is made by cutting a slice from the atrium (Fig. 1, 1-1) or the ventricles (Fig. 1, 2-2); in the latter case a double ring is obtained in animals with septal hearts; although a single ring is obtained with the turtle heart.

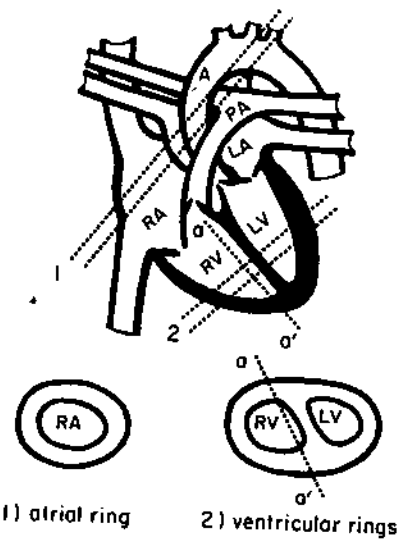

Fig. 1: Sections through the heart to produce rings of excitable tissue.

Using a ring of myocardium, it is easy to demonstrate the re-entrant excitation that underlies the maintenance of ventricular fibrillation. If a stimulus is delivered to such a ring, as shown in Fig. 2A, excitation will progress up both sides of the ring (B), and when it reaches the top (C), the waves of excitation run into each other and no further excitation can take place, since tissue is refractory when excited. Meanwhile, in uniform tissue, recovery follows excitation.

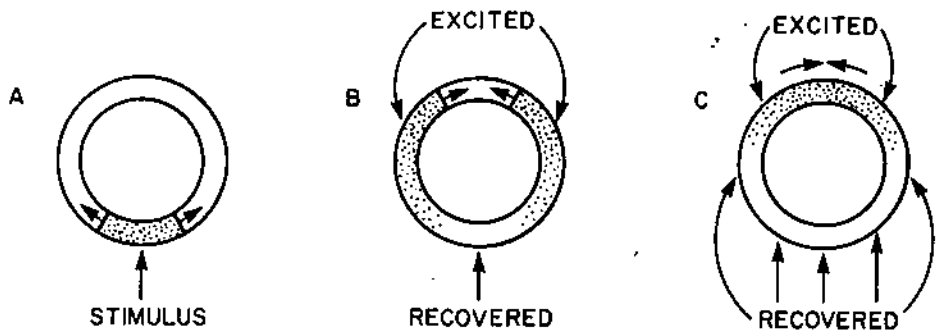

Fig. 2: Stimulation of an homogeneous ring of excitable tissue.

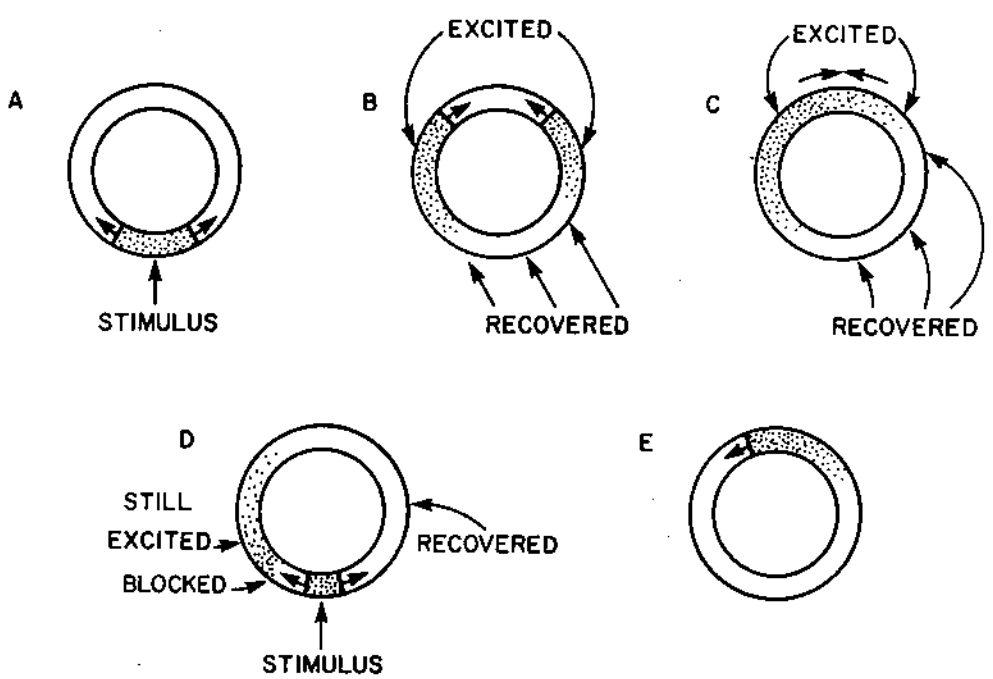

Fig. 3: Circus (re-entrant) excitation in a ring of excitable tissue.

Now, if the two sides of the ring are slightly different, recovery will occur earlier on one side. In this case, the response to subsequent stimulation can be quite different. If, as before, a stimulus is delivered (Fig. 3A), excitation progresses up both sides of the ring (B); but recovery will occur later on one side, as shown by the dots in Fig. 3-B, C. Now if a second, appropriately timed stimulus is delivered, as shown in Fig. 3D, it cannot be propagated to the left, because the tissue there has not recovered. It can, however, be propagated up the

right side. If, when excitation reaches the top of the ring, recovery in the left side has occurred, then the wave of excitation can travel around the ring (Fig. 3E), if the ring is large enough, the propagation velocity and the recovery (refractory) period are appropriate. In Mines' preparation the circus (re-entrant) motion was sustained for 50 trips and in Garrey's, it persisted for 7 hours. When one views ventricular fibrillation in a large exposed heart, especially if it is hypoxic, the circulating waves of contraction and relaxation are easily visible.

Therefore, the requirement for the maintenance of fibrillation is that there exists a relation between the propagation velocity for excitation, the size of the excitable tissue and the duration of the refractory period. The former and latter are properties of myocardium; the ventricular size pertains to the size of the subject. McWilliam (1887) showed that the ventricles of small warm-blooded animals (e.g. cat, rabbit, rat, mouse, hedgedog and fowl) spontaneously defibrillate; while those of larger animals remain in fibrillation. Interestingly, the ventricles of puppies defibrillate spontaneously; when the puppies grow into dogs, fibrillation persists, offering support for the critical mass factor.

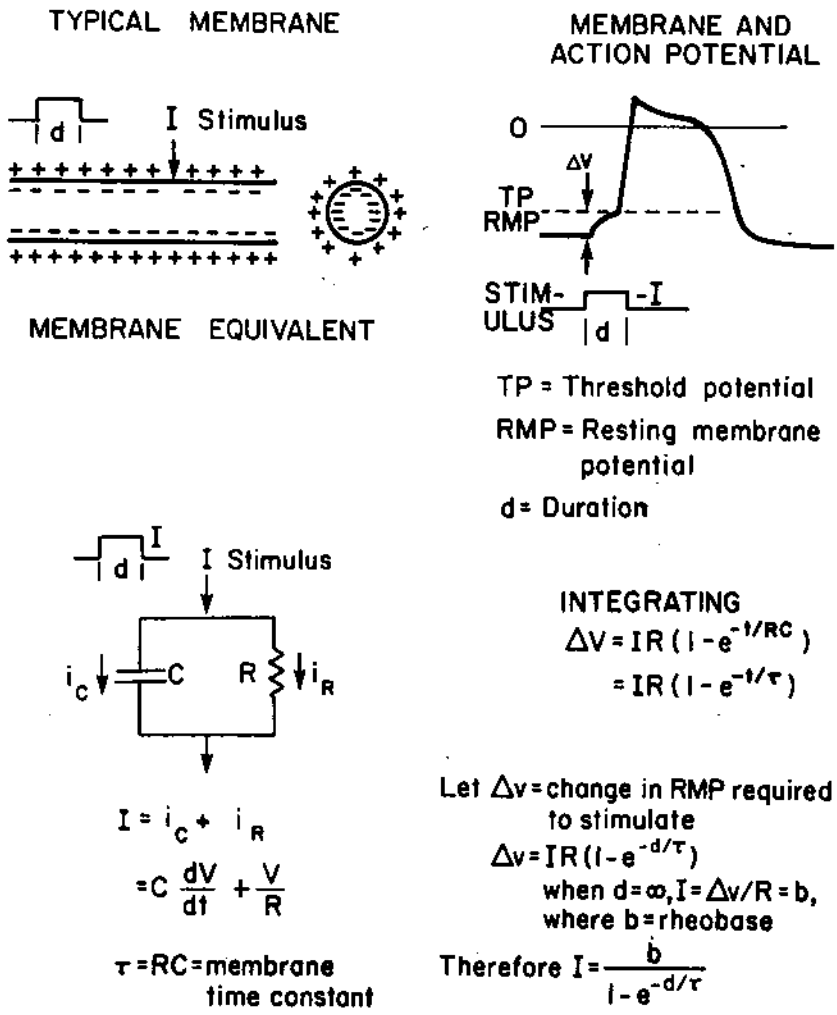

Fig. 4: Stimulation of a strip of excitable tissue and an electrical analog of the cell membrane.

TISSUE STIMULATION

To stimulate excitable tissue, it is only necessary to apply a pulse of current of adequate strength to decrease the resting membrane potential (RMP) of a cell to the threshold potential (TP) as shown in Fig. 4, after which a regenerative process occurs and the cell depolarizes (becomes excited) and repolarizes (recovers). The depolarization is propagated over the tissue, and in muscle, contraction ensues. Figure 4 illustrates the membrane of a strip of excitable tissue to which a rectangular current stimulus (I), has been delivered. Cell membranes consist of a parallel capacitance (C) and resistance (R). The stimulating current divides between these components; Fig. 4 illustrates this current division and the resulting first-order differential equation which describes the circuit. Separating the variables, integrating, and entering the boundary condition of I=b for an infinitely long duration stimulus yields

$$I=b \Big/ \left[1-e^{-d/\tau}\right] \qquad (1)$$

where $\tau = RC$, the membrane time constant and d is the duration of the stimulus. This expression shows that the current required to stimulate increases as the stimulus duration is decreased. Figure 5 illustrates a family of current strength-duration curves for different values of τ, the membrane time constant. For mammalian myocardium, τ is about 2 msec. (Pearce et al 1982).

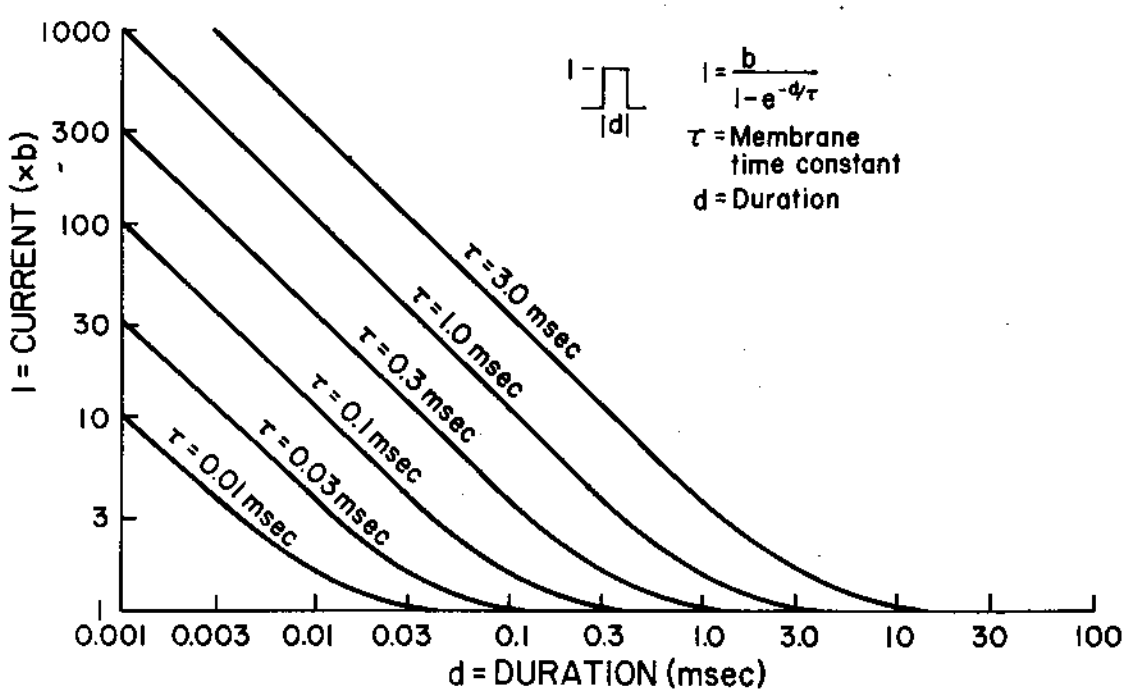

Fig. 5: Strength-duration curves for excitable tissues with different membrane time constants (τ).

Although it is current that excites, a stimulus is often described in terms of energy or charge, For a rectangular pulse, energy (U) is the product of the square of the current, the duration and the resistance through which the current flows. Charge (Q) is the product of current and duration (Q=Id). Figure 6 illustrates the strength-duration curves for current, energy and charge, normalized for duration in terms of d/τ. Note that there is no single duration for a minimum for all three quantities. Minimum current occurs with an infinitely long duration stimulus. Minimum energy occurs with a duration equal to 1.255τ. Minimum charge exists for an infinitely short duration pulse.

The foregoing was derived on the assumption that a typical cell membrane can be modeled as a parallel R-C circuit to which a single, rectangular current pulse was applied.

In general, for a stimulus to be effective, it must be intense enough, have an abrupt onset and last long enough. If the stimulus wavefront is not abrupt, (e.g. increasing exponentially, sinusoidally or linearly), the tissue can accommodate, and the threshold for stimulation is increased. The phenomenon of accommodation has been thoroughly investigated by Hill (1935).

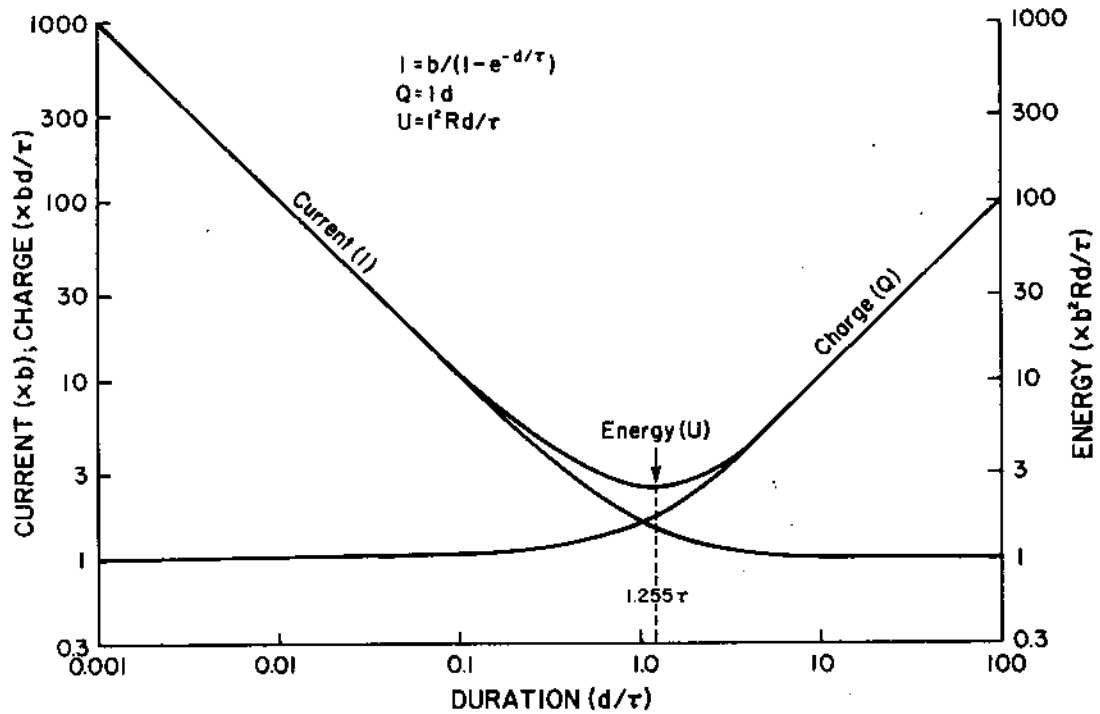

Fig. 6: Normalized strength-duration curves for current (I), energy (U) and charge (Q).

PRECIPITATION OF VENTRICULAR FIBRILLATION

Ventricular fibrillation can be precipitated by a single stimulus, as well as by repetitive stimuli. In the former case the vulnerable period is involved; in the latter the vulnerable period and multiple-pathway excitation participate. These situations will now be discussed.

VULNERABLE-PERIOD STIMULATION

The vulnerable period of the ventricles is the time in their recovery cycle when a single stimulus can evoke ventricular fibrillation. The recovery period occurs during the downslope of the excursion in trans-membrane potential, corresponding to the T wave of the ECG. Figure 7 (lower) makes this correlation. To be effective in precipitating fibrillation, the stimulus must be suprathreshold and be presented at the appropriate time in the recovery cycle. Figure 8 illustrates the precipitation of ventricular fibrillation by a single stimulus delivered during the T wave of the ECG.

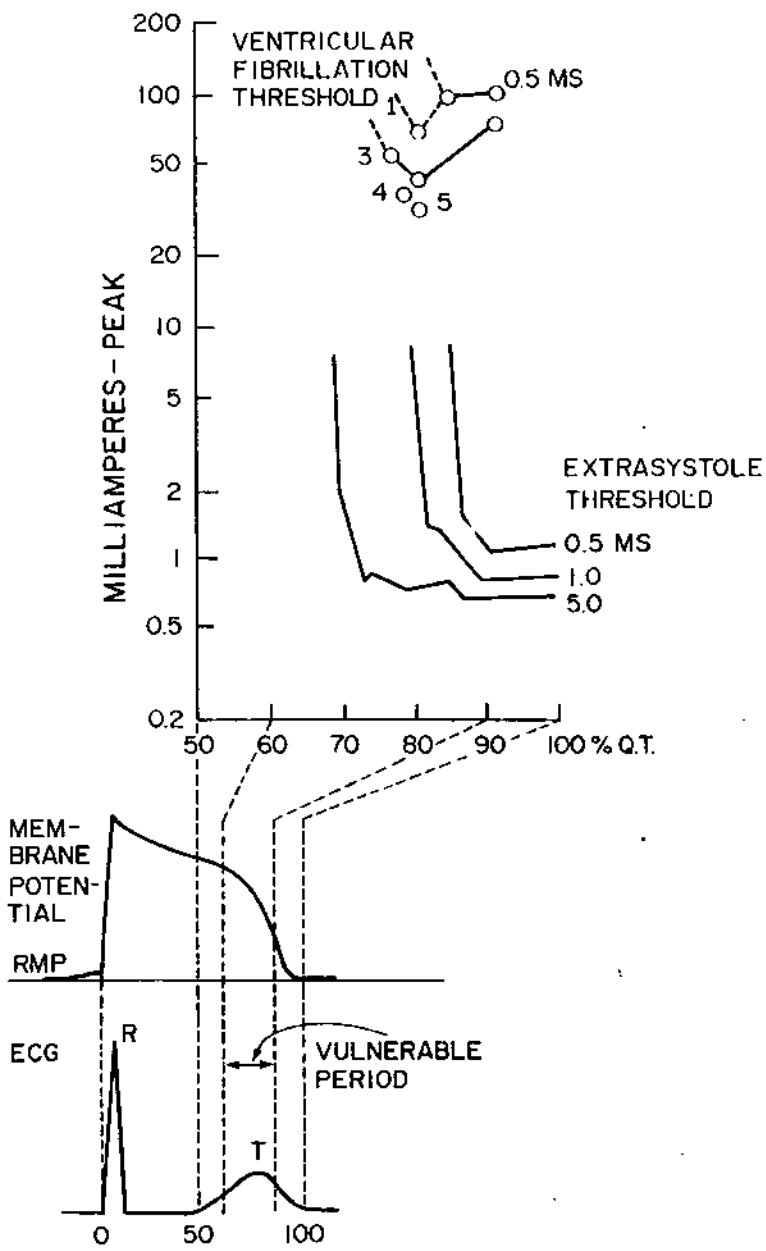

Fig. 7: The ECG, transmembrane potential and strength-interval curves, identifying the vulnerable period.

The sketch at the bottom of Fig. 7 illustrates the excursion in transmembrane potential that expresses excitation and recovery and the way these two fundamental events turn up as the R and T waves of the ECG. Above this sketch is a graph which illustrates strength-interval curves for evoking an extrasystole with 5, 1 and 0.5 msec stimuli delivered earlier and earlier in the ventricular cycle. Time in the cycle is expressed in terms of percent of the duration of one cycle, which is measured from the beginning of the R wave to the end of the T wave. Note that for each duration of stimulus, the intensity required to produce an excitation increases as the stimulus is delivered earlier in the cycle. For all durations, the intensity required increases abruptly as the refractory (inexcitable) period is approached. At the top of Fig. 7 are threshold stimulus intensities for precipitating ventricular fibrillation with single 0.5, 1, 3, 4 and 5 msec stimuli delivered at the times indicated in the ventricular cycle. These data illustrate clearly that the stimulus intensity required for inducing fibrillation is much higher than that required to evoke an extrasystole. Note also that there is only a narrow time window when such a stimulus can initiate fibrillation. This time window is the vulnerable period and extends from about 65 to 90% of the ventricular cycle.

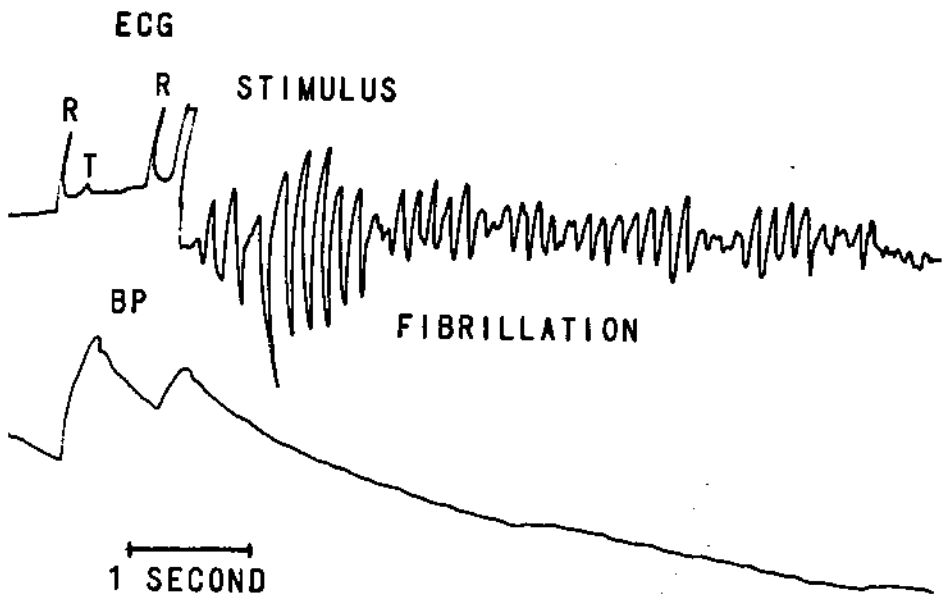

Fig. 8: Ventricular fibrillation by the delivery of a single stimulus during the vulnerable period.

The ratio of the stimulus intensity to evoke fibrillation to that for an extrasystole is somewhat dependent on electrode geometry. With direct-heart electrodes, the ratio may be 20-30 for normal hearts. With chest-surface pacing electrodes, the ratio is about 10-15 (Voorhees et al 1983). For diseased or metabolically compromised hearts, the ratio is less.

The mechanism of fibrillation by vulnerable-period stimulation is not fully explained. Some investigators believe that the suprathreshold stimulus alters excitability markedly at the site of stimulation and that a rhythmic oscillation in membrane potential (pacemaker) occurs, which continues to send out impulses long after the stimulus. Others believe that since the stimulus is delivered when the myocardium is maximally asymmetrical and excitation is blocked in one direction, propagates in another, returning when the blocked area recovers, as in re-entrant excitation. Despite uncertainty or the mechanism, vulnerable-period stimulation is a very real phenomenon of single pulse stimulation.

REPETITIVE STIMULATION

Ventricular fibrillation is most easily induced by rapidly occurring stimuli of a variety of waveforms; frequency is the critical factor. A frequency of 1.2/sec is typically used for cardiac pacing; each stimulus produces a single response. However when the frequency exceeds about 5/sec, the ventricles are reaching the limit of their ability to respond. Around this frequency, each stimulus falls in the vulnerable period of the previous cycle and the risk of fibrillation is high if the stimulus intensity is suprathreshold. With a higher frequency of stimulation, not all stimuli will excite the myocardium because it will not have recovered from the stimulus that excited it. Figure 9 illustrates the response to a train of 60 Hz sinusoidal stimuli applied to cardiac muscle which can be excited only as often as recovery permits. When such a stimulation exists, the ventricles are maximally asymmetrical in their recovery phase and excitation is blocked in one direction and not in another. The stage is set for re-entrant excitation and fibrillation.

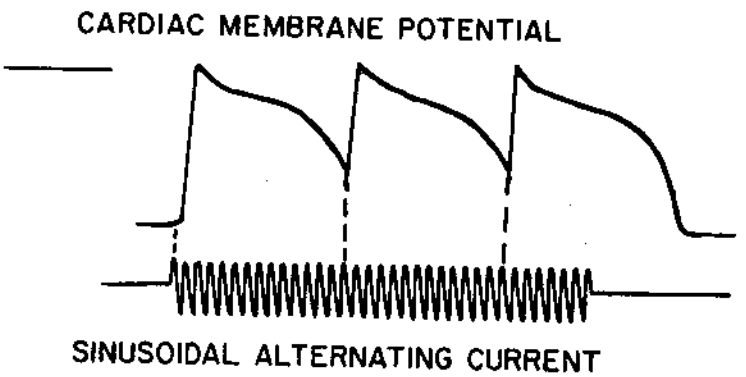

Fig. 9: Cardiac membrane potential and sinusoidal stimulation. Excitation occurs only after adequate recovery of the membrane potential.

Figure 10 illustrates the immediate precipitation of ventricular fibrillation by the application of 60 Hz sinusoidal current to the ventricles of a dog heart using a hand-held bipolar electrode. Note that after only a few excitations, fibrillation occurred, pulsatile cardiac pumping ceased and blood pressure fell precipitously.

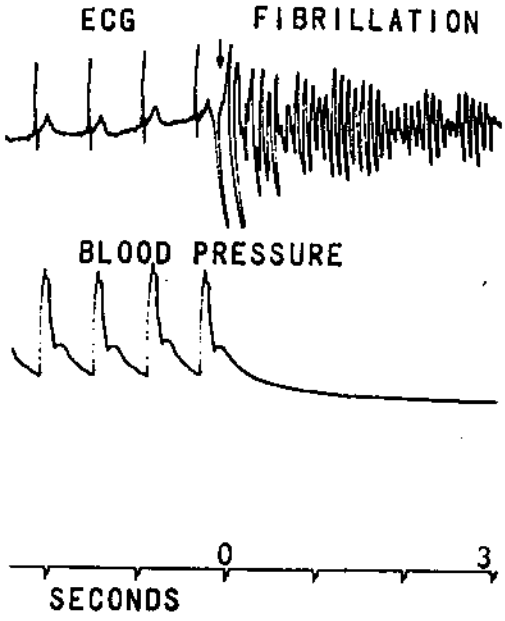

Fig. 10: The ECG and blood pressure before and during the application of 60 Hz stimulation which produced ventricular fibrillation.

For sinusoidal alternating current to produce fibrillation, it must attain a sufficient current density at the heart and be applied for an adequately long period. Geddes et al (1973) found that if the duration of application of 60 Hz sinusoidal alternating current is reduced to below about one second, the threshold current for fibrillation rises.

With sinusoidal alternating current, frequency is an important consideration. Although some accommodation occurs with sinusoidal current, this waveform can be equated roughly to a train of pulses (only a few of which will stimulate), having a duration equal to the the reciprocal of frequency. If this assumption is valid, theory predicts that the threshold current for fibrillation would increase as frequency is increased. Figure 11 makes this point and represents the result of a series of experiments on the induction of fibrillation in the dog with right and left ventricular catheter electrodes (Geddes et al 1971). In all studies, the current was applied for 5 seconds.

The strength-duration curve shown in Fig. 6 indicates that very high intensity current is required if the pulse duration is short. Ventricular fibrillation has been reported following the application of electrosurgical current which has a frequency in the megahertz range (Hungerbuhler et al 1974 and Geddes et al 1975). Whether the high frequency current precipitated fibrillation or whether modulation on it, which is removed by rectification by the electrode-electrolyte interface, produced fibrillation is not known. Figure 12 is presented to illustrate that 2.3 MHz electrosurgical current, occurring in 120/sec bursts can produce fibrillation.

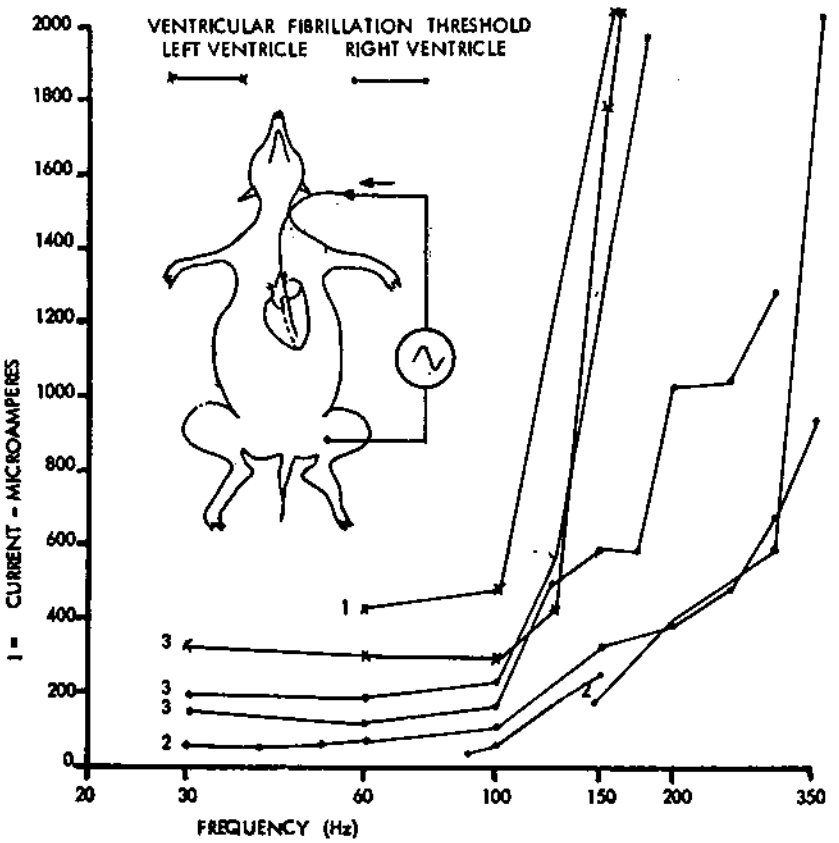

Fig. 11: Threshold for ventricular fibrillation versus frequency of sinusoidal alternating current applied to a catheter electrode in the heart.

To make this record a grounded right ventricular pacing catheter electrode was placed in a dog heart and electrosurgical current was applied to the chest with an active electrode connected to an electrosurgery machine.

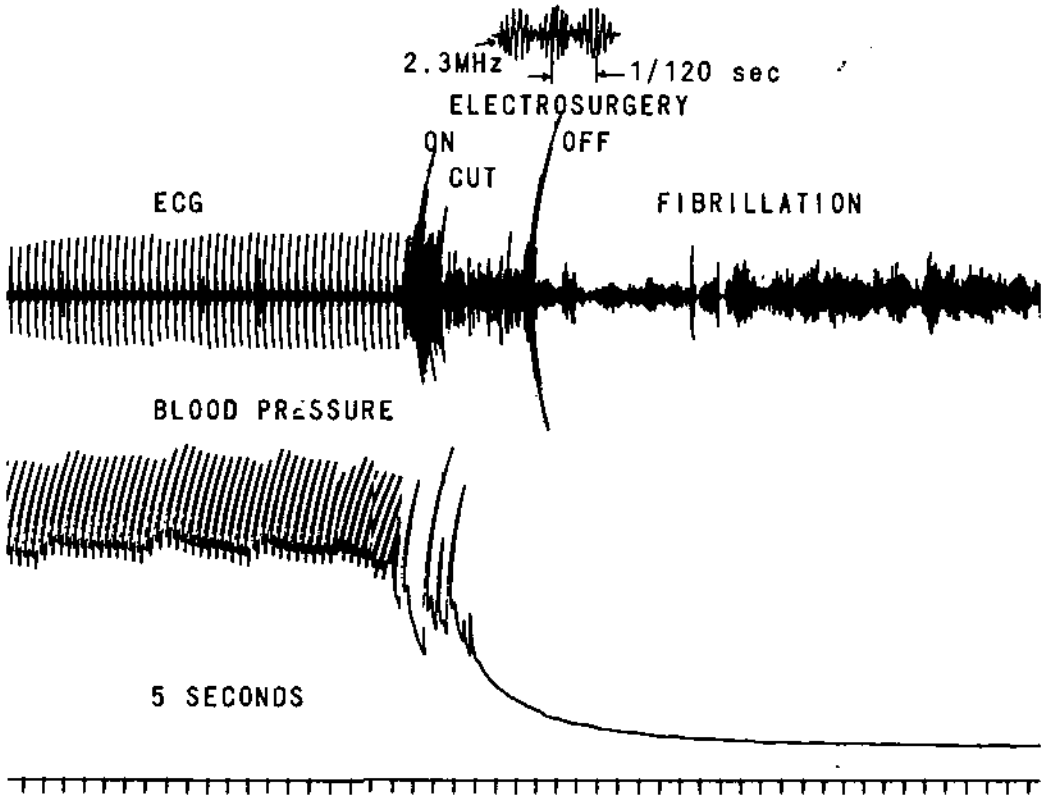

Fig. 12: The ECG and blood pressure prior to and during the application of 2.5 MHz electrosurgical current. Note the almost immediate precipitation of ventricular fibrillation.

SUMMARY

Ventricular fibrillation is an electrical dysrhythmia which results in circulatory collapse. It can be precipitated by a single or repetitive electrical stimulus. Irrespective of how initiated, the mechanism that sustains it is re-entrant excitation. To be effective, a single stimulus must have an adequate current intensity and duration; these two factors are reciprocally related. The energy and charge delivered by a single effective stimulus follow directly from the strength-duration curve for current. The minimum stimulating current occurs with an infinitely long duration stimulus. The minimum charge occurs with an infinitely short duration stimulus. The minimum energy occurs with a duration of about 2.5 msec. for cardiac muscle.

For a single stimulus to precipitate fibrillation, it must be suprathreshold and fall during the vulnerable period of the ventricles. For a repetitive pulse train to precipitate fibrillation, the intensity need only be at threshold and the fre-

quency be in excess of about 5/sec. Above this frequency, not all pulses in the train will be effective stimuli; only those delivered beyond the refractory period can stimulate. In general, with sinusoidal current, the higher the frequency, the higher the threshold for producing fibrillation. The high frequency limit is not known at this time.

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DISCUSSIONS

KNICKERBOCKER: Regarding your observations of the role of size of heart and the propensity of the heart toward fibrillation, particularly as reflected in the aging puppy, is the observation of N.L. Gurvich that fibrillation occurs in the puppy heart only after the appearance (on optical microscopy) of the intercalated disk (1) a currently credible observation and; (2) another important factor in the determination of whether fibrillation will or will not occur.

GEDDES: I don't think I can answer that question but Dr. Antoni may be able to answer that question.

ANTONI: I think I can give a comment to this. An interesting finding to note is that the velocity of conduction in cardiac muscle is not only dependent on the properties of the surface membrane but also on the resistance of the transverse cell boundaries represented by the intercalated discs. These structures, which are normally easily permeable for intracellular ions, develop a higher resistance when the intracellular concentration of Ca^{++} ions rises above a critical level. In a damaged cell for instance, when Ca^{++} leaks into the cell, the intercalated discs become less permeable and the longitudinal resistance rises. I don't know, however, whether these structures change their resistance during the development or during hypertrophy.

GEDDES: Dr. Antoni has given a very good review of this question. The histological evidence to date has not been correlated with the ability of hearts to sustain fibrillation of the ventricles. The discussion, however, was not on the propensity to fibrillate, rather on the ability of hearts to sustain fibrillation when induced electrically. Atrial fibrillation is not sustained in the dog, it is in horses. Atrial fibrillation is sustained in man with enlarged atria. Both examples favour the 'critical mass' concept. There's another factor, by the way, that comes into play and Dr. Griffin alluded to it this morning. If you take a heart that is transitional you can stimulate it, and then you stop stimulating it and it will go for a few beats. It may look like it is in fibrillation and it will spontaneously defibrillate. If you adjust the frequency and the intensity and maintain a tachycardia for quite a long time, you will stimulate sympathetic

nerve fibres in the myocardium which will shorten the refractory period and the fibrillation will last a great deal longer. It won't be permanent, but it will last quite a long time (maybe minutes). So there are second order factors and I think the intercalated discs and the sympathetic tone are two important factors.

POMERANZ: In Figure 7 showing the vulnerable period, you had two graphs, one showing the ventricular fibrillation threshold and the other showing the extrasystole threshold. The ventricular fibrillation threshold was shown to be about a factor of 100 greater than the extrasystole threshold. Two questions, first why weren't they the same, and second if you use multiple pulses instead of single pulses would not the extrasystole threshold become more relevant, and the threshold be a hundred times less if you used a train of pulses say, or ac?

GEDDES: There are several questions contained in your question and your comment. First, why are the extrasystole and the fibrillation threshold different? For extrasystoles, all you have to do is depolarize a single myocardial cell. For re-entrant excitation, there has to be a gradation of myocardium that is not excitable and that is excitable. As Dr. Antoni mentioned, what exactly happens during a super threshold stimulus is not well worked out. It would appear that it does create unidirectional block so that one would expect an increased current pulse required for vulnerable period fibrillation on the basis of local excitability. Why the factor is one hundred times or fifty times, I do not know. I can tell you this though, that the electrodes that we used were very small electrodes and they were placed directly on the surfaces of the right and left ventricles. As I said, when we tried with large electrodes on the surface of the chest, the threshold ratio was about 10 to 1. Dr. Antoni presented some information this morning that is in the same direction. What determines that ratio no one really knows. I suspect that it's going to be sensitive to temperature, intracellular K and extracellular Na.

JACKMAN: I don't understand why cells are more susceptible to some permanent electrical depression based on the timing in the cycle. What confuses me is why the timing of the shock is so critical. If the shock energy itself is capable of depressing conduction for long periods of time (enough to establish ventricular fibrillation for a few seconds) why (if that shock is delivered shortly after the upstroke of the action potential) does it take so much greater, (almost an infinitely greater amount) of energy to fibrillate than it does if that shock is delivered while some of the cells are repolarizing?

GEDDES: I don't quite know how to handle that question because in order to get fibrillation you have to have a massive myocardium, you have to have a lot of cells. So, what you need to produce fibrillation is preferential excitation in one direction. Those cells that were refractory when the stimulus was given, can recover and the impulse will come around and can keep circulating around. So one doesn't need injury, one just needs prolonged refractoriness. The condition for this exists in the heart to start with because of the way the coronary circulation is distributed. All parts of the ventricle do not recover at the same time. There is a total gradation of early recovery and late recovery as there is a gradation of the spread of excitation which sustains fibrillation. I don't think I can answer your question, but I would suggest that you think globally. Don't think of "the membrane", think of all of the cardiac muscle membranes. There are spatial and temporal characteristics that one must consider. It is not so much propagation velocity that is depressed, it is recovery that is altered tremendously.

GRIFFIN: I think my question will be a fairly simple one. Given that most of these studies are performed using bipolar electrodes of various surface areas and reasonably fixed proximities, say one to a few centimeters, do you think that as you increase the stimulus pulse, the recruitment of additional myocardium or the expansion of the electrical field plays a role in this phenomenon?

GEDDES: Yes. Inasmuch as patchy refractoriness is needed to favour re-entrant excitation, the increased stimulus intensity (when vulnerable-period stimulation is sought) will effect heart cells distant from the stimulating electrode.

GAMS: In the experiments presented today, the parameters of the experiments have not been defined. It would help in the comparison of various research results if scientists would report in a uniform format parameters such as: electrode surface area, current density, site of stimulation, electrode material, electrode geography, etc. This is only good science.

GEDDES: I could not agree more.

TARCHALSKI: Regarding a victim of electric shock, a lay rescue person can only determine presence or absence of heartbeat, should the rescue program include an external mechanical stimulus to start the heart action?

GEDDES: A mechanical stimulus can be dangerous as well as beneficial in a pulseless subject. If delivered during a heart beat, it can precipitate fibrillation; if delivered when no beat is present, a heart beat can be produced. Because of the ambiguity in a practical situation, clinicians now prefer to perform CPR on all pulseless patients in the field. Enthusiasm for the chest thump has been largely abandoned by those who proposed it.

BERNSTEIN: Your Figure 11 shows the effect of frequency on fibrillation current threshold. The fibrillation current level begins to increase at frequencies above 100 Hz. How is this reconciled to AAMI and VL standards where the fibrillation current threshold is taken to be flat to 1 kHz?

GEDDES: In our direct-heart and closed-chest animal studies, the threshold current for ventricular fibrillation starts to rise when the frequency exceeds about 100 Hz. This is to be expected from the strength-duration curve for cardiac muscle. Sinusoidal current can be considered (roughly) to resemble a train of pulses, the duration of which is the reciprocal of the frequency, ie, the period. Others have found the same relationship. I cannot comment on AAMI standards.

POTENTIAL DISTRIBUTIONS IN THE VICINITY OF THE HEARTS OF PRIMATES ARISING FROM 60 Hz LIMB-TO-LIMB BODY CURRENTS

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ABSTRACT

A series of *in vivo* invasive tests were conducted on baboons to develop a noninvasive way of determining the electric fields or current densities near the human heart arising from 60 Hz body currents. An electrode in the form of a catheter was implanted in the heart of a baboon and the potential of this electrode was compared to the potential of other electrodes implanted on the surface of the baboon's thorax. A four-probe resistance measurement method was also used to develop the differential resistivity in various portions of the thorax. The current densities were developed from the electric fields and differential resistivity measurements. Several different limb-to-limb 60 Hz current flow conditions were used.

Electrodes on the surface of the chest directly adjacent to the heart (just above the heart if the primate is lying flat) were found to be nearly identical in potential with the heart catheter electrode for 60 Hz currents flowing through the body. The noninvasive, four-probe method was also confirmed in tests on baboons which allowed development of the gross resistivity and calculation of current density.

These findings are highly significant inasmuch as current densities and potential gradients in the immediate vicinity of the human and test animal hearts can now be approximately developed by noninvasive measurements made on the surface of the thorax. This method might also permit a more scientific extrapolation of test results conducted on nonhuman animals (such as quadrupeds) to the human situation.

KEYWORDS

Electric shock; electrical safety; fibrillation current, fibrillation current density; electrical parameters of primates, cardiac pacemaker; cardiac pacemaker interferences.

INTRODUCTION

Over the last decade, IIT Research Institute conducted a study to determine the effect of 60 Hz electric fields on patients with implanted cardiac pacemakers (Valentino, Miller, and Bridges, 1972; Zalewski, 1975; Bridges and Frazier, 1979a; Bridges, Frazier, and Hauser, 1978; Frazier, Bridges, and Hauser, 1978; Bridges and Frazier, 1979b). During this program, a modeling method was developed which permitted extrapolation of invasive tests on nonhuman primates to noninvasive tests on humans to predict the performance of implanted cardiac pacemakers.

This technique and other methods made it possible to predict the response of implanted cardiac pacemakers to body currents from various types of sources, either from household appliances or from electric fields from power lines. Some of the experimental methods and modeling techniques developed in that program may be useful to extrapolate the results of shock tests on nonhuman subjects to the human situation.

The primary purpose of this paper is to summarize some of the test results applicable to direct electrical shock. A second objective is to discuss some of the proposed body-weight shock threshold scaling relationships and indicate how the modeling/measurement method might be used to resolve the scaling problem.

In typical pacemaker implants, one electrode is emplaced in the heart and another (generally formed by the metallic shell of the pacemaker) is implanted just beneath the skin either in the shoulder (pectoral) or in the abdomen (abdominal). If a patient with an implanted pacemaker touches an energized household appliance, leakage currents from the appliance can flow through the body and cause a potential difference between electrodes. This difference, in the case of certain pacemakers and physiological conditions, can alter the operation of the pacemaker.

One goal of the series of tests on baboons reported here was to develop a relationship between potential measurements made on the surface of the thorax and actual potential differences between the implanted electrodes of the pacemaker. A second goal was to measure empirically, using noninvasive techniques, the differential resistivity of the human thorax. From the measurement of the potentials on the surface of the thorax and the development of the differential resistance, the current densities in the vicinity of the heart can be calculated. If such relationships could be established, then the behavior of implanted pacemakers could be predicted by making noninvasive measurements on the chest of humans experiencing innocuous levels of body current flows.

In typical monopolar pacemaker implants, the catheter within the heart is the electrode farthest removed from the surface of the body. The shell of the pulse generator serves as the second electrode and is generally located immediately below the skin. Skin potential measurements made near the pulse generator therefore provide a reasonably accurate indication of the potential of the pulse generator electrode. The heart, however, is located deep within the body and is separated from the surface by the rib cage. Since the catheter is located inside the heart (for an endocardial emplacement), there is some question whether potentials measured on the skin of the thorax, directly adjacent to the heart, would be representative of the catheter tip potential.

EXPERIMENTAL SECTION

Internal and External Potentials

After the electrical tests on a baboon with a completely implanted pacemaker were ended, the pulse generator (pacemaker) was removed, but the catheter was left in the body. Before the second implant with the animal, the connector end of the catheter was exposed in the abdominal region and connected to one side of a small, compact battery-operated telemetry transmitter. The other lead of the telemetry transmitter was connected to a needle probe which could be inserted 3/16 in. into the skin for probing measurements. In effect, the telemetry unit served as a high-impedance, wireless voltmeter to sense the potential between the catheter tip within the heart and various points on the body surface for various current injection connections.

Several different current flow conditions were used in the testing: one arm to both feet (i.e., a wire connection between the feet), one arm to one foot and arm-to-arm. Figure 1 shows the test setup in schematic form for head-to-feet current flow. The current flowing through the body was determined by measuring the voltage drop across the 1-kΩ resistor, which was in series with one of the signal generator leads. The signal source connections to the body were made by needles inserted subcutaneously.

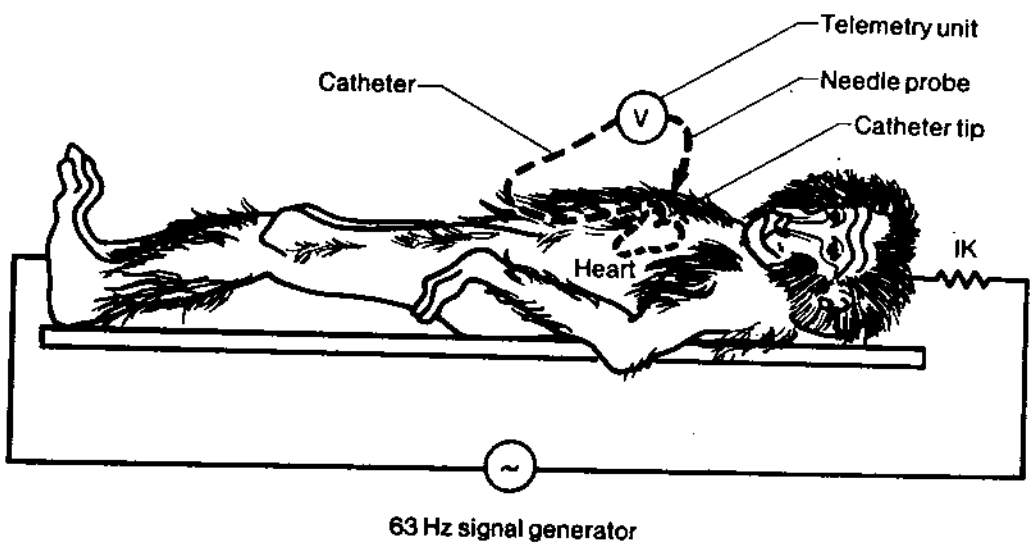

Fig. 1. Test arrangement for catheter tip experiment.

The points on the skin surface which were equipotential with the heart catheter tip were identified by locating points on the body surface which produced a null-zero voltage reading while current was flowing through the body. Other equipotential lines were determined by establishing a reference voltage reading at a point of interest, then determining other points in the vicinity which produced the same potential. The various points determined to lie on equipotential lines were connected with colored markers. Figure 2 is a drawing of various equipotential lines drawn on the chest. The lines marked "A" were obtained for head-to-feet current flow. The lower line A is the heart catheter tip equipotential line, while the top line A is an equipotential line in the pectoral region. Both lines are normal to the anticipated direction of current flow.

The lines denoted B in Fig. 2 are for current flow from right arm to feet. The lower B line overlaps the previous line which is equipotential to the catheter tip. The upper B line curves around the shoulder. The C lines are similar to the B lines, but for left arm excitation. The D line is equipotential with the catheter tip for excitation arm-to-arm. This equipotential,line tends to be nearly vertical and extends from near the center of the neck down through a point on the chest directly above the catheter tip within the heart, and then down to the left abdominal region.

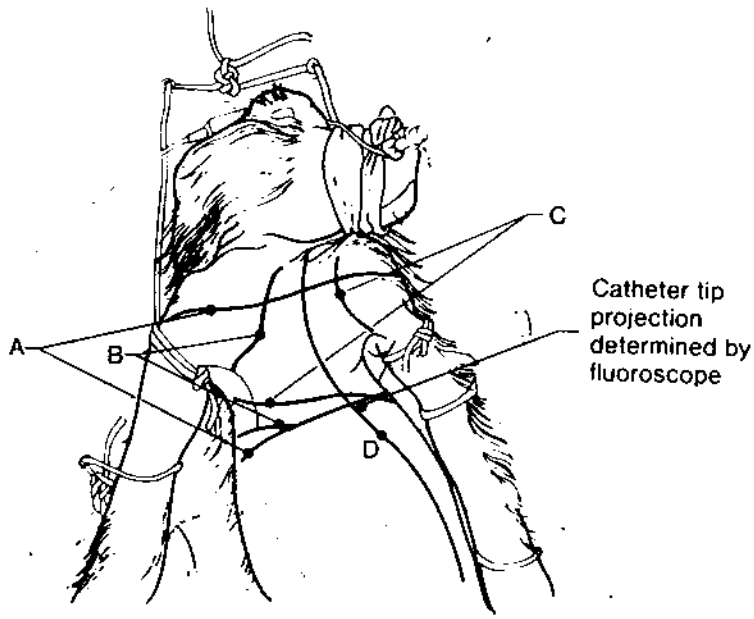

Fig. 2. Equipotential lines drawn on test baboon.

From the above measurements, it can be concluded that the points on the chest directly adjacent to the heart (above the heart if the primate is lying flat) are equipotential with the heart catheter electrode for 60-Hz current flowing through the body along the thorax axis. Therefore, the potential caused by 60-Hz current flow between the heart and any other point on the body, can be determined by measuring the potential between the heart projection point on the external chest to the other point of interest. This is a highly significant aspect for predicting, by noninvasive measurements, the potential which will be induced on implanted devices by 60-Hz body currents.

Measurement of Differential Body Resistance

To obtain further information on the resistivity or conductivity of the human body and any related spatial variations for the pacemaker study, we developed a measurement technique by first using invasive measurements on the nonhuman primate subjects discussed previously. These invasive measurements confirmed that a related noninvasive technique which could be used on humans was valid.

Basically, the measurement concept is an extension of the four-probe method used to determine the resistivity of the earth (Sunde, 1968). This technique can be applied to the human body and allows development of the differential resistance of the human body between two equipotential lines. The average resistivity of the human body between these lines can then be determined by

$$\rho = RA(z)^{-1}$$

where

ρ is the resistivity
R is the observed differential resistance
A is the mean area
z is the mean separation between equipotential lines.

Measurement of the resistivity, ρ, allows calculation of the current density, J, as follows:

$$J = \frac{E}{\rho} = \frac{V}{z\rho}$$

where

E is the electric field
V is the potential between equipotential lines
z is the mean separation between equipotential lines.

To see how this may be done, we used the test arrangement shown in Fig. 3. Below perception level currents were applied, and the differential voltages were measured along the thorax with a voltmeter-telemetry system. This system suppressed stray pickup and ensured the safety of the subject.

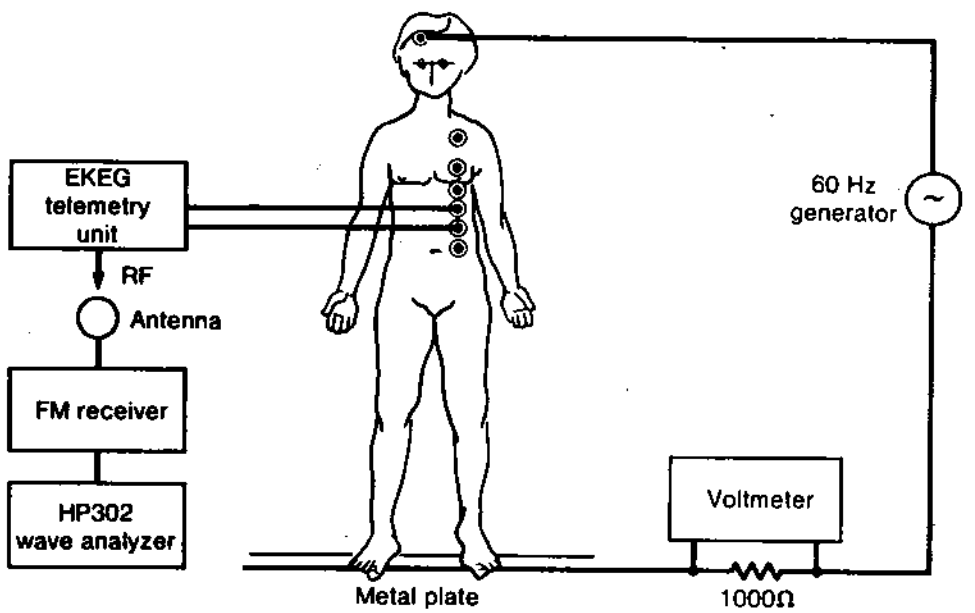

Fig. 3. Human thorax differential resistance test setup.

The differential resistance is determined by dividing the measured differential voltage by the injected current. The differential resistance values were obtained along the thorax for four volunteer human subjects. The data which were obtained agreed quite well with a more extensive series of measurements reported by Gamboa and Adair (1967) on 45 test subjects.

DISCUSSION

Determination of Pacemaker Performance

The methods discussed above and others described elsewhere (Bridges and Frazier, 1979a; Bridges, Frazier, and Hauser, 1978; Frazier, Bridges, and Hauser, 1978; Bridges and Frazier, 1979b) were first used successfully to predict the behavior of implanted pacemakers in baboons. This method is currently being investigated to predict the performance of pacemakers in human subjects (Moss, 1982; Butrous, 1982). The results of these studies to date confirm the efficacy of the prediction method.

Application to Electric Shock Hazards

The techniques described in this paper allow empirical development, based on noninvasive measurements, of the electric fields, current densities, and internal body resistivities near human or laboratory animal hearts. The measurements are reasonably accurate, at least in gross terms, despite known variations in the spatial distribution of the resistivity of muscle, fat, fluids, and bone. These measurements could serve as a way to better normalize the results of fibrillation tests taken on laboratory animals of different weights, geometries, or species. They could also help demonstrate whether the minimum fibrillation threshold is a function of current density or a function of the fraction of the total body current intercepted by the heart.

Problems with scaling test results. This approach can be better appreciated in the context of some of the existing data on scaling results on laboratory animals to humans. Such data can be interpreted to show that fibrillation thresholds are related to body weight, which implies a current density threshold (Dalziel, 1972). On the other hand, the wide variation in results and test approaches, allows nearly the same data to be reasonably interpreted to demonstrate little dependence on body weight for a given species. This means that the fraction of body current intercepted by the heart might well be a suitable criterion. Measurement of the current density near the hearts of test animals would thus confirm or disprove either hypothesis.

Lee (1966) noted that combining test results (as stated in terms of the total limb-to-limb body current) taken on animals of different geometries or having radically different proportions between anatomical features presents difficulties which have not been addressed in past studies. With few exceptions, all of the subject animals to date have been quadrupeds. There are significant anatomical variations within this group, such as a relatively larger cardiovascular system for the dog or disproportionately larger weight in the legs of pigs. Significant differences may exist between quadrupeds and bipeds (large primates) in the internal spatial distribution of body currents near the heart. Until such differences are resolved, extrapolation of test results on quadrupeds of varying anatomical features to primates or humans, either by weight or some other feature, may well be subject to some as yet unidentified error. Lee (1966) also voices reservations about Dalziel's analyses and data sources (Dalziel, 1972).

Experimental procedures may also influence this extrapolation. For example, during pacemaker evaluation tests on calves (Valentino, Miller, and Bridges, 1972), the position of the heart was found to shift significantly, depending on whether the test animal was standing or lying down. Such shifts could either remove or insert the heart into a region of higher body current. This may be significant, since many of the tests were conducted on dogs lying on their backs.

The role of current density. Support for the concept that current density is an appropriate shock hazard criterion may be noted in the electric shock hazards (microshock) which have occurred in clinical cardiology (Whalen and Starmer, 1967). During catherization tests on the heart or in open heart surgery, leakage currents of about 100 μA applied to the heart via the catheter or from monitoring equipment induced ventricular fibrillation in human patients. This phenomenon lead to a rigorous program to reduce the leakage currents of hospital electrical and electronic equipments. This ~100 μA fibrillation threshold observed for an electrode in nearly direct contact with the heart compares with the 50 to 100 ma threshold used in safety standards for limb-to-limb shocks. This 500 times increase in fibrillation threshold for limb-to-limb shocks can be explained on the basis of a current density fibrillation criterion.

Tests on both humans and dogs (Rafferty, Green, and Yacoub, 1975; Rafferty, Green, and Gregory, 1975) with electrodes placed in the heart or on the myocardium show that the minimum fibrillation current for either set of subjects is about the same. Since the same current density is produced in the immediate vicinity of the electrode in the heart for similar electrodes and catheter currents, these results can be interpreted to indicate that current density is the principal fibrillation criterion. Assuming this is the case, the minimum body current to cause fibrillation would be dependent on the weights and geometries on the subjects.

The same data, however, can be interpreted to suggest that the fibrillation shock criterion should be the fraction of the body current intercepted by the heart. This fraction is proportional to the current density and an "effective area" for the heart. Assuming that the fraction of body current intercepted is the dominant criterion, the fibrillation threshold would be about the same for animals of nearly similar geometries but of different sizes and weights.

The role of current-density fibrillation. In the data developed on dogs there is some evidence which suggests that the limb-to-limb fibrillation thresholds vary with body weight. One such body weight correlation was developed by Dalziel (1972) based on the minimum fibrillation currents for 3-sec. durations which are plotted as a function of body weight for 45 dogs ranging in body weight from 6 to 28 kg. A straight line of best fit (regression line) was calculated by the method of least squares. This empirically developed curve is plotted in Figure 4 as the Mean Square Fit curve. From these and additional data, Dalziel concluded that the fibrillation threshold current is approximately proportional to body weight.

A different conclusion, based on more recent tests, was reached by Geddes (Geddes and Baker, 1975), who demonstrated that the fibrillation threshold varied with the square root of the body weight. For comparison purposes, this is also plotted in Figure 4 as the Square Root Weight curve.

A similar curve can be developed on the assumption that the fibrillation threshold is a function of current density which results in a 2/3 power weight relationship. This 2/3 power relationship is easily developed; for a given shape but different sizes or weights, a selected cross-sectional area varies as the 2/3 power of the weight, W_n. Assuming the fibrillation threshold in differently weighted animals of the same species occurs for the same current density, J_n, the fibrillating current, I_n, can be developed as follows:

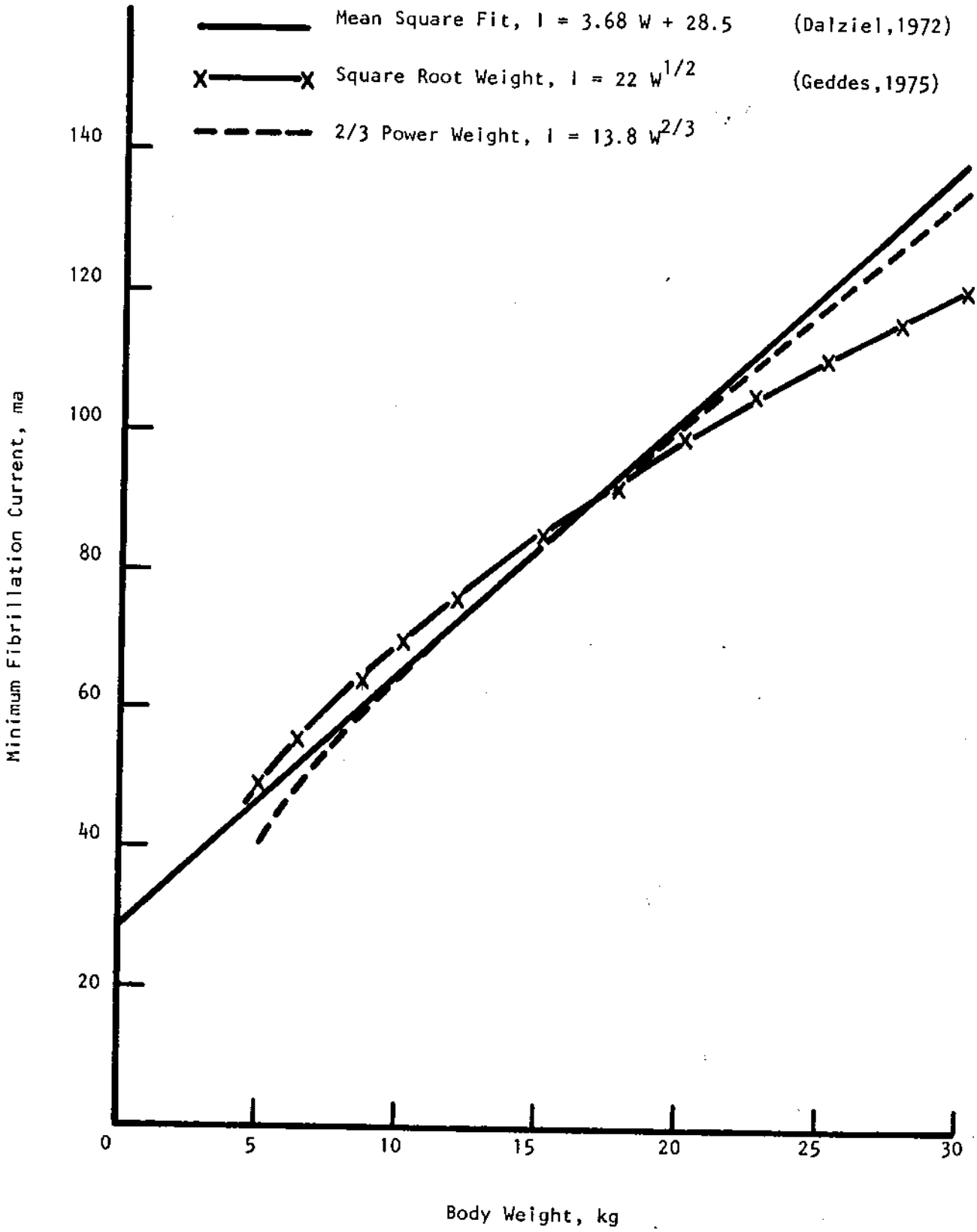

Fig. 4. Relation of fibrillation threshold body weight correlation model to mean square best fit for dogs (3.0-sec shocks).

$$(I_1)\ (W_1)^{-2/3} = J_1 = J_2 = K(I_2)\ (W_2)^{-2/3}$$

$$(I_1/I_2) = (W_1/W_2)^{2/3}$$

where K is a constant and the subscripts note a specific animal.

For comparison purposes, a curve based on the body weight to the 2/3 power is also plotted in Figure 4 as the 2/3 Power Weight.

Note that the three curves are in remarkably close arrangement over the weight range from 5 to 30 kg. The 2/3 power or current density criterion curve provides slightly better match with the empirically developed Mean Square Fit line based on tests made on 45 dogs.

Scaling is only reasonably valid between small and large animals of the same general proportions. More reliable results can be achieved by including further refining factors, such as possibly correcting for actual measured current densities and control of the position of the subject's heart during tests.

CONCLUSIONS

An approximate, noninvasive method was developed to measure the current density, electric fields, and tissue resistivity near the hearts of either test animals or human subjects. To date, detailed results on nonhuman primates and preliminary results on human patients with implanted pacemakers suggest that the technique is reasonably accurate and could aid in scaling the results of animal shock tests to the human situation. This noninvasive technique could be used to develop the minimum current density in the vicinity of the heart to cause fibrillation in laboratory animals. Such data would aid in determining the actual electrophysiological mechanism which causes fibrillation, and thereby resolve the effect of body-weight or size on the applied current fibrillation threshold.

ACKNOWLEDGMENT

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CAPACITIVE DISCHARGE STUDIES

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Wood Veterans Administration Medical Center
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ABSTRACT

Fibrillation and skin burns due to capacitive discharges were investigated in 3 mongrel dogs (40-50 kg) and 4 hogs (60-90 kg). All animals were anesthetized with sodium pentobarbitol. Potentials from 800 to 2500 volts were discharged from 10 to 100 microfarad capacitors. For all studies, a 40 x 60 cm steel plate was placed under the hind quarter of the animal as one terminal of the circuit. The other terminal was connected to stainless steel disk electrodes ranging from 0.5 to 5.0 cm diameter which were brought into contact with the chest over the heart and the fore limbs. In one dog and one hog, current applications were also made directly to the heart. For the burn studies, the electrodes were brought into contact with the opposite hind quarter. The current and voltage applied to the animal were measured using a Honeywell Model 1858 Visicorder. The EKG was observed using a GE Monitor. The circuit was triggered to supply the pulse during the p and t waves of the EKG to obtain maximum fibrillation susceptibility.

In these and other studies in our laboratory, fibrillation has been routinely obtained with 0.4 A, 60 Hz, currents of 1-3 seconds duration. With capacitive discharge, no fibrillation was observed at up to 2500 V at 40 microfarads (μF). With application directly to the heart, 2200 V from a 22 μF capacitor produced fibrillation in a dog. The application of 1600 volts from a 100 μF capacitor caused fibrillation in the hog. The associated energy was 128 J.

When electrodes of 2.5 cm diameter or less were used to discharge 1100 volts from 10-40 μF capacitors, second and third degree burns were observed under the electrode.

KEYWORDS

Capacitive discharge; fibrillation, hogs, dogs, electrical burns.

INTRODUCTION

The application of electricity to the heart has a disruptive effect upon the cardiac cycle. It may advance or delay following beats and in extreme cases

results in ventricular fibrillation. Although the particular physiological mechanisms are unclear (Winfree, 1983), the 60 Hz currents which produce fibrillation have been extensively investigated (Dalziel and Lee, 1968; Geddes and Baker, 1968). Geddes (Geddes and Baker, 1968) estimated that 60 Hz currents of 320 mA applied to the thorax would cause fibrillation in a 150 pound man. For contact times from 8.3 ms to 5 s, Dalziel (Dalziel and Lee, 1968) suggested that the threshold fibrillation current could be approximated by the formula

$$\frac{116 \text{ to } 185}{\sqrt{T}} \quad \text{mA rms}$$

where T is the contact time in seconds.

In contrast, larger currents are required to produce fibrillation with short duration pulses or capacitive discharges (Dalziel, 1953; Sugimoto, Schaal, and Wallace, 1967). To investigate fibrillation and skin burns associated with capacitive discharges, studies were conducted in anesthetized hogs and mongrel dogs.

METHODS

Three mongrel dogs (40-50 kg) and 4 hogs (60-90 kg) were used. All animals were anesthetized with sodium pentobarbitol. Potentials from 800 to 2500 volts were discharged from 10 to 100 microfarad capacitors. For all studies, a 40 x 60 cm steel plate was placed under the hind quarter of the animal as one terminal of the circuit. The other terminal was connected to stainless steel disk electrodes ranging from 0.5 to 5.0 cm diameter which were brought into contact with the chest over the heart and the fore limbs. In one dog and one hog, current applications were also made directly to the heart. For the burn studies, the electrodes were brought into contact with the opposite hind quarter. The current and voltage applied to the animal were measured using a Honeywell Model 1858 Visicorder. The EKG was monitored and the capacitor circuit was triggered to supply the pulse during the p and t waves of the EKG to obtain maximum fibrillation susceptibility.

RESULTS

A total of 30 capacitive discharges were applied across the thorax and between the forelimbs of the three dogs with capacitors from 13.5 to 22 μF and potentials from 500 to 2500 volts. The corresponding calculated total energies were 1.5 to 42J. The measured peak currents ranged from 300 mA to 6.85A with calculated resistances of 325 to 2000 ohms. Fibrillation was observed with potentials in excess of 2200 V using the 22 μF capacitor.

Forty-seven discharges using capacitors from 13.5 to 100 μF at potentials from 600 to 2350 V were applied across the thorax and between the forelimbs of the four hogs (Table 1). The calculated total energy ranged from 2.4 to 128 J. Measured peak currents ranged from 0.34 to 10 A and the corresponding calculated resistance ranged from 240 to 1765 ohms. Fibrillation was observed with 1600 V discharged across the thorax from the 100 μF capacitor. The measured current was 4.5 A.

The resistance was approximately inversely proportioned to the diameter of the 0.5-5 cm circular disk electrodes (Table 2). When an 8 cm long, 2 mm diameter wire was used, the resistance was approximately 500 ohms. When 1100 volts was discharged from 10-40 μF capacitors, second and third degree burns were observed at the edges of the electrodes. The severity of the burn was related to the applied energy and inversely related to the size of the electrode.

DISCUSSION

The levels for fibrillation observed in this study are similar to those reported in the literature. Milnor, Knickerbocker, and Kouwenhoven (Milnor, Knickerbocker, and Kouwenhoven, 1958) did not produce fibrillation in dogs at less than 2,700 volts from a 25 μF capacitor. These studies suggest that the applied energy is the critical parameter for fibrillation in capacitive discharge accidents. The current and energy required to produce fibrillation from a single pulse is considerably higher than the levels required for 60 Hz currents of 1-3 seconds duration. Sugimoto, Schaal, and Wallace suggest that the difference is due to the disruption of the cardiac rhythm induced by the initial cycles of the AC currents (Sugimoto, Schaal, Wallace, 1967). In their studies, when the single pulse was preceded by a conditioning stimulus, the threshold for fibrillation was markedly decreased.

The resistances and corresponding variation with contact dimensions observed in the present study are similar to those previously reported (Sances and others, 1981a; Sances and others, 1981b; Sances and others, 1979). Since electrode paste was not used, the resistance was higher than in other studies of fibrillation (Milnor, Knickerbocker, and Kouwenhoven, 1958) but are probably closer to the levels which exist in electrical accidents. Both fibrillation and burns which result from capacitive discharges are related to the applied energy and electrode circumference (Geddes and others, 1980). Since the contact resistance, the energy dissipated at the electrode, and the resulting burn, is greater for the small electrodes, it is likely that the total energy required to produce fibrillation is inversely related to contact size.

ACKNOWLEDGEMENT

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TABLE 1 Applied Voltages and Measured Current and Resistance with Each Capacitor in the Hog. Fibrillation from External Contacts was Only Obtained with the 100 F Capacitor.

Capacitor (F)	Voltage Range (V)	Measured Peak Current (Amperes)	Calculated Resistance (ohms)	Calculated Total Applied Energy (Joules)	
13.5	600-2000	0.34-4	460-1765	2.4-27	No fibrillation
22	500-2350	0.5-10	240-1000	2.75-60	No fibrillation
40	1000-2300	2-8	300-510	20-106	No fibrillation
100	1600	4-5	356	128	Fibrillation

TABLE 2 Calculated Mean Resistance for Each of the 5 Circular Electrodes Used. Each Value is Based on at Least 4 Applications.

Electrode diameter (cm)	Mean resistance (ohms)
0.5	1237.5
1.0	1025
1.25	952
2.5	537
5.0	525

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DISCUSSION

W. JACKMAN: High energy short duration direct current pulses have been delivered through catheter electrodes in the heart to selectively destroy small amounts of cardiac muscle which are responsible for rapid rhythm disorders. Are the destructive effects of the shocks solely mediated by the heat produced or is there some other destructive effect of the current on the cells?

CHILBERT: The result of electro-thermal tissue destruction has not been presented in the literature. However, in the medical literature, long-term neural stimulation has, on occasion, been shown to cause neural damage due to polarization of the electrode. Preliminary studies at our institution indicate that there may be a purely electrical component in electrical injury to peripheral nerves, but the data is incomplete and the results may not be applicable to the cardiac tissue. The major component of destruction is thermal.

ELECTRICAL STIMULATION OF THE ISOLATED RABBIT HEART BY SHORT DURATION TRANSIENTS

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ABSTRACT

The effects of short duration, large amplitude electrical waveforms were studied. Stimulation thresholds were determined by applying transients directly to an isolated rabbit heart through electrodes of 1 cm^2 and 1 mm^2 surface area. Several oscillatory waveforms and pulse configurations were studied. Results indicate that for transients less than 100 μsec in length stimulation thresholds approach a constant current transfer density of 3.4 $\mu C/cm^2$ and that for waveforms which contain both anodal and cathodal components net charge contained within the waveform must be considered.

KEYWORDS

Electrical transients, stimulation and fibrillation thresholds, electrical safety.

INTRODUCTION

There is increasing interest in the effect of short duration electrical pulses and transient waveforms on cardiac rhythm. Such high speed transients can occur in electrical substations as the result of breakdown in sulfur hexaflouride(SF_6) insulated high voltage systems. Breakdown between grounded gas insulated switch gear enclosures and other grounded components can produce a transient ground rise of substantial magnitude, in the order of 100 kV with durations up to a few hundred nanoseconds. Shocks have been experienced by personnel in contact with the enclosures and concern has been expressed as to the effect of such transients on humans.

In order to determine the disruptive effect of transient current flows, cardiac stimulation thresholds were studied on isolated rabbit hearts for a variety of simulated transient conditions. Cardiac stimulation thresholds were chosen because this parameter is the most sensitive indicator of cardiac rhythm disruption and is a precursor of more lethal arrythmias. The isolated rabbit heart preparation was chosen because it is a stable preparation whose

electrochemistry can be controlled and whose stimulation and fibrillation properties have been well documented (MacConaill 1967). The electrical transient waveforms were chosen to simulate the transients which have been described (Ford 1980) during ground rise conditions. The waveforms used for these experiments included:

a) single cathodal pulses of pulse duration varying from 200 nsec to 10 msec,

b) trains of anodal, cathodal, and symmetrical sine waves applied for periods or gate widths varying from 0.2 to 10 msec, and with sine wave frequencies varying from 500 Hz to 1 MHz.

METHODS

Experiments were performed using an isolated rabbit heart Langendorf preparation. The heart and lungs were rapidly removed from New Zealand rabbits under light anaesthesia via a midsternal thoracotomy. A catheter was inserted into the superior vena cava and advanced into the right atrium. Within three minutes of the beginning of surgery the heart was being perfused with a Krebs solution. The lungs were then removed and a balloon catheter was inserted into the left ventricle. The catheter was filled with fluid and attached to a Statham P-16 pressure transducer.

Stimulation thresholds for two electrode areas were studied. Silver - silver chloride electrodes 1 cm^2 and 1 mm^2 were attached to the surface of the left ventricle and a return path was provided by a 15 cm^2 indifferent electrode located remotely from the heart. The 1 cm^2 electrode was chosen because the resulting current density approaches the whole body current density required for stimulation and fibrillation (Roy, 1980). These fibrillation thresholds as a function of electrode area are shown in Figure 1. The results are a summary of all published fibrillation thresholds, including those for human hearts. The 1 mm^2 electrode was chosen because the lower total current threshold of small surface area electrodes (Roy, 1980) extended the capabilities of the pulse generating apparatus. Anodal and cathodal polarities refer to the polarity of the electrode on the heart with respect to the indifferent electrode.

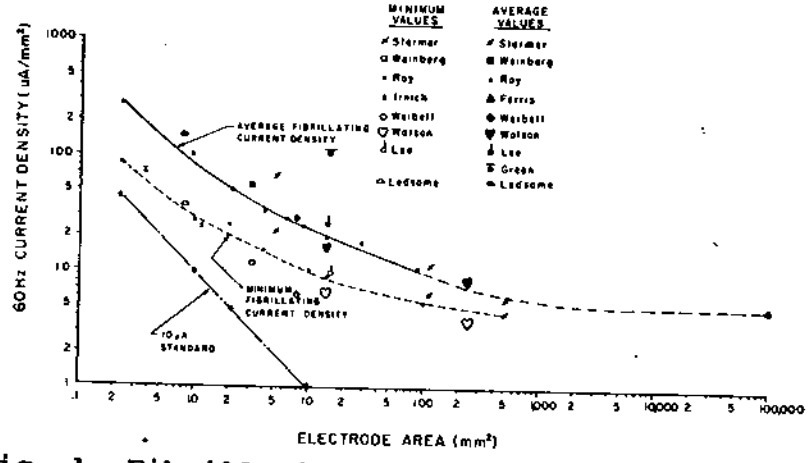

Fig. 1 Fibrillation current densities (rms) as a function of electrode area.

The isolated heart was partially submerged in the Kreb's solution. The stimulating electrodes remained out of the solution at all times. Thresholds were determined by applying current pulses at a rate higher than normal sinus rhythm. A Cober high voltage pulse generator (Model No. 606) was used to produce a stimulating pulse with a repetition rate faster than the normal heart rate. The current and voltage were measured by using a wide bandwidth oscilloscope (Tektronics 434). A function generator (IEC F72) was used for pulse train experiments and produced both square waves and sine waves. Stimulation thresholds were determined both by increasing pulse current amplitudes until capture was achieved and by decreasing current amplitudes until capture was lost. The procedure was repeated three times for each pulse configuration and electrode area.

RESULTS

Stimulation Thresholds for Single Cathodal Pulses. Cathodal pulse stimulation thresholds for twelve rabbit hearts, mean weight 12 ±1 gm, are shown in Figure 2. Stimulating current and charge thresholds are shown for pulse widths varying from 200 ns to 10 ms and for electrode areas of 1 cm^2 and 1 mm^2. As shown the current thresholds for short pulses follow the well know relationship (Lapicque 1909).

$$I_{Threshold} = I_{rheo} \left(1 + \frac{\tau}{t}\right)$$

where τ is the chronaxie time constant t is the stimulating pulse width, and I_{rheo} is the rheobase current level.

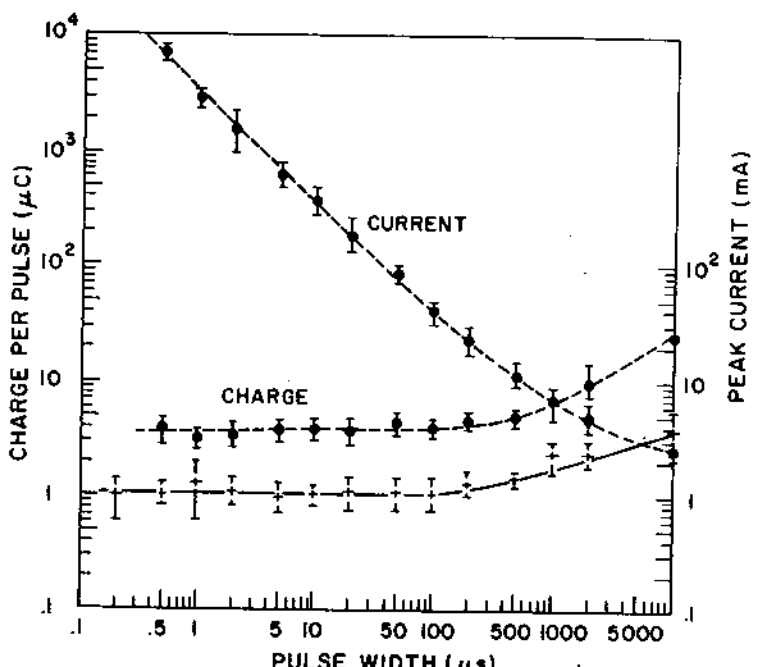

Fig. 2 Myocardial stimulation thresholds for single cathodal pulses. Both peak current and charge thresholds curves are shown for electrode areas 1 cm^2 (•)and 1 mm^2 (+). Each point represents mean ∓S.D.

Figure 2 also shows stimulation thresholds as a function of charge transfer. Charge transfer was determined by multiplying current amplitude by pulse width. As shown for single cathodal pulses of pulse widths less than 100 μsec, the rhythm disrupting charge transfer approaches constant values of 3.4 ± .8μC for the 1 cm^2 electrode area and 1.1 ± 0.4 μC for the 1 mm^2 electrode area.

Stimulation Thresholds for Trains of Cathodal Sine Waves. To study the effects of cathodal high frequency oscillatory transients, each single cathodal pulse was replaced by a train of cathodal sine waves. The cathodal wave trains had frequencies varying from 500 Hz to 1 MHz and were gated on and off for durations varying from 0.2 to 10 ms.

Figure 3 shows the stimulation thresholds for 5 rabbit hearts using a 1 cm^2 electrode for both single cathodal pulses and for a train of cathodal sine waves. Over the gate duration range shown the stimulation threshold for the cathodal pulse trains was independent of pulse train frequency and equal to the threshold of a single cathodal square wave pulse of the same duration. The results indicate that the disruptive effects produced by cathodal high frequency transients can be estimated by relating them to the single pulse charge transfer thresholds.

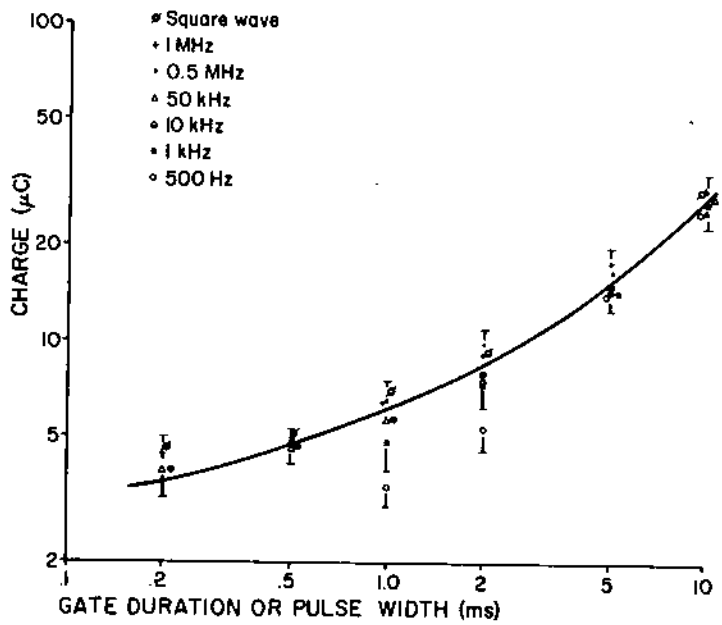

Fig. 3 Charge required for stimulation using 1 cm^2 electrode, by trains of cathodal sine waves with wave train frequencies varying from 500 Hz to 1 MHz and gate durations varying from 0.2 ms to 10 ms. The stimulation threshold for a single cathodal square wave of the same duration is also shown, each point represents mean ∓S.D.

Stimulation Thresholds as a Function of Symmetry. Stimulation thresholds for single anodal pulses and anodal sine wave trains with frequency varying from 500 Hz to 1 MHz are shown in Figure 4.

The sine wave trains had durations lasting from 0.2 to 10 ms. The threshold for anodal transients approaches a value of 6.1 μC and is on an average 1.8 ∓ .2 times greater than that for a cathodal waveform of the same duration. The difference between anodal and cathodal stimulation is in agreement with previously reported results of Thalen (1969) and Cranfield (1957), and is thought to be due to the hyperpolarization of the cell membrane.

The results shown in Figure 4 indicate that, just as in the cathodal case, the disruptive effects produced by anodal high frequency transients can be related to the single pulse charge transfer thresholds.

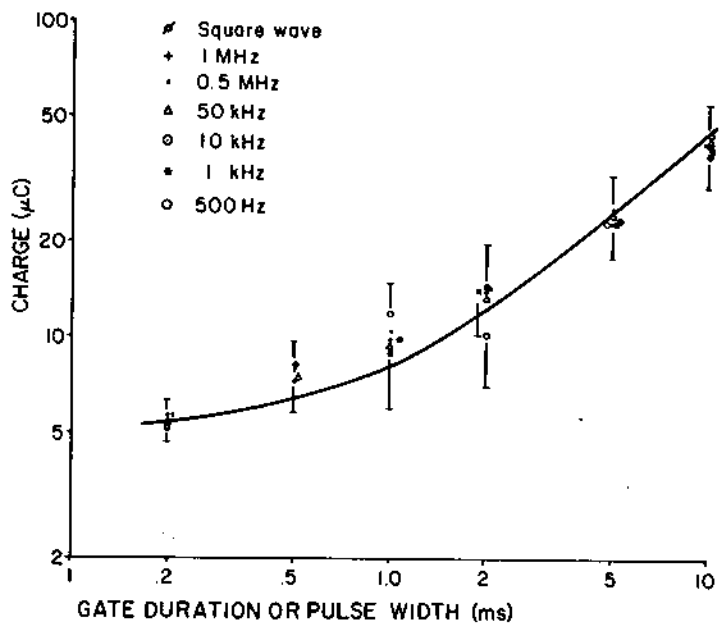

Fig. 4 Charge required for stimulation by trains of anodal sine waves with wave train frequencies varying from 500 Hz to 1 MHz and gate durations varying from 0.2 ms to 10 ms. Each point represents mean ∓S.D.

To investigate the effect of waveform polarity further, a study of the effects of transient symmetry on stimulation thresholds was made. Symmetry is determined by the net charge transferred over the durations of the transient. Thus a perfectly symmetrical transient would have a net charge transfer of zero.

Threshold characteristics were studied for a 1 KHz sine wave as a function of waveform symmetry and transient durations. Figure 5 shows the current stimulation thresholds for one cycle and 10 cycle of 1 KHz sine waves and indicates that under symmetrical conditions current stimulation thresholds rise dramatically to the same threshold level (no significant difference $p<.05$ for both curves). Also shown in Figure 5 is the fact that under symmetrical condition stimulation thresholds become independent of the number of oscillatory cycles. This is further illustrated in Figure 6 where stimulation thresholds for 1 KHz and 500 Hz symmetrical sine waves

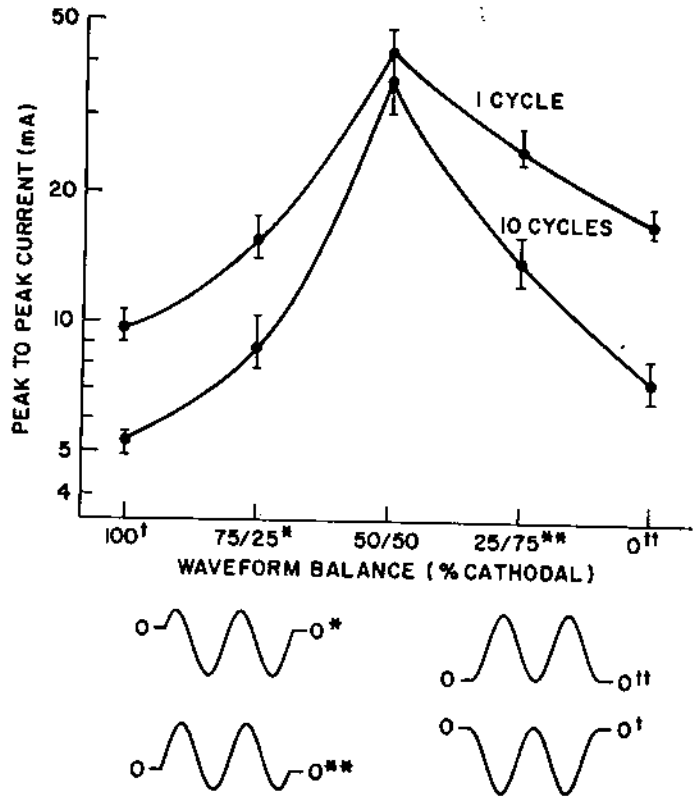

Fig. 5 Peak to peak current stimulation thresholds as a function of waveform symmetry or balance for 1 cycle and 10 cycles of 1 kHz sine waves. Each point represents the mean ∓S.D.

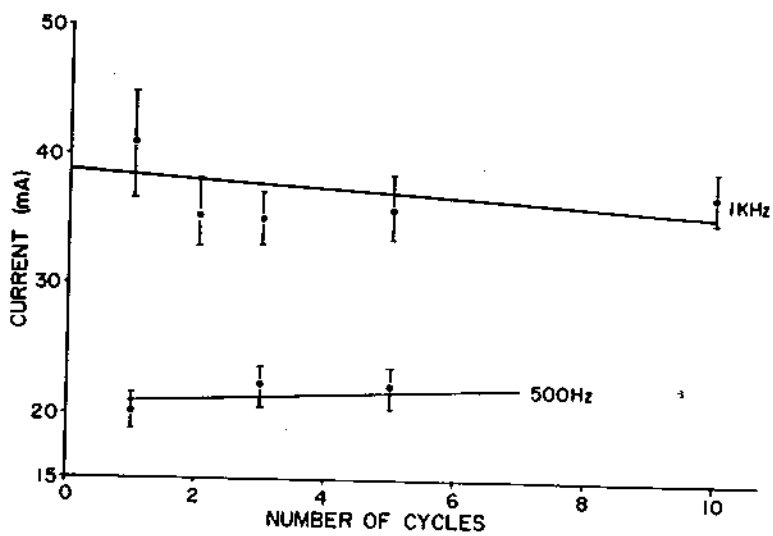

Fig. 6 Current stimulation thresholds for one to ten cycles of 1 kHz and 500 Hz sine waves each point represents mean ∓S.D. Lines shown are the best least squares fit. No significant difference was obtained between each set of data points using analysis of variance.

are shown as a function of the number of cycles. For wave trains of 1 cycle or more, the current required for stimulation is constant. No significant difference was observed between the data points when compared using analysis of variance at an acceptance level of $p<.05$, indicating that the first cycle of the wave train illicits a contraction. A calculation of the net charge transfer for the various modalities shown in Figure 5, produces the results shown in Figure 7. The net charge transfer was calculated for the non-symmetric case by using the average current value mutiplied by the time of current flow, for the symmetric case the charge transfer was that calculated from the average value of a single half sine wave.

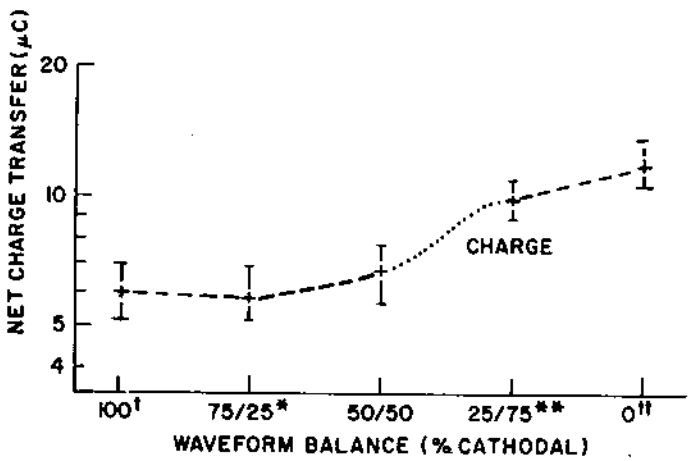

Fig. 7 Calculated charge stimulation thresholds as a function of symmetry for one cycles of 1 kHz sine waves. Calculations use the data shown in Fig. 5. Each point represents a calculation from the mean ±SEM.

The calculated net charge transfer, at symmetry, shown in Figure 7, was for a single cathodal half since wave. It was assumed that,

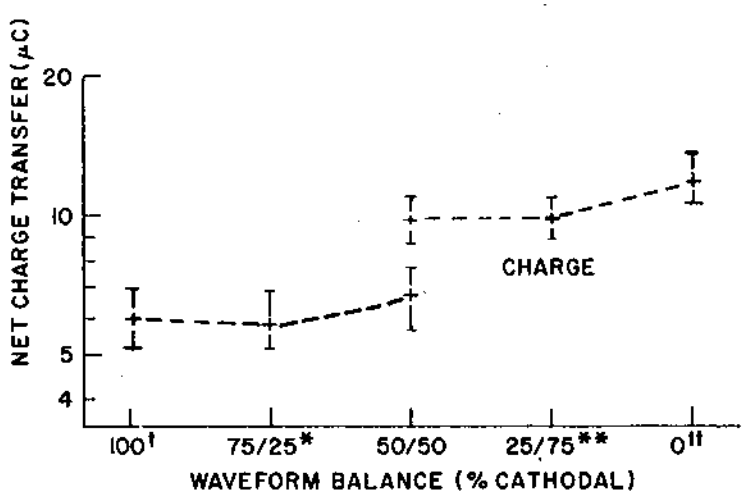

Figure 8 Calculated charge stimulation thresholds, as in Figure 7 with consideration of the polarity for the first excursion at symmetry.

because of its lower value (3.4 μC compared to 6.1 μC), the cathodal excursion would determine the stimulation threshold. We have subsequently found that the polarity of the first excursion must be considered. Figure 8 shows the curve of the net charge transfer when the polarity of the first excursion is taken into account. It appears that the first anodal excursion hyperpolarizes the heart cells causing the stimulation threshold to increase to their anodal level.

DISCUSSION

It has been reported (Daziel, 1956) that for surge discharge, the energy required for fibrillation was a constant 27 watt seconds. The results of our studies indicate that for high frequency oscillatory transients or short duration pulses, (at frequencies greater than 1 kHz) cardiac stimulation is a function of the net charge transferred. Our experiments were conducted using large surface area electrodes (1 cm^2), thus the results in terms of current density and charge transfer density, are applicable to whole body currents flow, i.e. for currents applied to the surface of the body. It would appear that for cathodal pulses of less than 100 μsec in duration, stimulation thresholds approach a constant charge transfer value of 3.4 $\mu C/cm^2$, for anodal stimulating pulses the charge transfer value is 6.1 $\mu C/cm^2$. We have also been able to stimulate the heart with pulses as short as 200 nanoseconds, the limit of our experimental equipment. There is no indication that the heart would not respond to even shorter pulses. These results are in general agreement with the recently published results of Pearce (1982).

Although it is difficult to simulate the effect of all transient waveforms, our results indicate that, for currents applied directly to the heart, a good approximation of rhythm disruption thresholds can be made by relating the net charge contained in a transient waveform to that of a single cathodal or anodal pulse of the same duration. For symmetrical oscillatory transients lasting up to 10 msec, cardiac stimulation is achieved by the first excursion which exceeds the charge threshold density of 3.4 $\mu C/cm^2$.

CONCLUSION

The results given in this paper concentrate on cardiac stimulation thresholds for currents applied directly to the heart. Our studies indicate that rhythm disrupting thresholds, for pulses shorter than 100 μsec or for high frequency oscillatory transients, are a function of net charge transfer. Cardiac stimulation can be achieved with cathodal charge densities of 3.4 $\mu C/cm^2$and with anodal charge densities of 6.1 $\mu C/cm^2$. It is known that a pacemaker pulse can induce fibrillation (Bilitch 1969, Castellanos 1966) if the stimulus happens to fall into the vulnerable period of the heart cycle. This possibility has led to the development of non-competitive pacemakers and the limited use of the fixed rate asynchronous pacemakers. In early pacemaker systems, fibrillation could be induced when pulses, 10 to 15 mA in amplitude, 2 msec in pulse width were passed through electrodes 1 cm^2 in areas. Current stimulation thresholds for a 1 cm^2 electrode averaged 1 ma thus the

ratio between stimulation and fibrillation thresholds was between 10 and 15 to 1. It would seem that this factor could be applied to our results, indicating that a fatal fibrillation situation could be induced with a net charge transfer density of 34 $\mu C/cm^2$. The accuracy of such a relationship will have to await experimental validation.

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DISCUSSIONS

BRIDGES: The slide showing current density versus electrode area data from a number of researchers if replotted showing current density versus electrode diameter or $(area)^{1/2}$ should show a linear threshold level. This observation is based on some of the observations of Prieto and also Geddes. They show that the effect of an electrode is proportional to the diameter rather than the area. Similar theoretical analyses can demonstrate that the current density is a fraction of the diameter and total current rather than area and total current. Could you comment?

ROY: This may indeed be true and we will replot our data as a function of diameter. The references you cite I believe show a relationship to diameter for metal disc electrodes and for square pulse application. Our results include fluid filled catheters and ball tip electrodes with a 60 Hz current flow.

GRIFFIN: Do you have any data regarding the relationship between heart size, electrode size and ventricular fibrillation threshold?

ROY: We have not compared the rabbit heart data shown here, but we have found no differences in dog and man using electrodes of the same size. The data that we have compares dog and human hearts. For this size differential we see no difference in response between these hearts. The behaviour of these hearts, for electrode areas varying from 0.224 mm^2 to 1 cm^2 is the same.

Chapter 2

Panel Meeting on Physiology of Electrical Shocks

PANEL MEETING ON PHYSIOLOGY OF ELECTRICAL SHOCKS

Chairman: Prof. L.A. Geddes, Purdue University, USA

Vice Chairman: Prof. H. Antoni, Institute of Physiology, Freiburg, Germany

Panel: J.E. Bridges, Dr. J. Cabanes, Dr. J.C. Griffin, A. Dolan, Prof. W.R. Lee, Dr. J. Myklebust, G. Knickerbocker

GEDDES: Our charge is to dispense considerable wisdom. I can only say that I am not overflowing with wisdom. Committees cannot decide scientific facts. They can only evaluate them and our task this afternoon is to identify gaps in knowledge. In other words, the sponsors of the conference would like us to use our wisdom to identify the kinds of research that needs to be done to answer important questions. We will have the panel introduce themselves in just a moment. They are all behind me, ready for you to take shots at them and they may duck, of course if they have to.

At this time, I thought it might be a good idea to think about what happens to the body when one passes electric current through it. First, let us engage in what I call a little retrospectroscopy, which is the name given to looking backwards in time. The retrospectroscope is not my term, it was coined by Julius Comroe, who wrote a lovely little book on the history of discoveries. So, look back with me for a moment just to break the tempo, because the climate is going to warm up quite a bit very shortly, I think. Let me entertain you just for a few moments and show you some of the fascinating intentional applications of current to the body and make a few comments on whether they were useful or not.

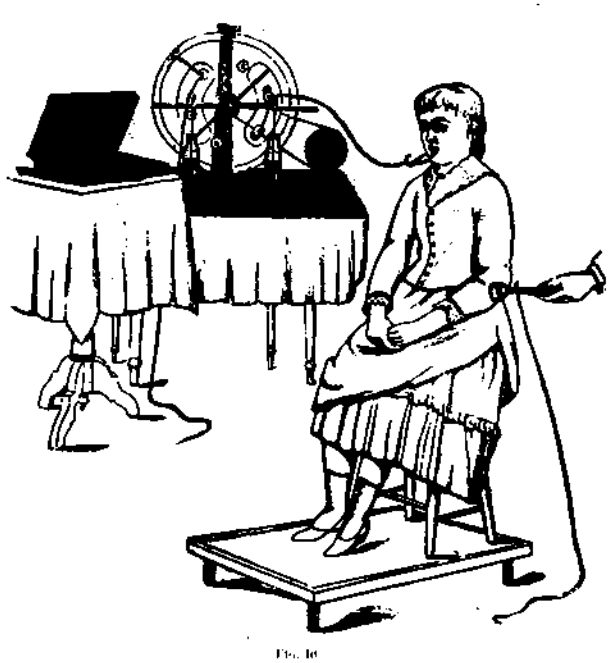

Figure 1. Static (Franklinic) electrotherapy, delivered by an electrostatic generator.

Figure 1 illustrates a young lady sitting on a chair placed on a platform. The scene is circa 1780 or 1790. The table has glass legs and there is an electrostatic generator with a wire clipped to the collar of her dress. The other wire from the generator is on the floor. The electrostatic generator applied considerable voltage to the patient; so much so that the hair would rise up on the head and on exposed skin surfaces. In the dark one could see a halo or corona discharge around the subject. This was the approved treatment for all those things that drugs could not cure. Interestingly enough, the patient had a remarkable sensation of warmth and relaxation and usually slept for a little while after the treatment. One weekly treatment for about a month was typical. Such "therapeutic cures" are written up in old books on electrotherapy.

Figure 1 also shows a hand with a conductor and a wire leading to the ground. The conductor was for what is called "drawing of sparks". As a matter of fact, there was a lot of hysterical paralysis around at that time. This is a paralysis of central nervous system origin, but the patient has no lesion and believes that he cannot use his muscles. Surprisingly enough, there were many such patients around. By drawing sparks the subject would be discharged to ground at the appropriate place and the muscles would twitch. The patient then would see the twitching muscles and be cured of the hysterical paralysis.

Figure 2. Static discharge therapy applied to the testes.

Another favourite treatment is shown in Figure 2, an electrostatic generator was used to draw sparks from the testes. Such a treatment was used for impotence or to restore the vigour of youth. A similar treatment was applied to ladies for barrenness; in other words infertility.

Figures 1 and 2 characterize electrostatic (Franklinic) therapy. Tremendous voltages were applied. One would wonder if there was any danger to electrostatic voltage. Could such discharges fibrillate? The answer is yes. There is one published paper in which modern investigators placed a catheter electrode in the right heart of a dog and noticed that when they shuffled over the carpet and touched the catheter electrode they produced an extrasystole. They then started a study in which high voltage capacitor discharge of very, very short duration

(nanoseconds) were delivered to the catheter electrode. They found out they couldn't fibrillate the ventricles unless they induced a myocardial infarction in the dog. The increased irritability resulted in ventricular fibrillation from a single capacitor discharge.

After Volta developed the so-called galvanic cell, which is really a voltaic cell, the electric-bath treatment was very popular. Figure 3 illustrates a subject in a bath with head and foot electrodes. Physicians were very careful to make the head electrode the anode, because the patient felt very badly if the head electrode was made the cathode. Current of about 100 milliamperes flowed in the water. Such a treatment would be adjusted by the physician putting his hand in the water to feel if the current was adequate. The electric bath was used for rheumatism, gout, and aches and pains of all kinds.

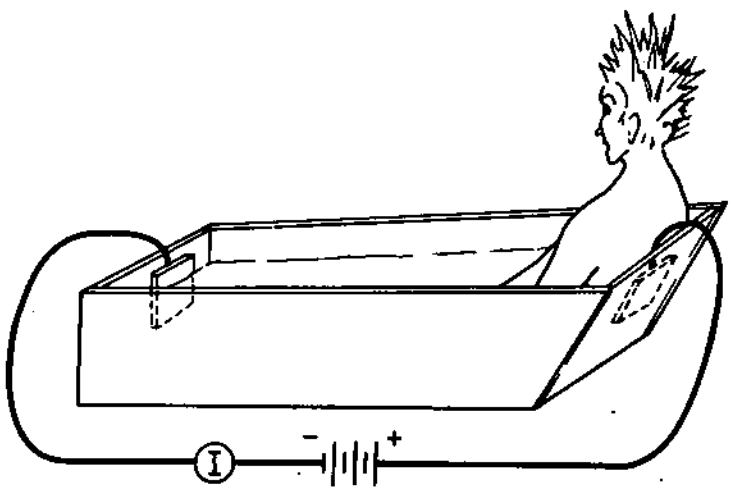

Figure 3. The electric-bath treatment in which direct current was passed through the bath water.

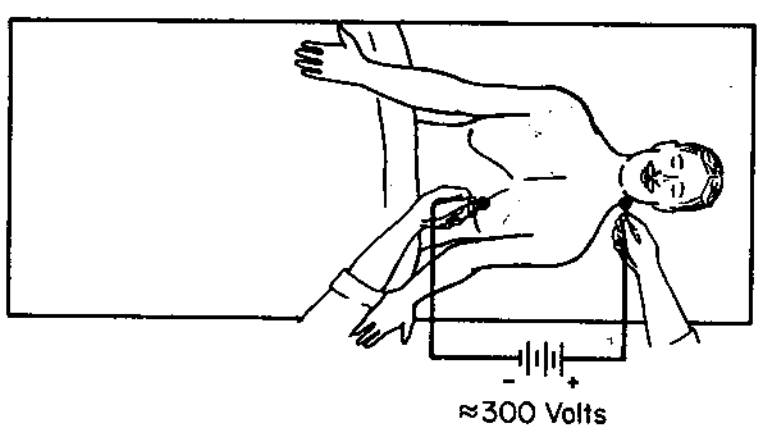

Figure 4. Cardiorespiratory resuscitation performed by touching one electrode to the neck over the phrenic-nerve roots and to the left chest over the cardiac apex. Intermittent application of the electrodes twitched the diaphragm and probably evoked an extrasystole.

Figure 4 shows a form of galvanic therapy that really did achieve a cure. The subject is lying on an operating table with a battery of up to about 300 volts beside him. Hands are shown holding electrodes on the neck and over the seventh rib, near the apex beat area. The problem of the day was cardiac and respiratory

arrest due to overdose of chloroform anesthesia. Chloroform syncope was the term used for this disaster. The patient would become pulseless and stop breathing. This interesting technique of applying a direct-current pulse to the neck could stimulate the heart. A twitch of the respiratory muscles would be produced as well as a ventricular contraction of the heart. Such therapy was reported in the British Medical Journal in 1872; 5 out of 7 patients were resuscitated. Quite remarkable for those days!

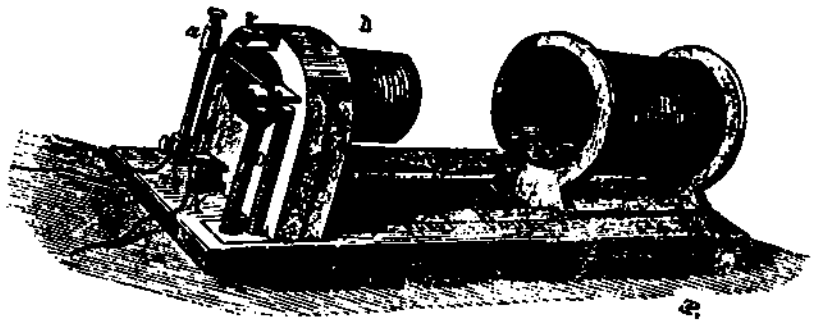

Figure 5. The du Bois Reymond induction-coil stimulator. The output was controlled by sliding the larger (secondary) coil over the smaller (primary) coil.

Figure 6. The electric-hand treatment with the induction coil. The therapist (standing) was in series with the induction coil and the patient (seated) with his feet on a plate electrode.

The induction coil, which is just a transformer, was developed by Henry and Faraday and is shown in Figure 5. It was introduced to physiology by du Bois Reymond, and consists of primary and secondary coils, with a current interrupter in the primary circuit. The output is controlled by moving the secondary coil over the primary. Treatment with this device was called Faradism. The induction

coil produced a train of damped sine waves, a large pulse followed by a smaller one. Figure 6 illustrates one of the favourite treatments. The patient has his feet on an electrode connected to the induction machine. The physician is holding on to a metal sphere covered with a saline-soaked sponge. The current passes through the physician to the subject by the physicians other hand. This was called the electric-hand treatment. The hand was moved over the head, down the back and the muscles twitched. The patients loved this treatment which was continued for many years after it was found that it wasn't doing any good. The comments in the textbooks state that the physician might be very weary if he treated patients all day. There were suspected cases of ventricular fibrillation when this technique was employed with the electric bath. There is one report in the literature that a patient suddenly became pulseless; so we suspect that ventricular fibrillation occurred.

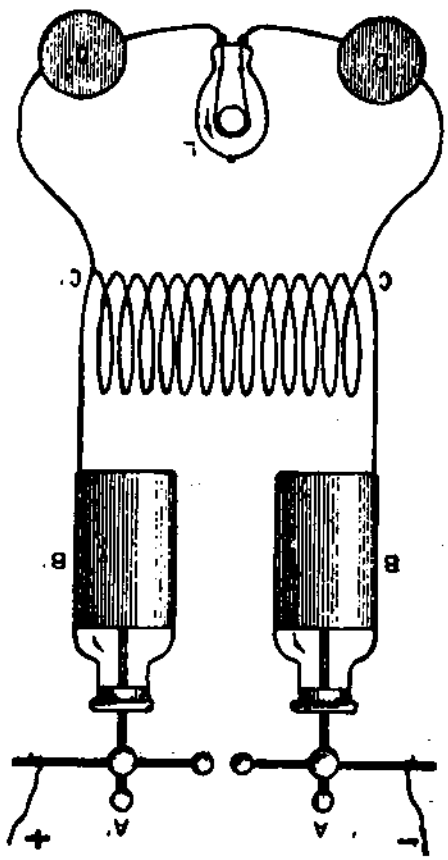

Figure 7. d'Arsonval's demonstration that 1 ampere of radiofrequency current (produced by the spark-gap generator) could be safely passed through two subjects (D,D) and a 100-watt light bulb (L).

The experiment shown in Figure 7 comes from d'Arsonval; (you may not know that he was a physician). At the top of the Figure is shown + and - which are the connections to a dc supply. Below is a spark gap and two Leyden jars and an inductor. This assembly constituted a spark-gap transmitter or radio-frequency generator. The two wires below are connected to two circles with D's therein, and a light-bulb. These two circles represent d'Arsonval's friends connected to a 100-watt light bulb. When the current was applied, the bulb glowed brilliantly. It was this experiment that showed that high-frequency sinusoidal alternating current did not stimulate nerve and muscle, but did produce heat. This is the beginning of diathermy around 1900. Figure 8 shows body heating by capacitive coupling to the radio-frequency generator. The subject lies on the couch (a chaise longue). The

secondary coil of the generator was attached to the metal frame which constituted one electrode; the other was held in the patient's hand. This treatment was used for the aches and pains of those days; it is still used today. Diathermy current is also applied using inductive coupling as shown in Figure 9. Diathermy is still used in physical therapy. The frequencies employed range from a megahertz to 27 megahertz. A current of an ampere or so is typical and produces a sensation of warmth.

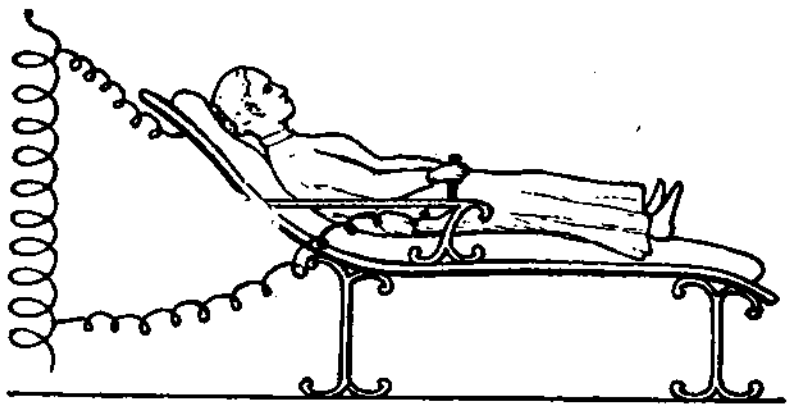

Figure 8. The condensing couch which was used for diathermy treatments. One electrode was held in the hand, the other was the mattress, which provided capacitive coupling to the patient.

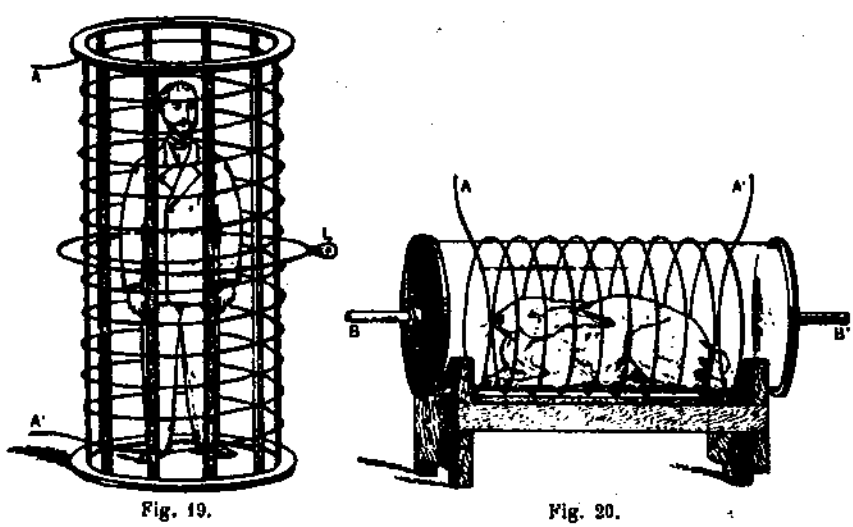

Fig. 19. Fig. 20.

Figure 9. Diathermy applied by induction heating.

Although high-frequency current so applied is safe, there have been reports of ventricular fibrillation in animals and man accompanying the use of high-frequency current in electrosurgical procedures. Research is needed in the area of cardiac stimulation with a train of short-duration pulse.

From the foregoing, it should be apparent that there is a vast literature on the application of current to the human body.

PANEL DISCUSSION

We will have our panelists introduce themselves and tell where they are from.

Joel Myklebust - Biomedical Engineer at the Medical College in Wisconsin Milwaukee, Wisconsin.

Jerry Griffin - Cardiologist on the faculty of Baylor College of Medicine, Houston, Texas

Jack Bridges - IIT Research Institute, Senior Engineering Advisor, Electrical Engineer.

Guy Knickerbocker - Now in the Philadelphia area with a biomedical engineering organization, but formerly involved in electric shock research in Baltimore. (I was with Kouwenhoven in the late 1960's and early 1970's.)

Alfred Dolan - Medical Engineer, private consultant in the Toronto area.

Helmut Antoni - Freiburg, Germany, physiologist mainly interested in electrophysiology of the heart.

Charles Lee - Physician from Manchester, England.

John Cabanes - Medical President, Chairman of the Medical Studies Group Of UNIPEDE and physician on the Medical Committee of Électricité and Gaz de France.

GEDDES: The panel has been charged with providing information on questions that are listed in the program and the letter I sent to each requesting information on additional questions that I provided.

Let us first address the questions that are listed in the program and ask for volunteers from the panel to provide information. Let me point out again that we may not be able to answer the questions; we are required to identify if more research needs to be carried out to answer these questions. So with that charge let us proceed with the items which have to do with body-weight scaling for ventricular fibrillation. This will be addressed tomorrow and probably Friday. Does anybody on the panel want to speak to that issue?

KNICKERBOCKER: I don't believe that I have definitive information to add to the body-weight scaling issue; but I would like to bring into perspective some of the work that was referred to in papers earlier in the day. Among the citations noted, it was suggested that there was not a body-weight influence upon ventricular fibrillation and identified that the work came out of our laboratory under Dr. Kouwenhoven's direction. My personal observation is that I would not like to exert a strong influence upon the decision about whether or not body weight is a factor in terms of ventricular fibrillation threshold. There is some history here and that is in our animal work, we used dogs that did not span a wide range of body weights and so it might have been difficult to find the body-weight dependence within the species that we were studying. Moreover, body weight was not a control factor that we studied closely. It was largely predicated on a very strong feeling of Dr. Kouwenhoven's regarding the developmental work that he had performed with the open chest defibrillation which was a technique which had been worked out in animals and had been translated directly to humans without change. These experiences cast in his mind, I believe, a strong feeling that there was not a marked body-weight dependence. From my own observation of what went on, I am a little bit uneasy to hear that this work was heavily referenced as evidence for no

body-weight dependence and would hope that other more solid controlled studies would enter into the discussion. I believe that this information may help to set the perspective for some future work.

GEDDES: I think that the last sentence by Dr. Knickerbocker contains the essential information. Assuredly, carefully controlled studies are needed. Would you agree with me on some possible controls; would one be current direction?

KNICKERBOCKER: Certainly, I think current pathway plays an important role in the response to current. Some of the work, particularly invoking ventricular fibrillation (and I'm thinking of some Soviet papers that I've seen), tend to indicate a polarity preference. I think that there is other work on this point, probably performed more thoroughly. Clearly I think that a factor that needs to be taken into account is current direction.

GEDDES: Therefore, an important factor is current direction, and the other is the type of current. Is this what you are saying?

KNICKERBOCKER: Yes.

GRIFFIN: Would you go so far as to include intensity, duration and waveform? Or do we have enough information on these points?

KNICKERBOCKER: Well, I am a great believer in a tightly controlled study, where you try to control the factors to manipulate one independent variable. It would be nice to be able to vary only one (say weight) and everything else is fixed. That is over idealized, but we should strive, I think, to have as closely controlled a study as possible.

GEDDES: We don't have to do the experiments right now, but we hope we will get lots of money to do these experiments; that's why we are here. How about other panel members, do they feel that more studies on the issue of body-weight scaling and the factors associated therewith are useful?

BRIDGES: I would like to comment on some of the factors that effect experimental results. As Jerry Griffin pointed out for a given animal at a given time, fibrillation threshold can vary about two or three fold. When there is that spread in fibrillation threshold, and a body weight variation that is only two to one or three to one, and if indeed there is a current density-related phenomenon, the resulting spread in the fibrillation threshold overwhelms any correlation with weight. For example a two-to-one variation in weight would only result in the mean fibrillation threshold being enhanced by 40%. Therefore, only a huge weight variation will result in a two- or three-to-one variation in the fibrillation threshold for a given animal.

GEDDES: Good point, Dr. Antoni would you like to comment on the subject?

ANTONI: Yes, I have a comment and a question too. May I ask you Mr. Chairman, whether you agree that inducing extrasystoles, inducing fibrillation, and defibrillation has the common mechanism, namely stimulation under certain conditions. Would you agree that all three effects go back to stimulation but under different conditions?

GEDDES: Correct.

ANTONI: I think we can draw information from the experience with defibrillation and although I have no direct experience, I can draw from physicians who report they have greater difficulty to defibrillate big persons than smaller ones. Does

this point to an influence of the body weight in the effectivity of stimulating the heart?

GEDDES: You have raised a good issue. It is a controversial observation that big people are more difficult to defibrillate and require more output from a defibrillator than small people. Certainly there is no dispute when one talks about children and adults. It is just bad practice to defibrillate a child with 400 joules. The heart will be defibrillated and it will produce an ECG; but it just won't produce a contraction. There results an uncoupling of the excitatory and contractile processes. So when discussing defibrillation among adults there are two schools of thought. The situation becomes difficult and I think we ought to ventilate the topic. The group in Belfast, Ireland, under Drs. Adgey Pantridge and Geddes, (not this Geddes) and some others believe in low-energy defibrillation and deliver multiple shocks. It is interesting that the only people who defibrillate in their institution are physicians who apply the electrodes firmly over apex beat area and below the clavicle on the right chest. They push hard on the electrodes and obtain a low impedance contact. They can defibrillate most adults with multiple 200-joules shocks. Whether the technique is any better than a single 400-joule shock to start with, is not yet proven. Although there are schools who believe that this is a good practice and there is some physiological evidence to support it. So the whole issue of body-weight scaling for defibrillation has that kind of a problem; but it also has other problems that we mentioned earlier; namely that the metabolic status of a human heart to be defibrillated is virtually unknown. We have seen, and it has been pointed out here, that the threshold for fibrillation, and certainly the threshold for defibrillation, is dependent on the metabolic status. This is a variable that is present from the outset. One does not defibrillate normal human hearts with chest electrodes. I know of no reason to do so in the closed-chest human. When one extrapolates from animals (which have normal hearts) to humans which are not normal there are obvious difficulties. Would you like to say something about that Dr. Griffin? (About the energy requirements or other problems.)

GRIFFIN: What you have said is particularly germane to the problem of defibrillation where the process of fibrillation in fact greatly contributes to the disordering of the metabolic state. Fibrillation is probably the most energy consumptive state of the ventricles, much more so than orderly rhythmic contraction. This is also very pertinent right now in the clinical area because from the engineering point of view, and I might add Dr. Geddes has been one of the pioneers in this area, we are approaching the point in time when a defibrillator can be implanted as a self-contained device. This speaks to the cause of death in almost a million Americans every year. This is a major health problem.

Getting back to the critical problems of scaling for fibrillation threshold. I think the first thing we have to do is be very careful to plan what we scale. Even if we all can agree on scaling factors for current path and for body weight and other factors, I think we must pay very close attention to the fact that the numbers obtained from such studies are all extremely model dependent over perhaps almost an order of magnitude. Moreover one must examine very carefully things like electrode surface area, spacing, the relationship to the myocardium, the heart size and many other factors before it is possible to relate actual numerical values from one study to another and particularly in extrapolating to the human case.

GEDDES: Any other observations?

MYKLEBUST: It seems to me that we have to be careful with our terminology. When we talk about scaling the dependence of fibrillation threshold on body weight, we are dealing with an approximation. What we are really interested in is how much current reaches the heart. In scaling for body weight it seems reasonable that when we increase the volume in which current is passed, we need to apply more

current. But what is really important, and I think the reason why Dr. Biegelmeier points out that it is difficult to compare from one species to another, is how the body weight is distributed. I just have one point to add, concerning a controlled experiment within a particular species. In trying to resolve this problem it seems to me that to get a large number of animals with a wide range of body weight within one species, will be difficult because one is dealing with a large number of animals at various stages of the maturation process which introduces other problems. For example, Dr. Geddes pointed out earlier that perhaps younger animals are more difficult to fibrillate, or else one is dealing with a large number of mature animals of different weight in which case as Dr. Biegelmeier pointed out, there is the case of the sportsman and the beer drinker, where weight is not distributed uniformly.

GEDDES: Do any other panel members want to make a comment?

CABANES: (interpreted) I think that the skin area might be a better factor by which to scale fibrillation current. The current density is a critical variable and what counts is the density of current within a given surface. This is proportional to the square whereas the weight is a function of the cubic power. So of course the surface of the body is proportional to the square. The surface area of the skin is used to determine the amount of medication that you would give to an adult as compared to a child.

GEDDES: In many studies it is customary to use surface area for normalizing a variety of parameters, particularly metabolism; cardiac index is normalized on the basis of body surface area, ie, cardiac output per square meter of body surface.

We now have several ideas from the committee about normalizing factors, and pertinent things to pay attention to. If the committee members have presented their principal views, we will solicit views from the audience. Now remember we may not settle important issues, we must decide whether more research needs to be carried out and what kind of research needs to be performed.

GAMS: There are a few observations which I would like to share with you which may generate further discussion. One, it was very difficult to evaluate the various results of various studies because many parameters have not been measured. By parameters, I mean items like surface area of electrode, current density, frequencies, etc. Also, there were various modes of stimulation: intracardiac, extracardiac, external, internal. How does one interpret results from so many different modes of experimentation without knowing the experimental modality and the parameters used? Returning to the immediate question, that is body-weight scaling, since the body is a volume conductor, it makes some sense to use a body as a volume and use a cubic instead of a square measure.

GEDDES: Here is a plea for more quantitative data, but let me add that the body is not a uniform volume conductor. The resistivity of tissues varies; for example lung is about 2000 ohm-cm, fat is about 5000 ohm-cm, bone is about 15 000 ohm-cm, blood is about 150 ohm-cm. Therefore, the pathway for the current will depend upon the distribution of these resistivities. This fact does not diminish the plea for more quantitative data.

HOYLE: I was simply concerned about the use of the term body size and body weight in what I think is rather loose fashion because one could take a seven-foot, three-hundred pound basketball player, three-hundred pound, five-foot six inch football linebacker and a three-hundred pound diabetic and the results might not be related in any way at all in spite of the constant three-hundred pound body weight; but the suggestion of the skin area might answer my question.

GEDDES: Your point is well taken. One hundred soldiers six feet high are not the same as six hundred soldiers one foot high are they? This was the mistake in the old Laurel and Hardy movie when Hardy sent Laurel out to get some soldiers. Laurel got the product right but the proportions wrong. I think I don't want to press this point too strongly, but I do think that we must pay attention to the point of injection and exit of the current. For example when one electrode is in the area of cardiac apex, current can gain very easy access to the heart and there is not much difference among body weights for fibrillation. In a limited series that we have studied as in catheter-electrode studies for example, there is even less variation of current for fibrillation. The variation in metabolism is important; thresholds that you want to measure vary if the metabolic status is not well controlled. Therefore location of the electrodes is terribly important and body proportions are equally important in quantitating ventricular fibrillation threshold.

DISCUSSIONS

BIEGELMEIER: When reading the literature of the past fifty years one has sometimes the impression that various authors have tried hard to prove that electricity is very dangerous by extrapolating experimental data far beyond reasonable limits. The so called body-weight scaling is a good example of this. When Ferris and his cooperators published in 1936 their classical experiments on ventricular fibrillation, nobody paid much attention to the very important fact, shown in Figure 1, that the fibrillation threshold drops significantly when the shock duration is longer than one heart period.

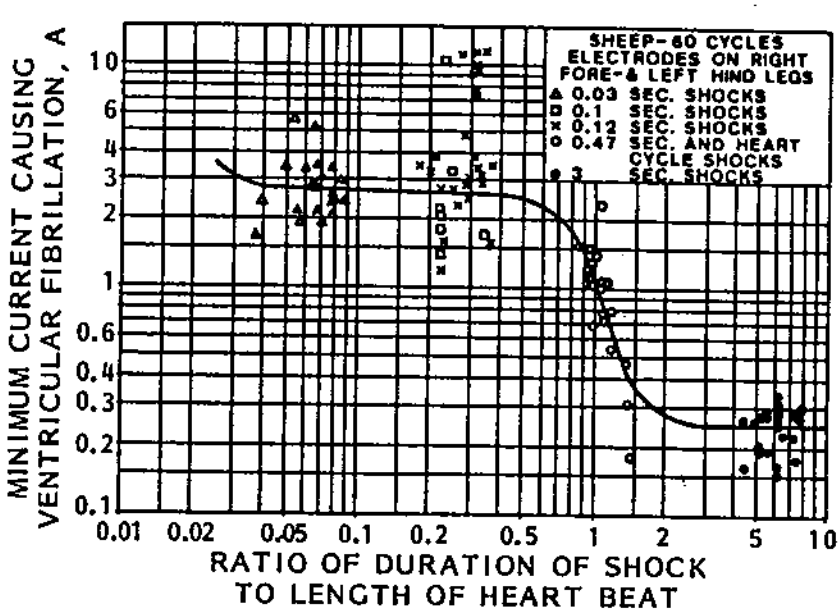

Fig. 1 Experiments of Ferris with sheep

On the other hand, many publishers concentrated on the Figure indicating that the threshold of various species varies with body-weight, as shown in Figure 2.

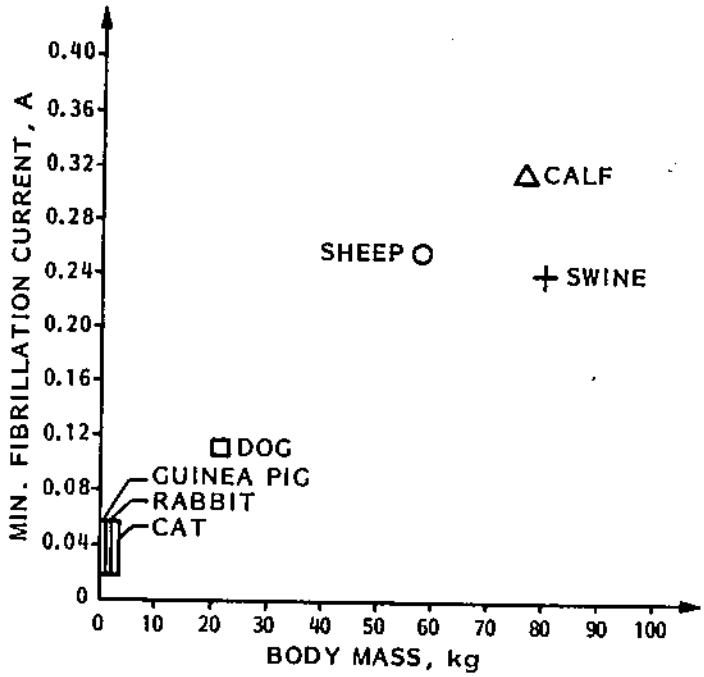

Fig. 2 Body-weight and fibrillating threshold for various species (Ferris)

To me it does not seem surprising that the fibrillation threshold of a rabbit is lower than that of a sheep. However, what is the variation of the threshold within one species? The paper of Ferris indicates that there is no relation between body-weight and threshold for one and the same species as shown in Figures 3 and 4.

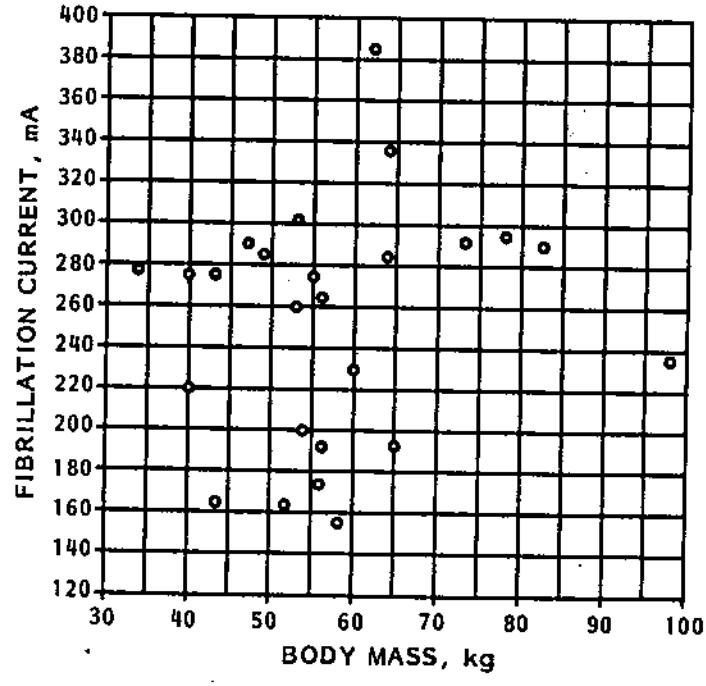

Fig. 3 Threshold and body-weight for a shock duration of 3 s for sheep

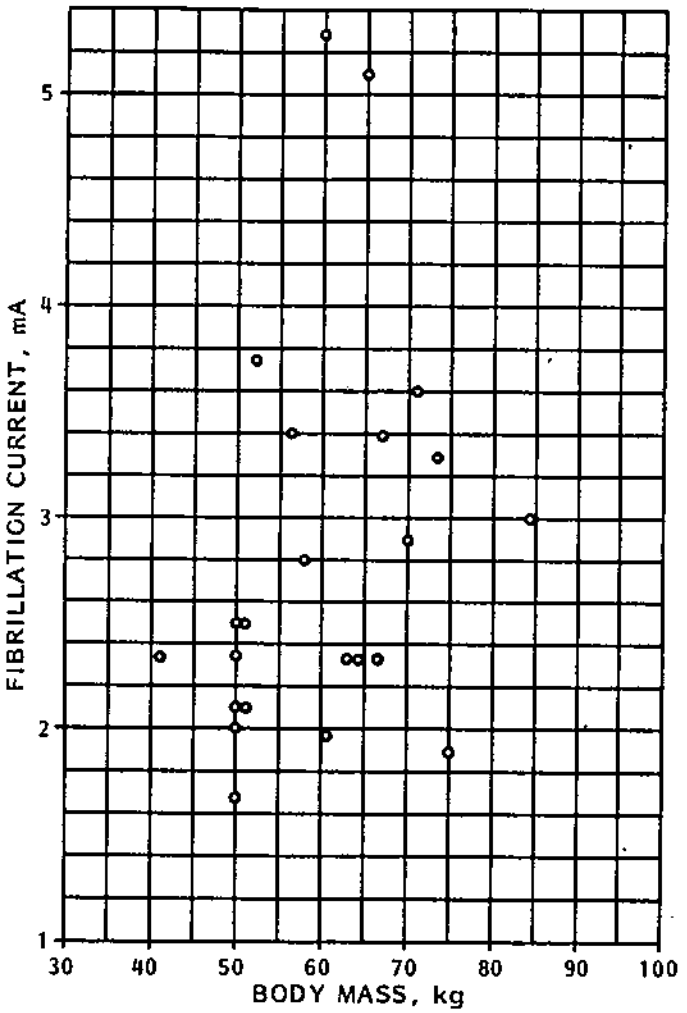

Fig. 4 Threshold and body-weight for a shock duration of 30 ms for sheep

These Figures clearly illustrate that no correlation exists between the thresholds and the body-weight.

During the discussion of the important Kouwenhoven paper it is said: "The weights of our animals were recorded but we failed to find any correlation between the body-weights and the minimum fibrillating current". The experiments were made in 1959 with dogs.

Experiments which were carried out in Australia with dogs in 1972 by Keefe, Ross et al., obtained the same result: "Currents up to the fibrillation threshold whilst causing extreme discomfort at the time, produce no permanent lasting effects. Body-weight within the species was not a significant factor in the Australian experiments".

The experiments of Geddes seem to indicate the same, as shown in Figure 5.

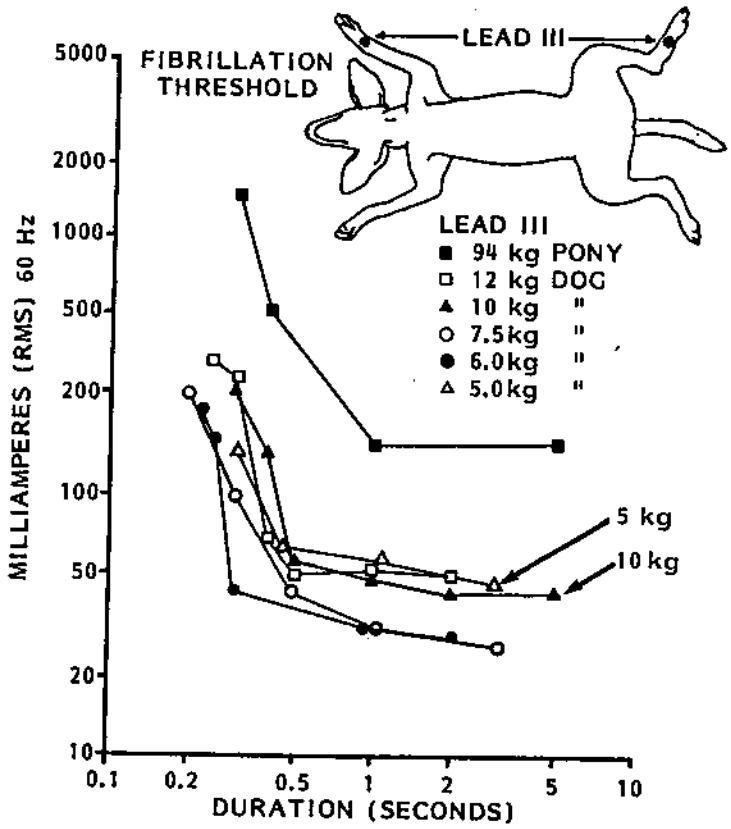

Fig. 5 Geddes experiments. Weight of the dogs and fibrillation threshold.

In addition, Jacobsen et al. conducted tests on young hybrid pigs with weights between 15 and 25 kg and found no dependency of the threshold of ventricular fibrillation on weight.

However, most convincing, are the newest results of experiments with pigs. Kupfer et al. determined in 1981 the fibrillation threshold of grown up pigs with a mean body weight of 105 kg fitted well into results of Ferris for grown up pigs taking into consideration the shock durations of 1.5 s and 3 s respectively.

On the other hand, Küttner and cooperators in Austria measured the threshold of 104 young pigs in 1982 with a mean body weight of 17 kg and found again practically the same threshold as Kupfer found for grown up pigs. This proves finally beyond any doubt that there can only be little influence of body weight on fibrillation thresholds. The values are shown in Table 1. In my opinion measurements on pigs are more reliable in that respect because pigs have all more or less the same physical geometry whilst dogs of various breeds differ much more.

I personally could never understand why a fat heavy person should be less endangered by electricity than a sportsman as shown in Figure 6.

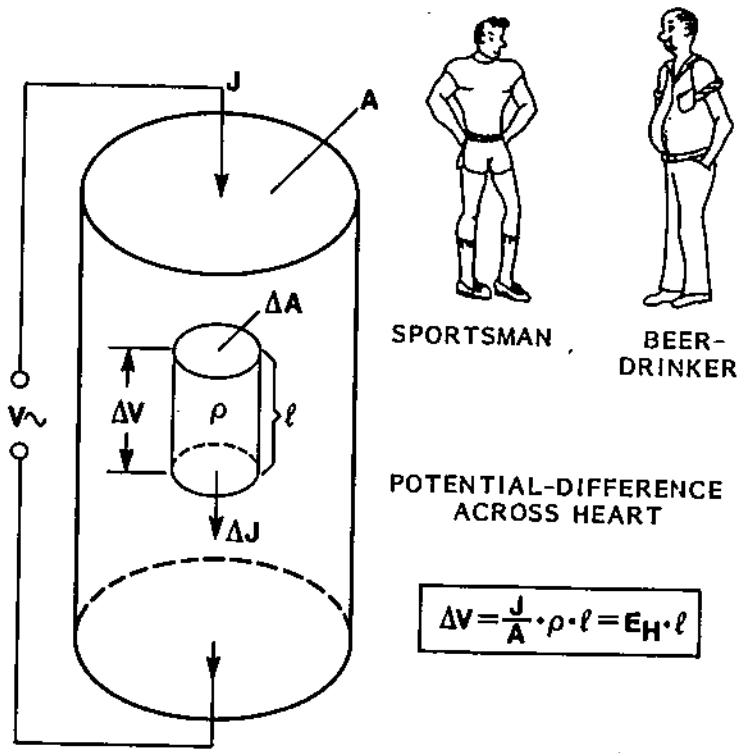

Fig. 6 Potential difference across the heart as a function of current density

Theoretically the potential difference across the heart decreases by the square root, if the dimensions of the heart and body increase, and the same current is flowing through the body, as shown in Figures 7 and 8.

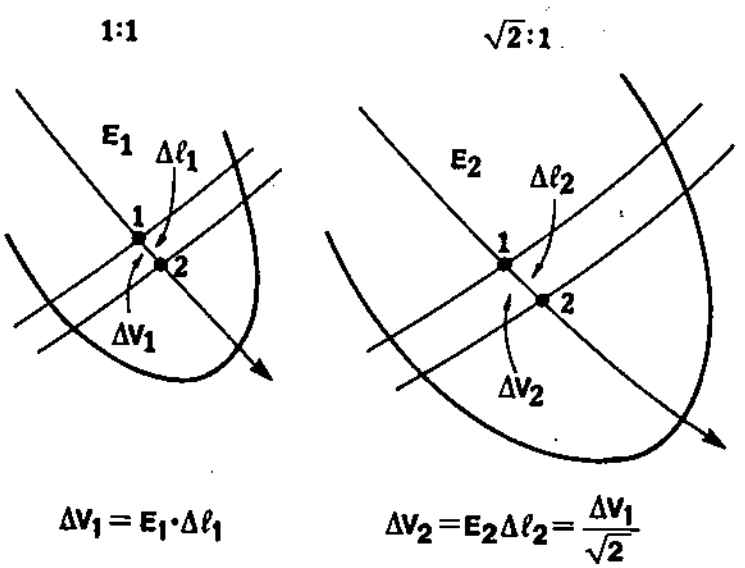

Fig. 7 Potential difference across the heart for two sizes of heart

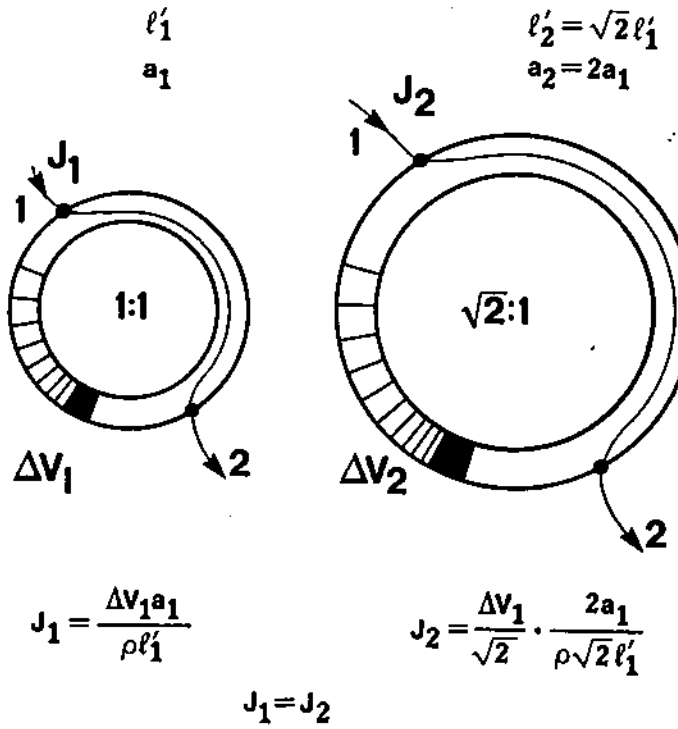

Fig. 8 Exciting current through the heart for two considered heart dimensions.

This leads directly to the statement of Mr. Bridges in his paper:

> "The same data, however, can be interpreted to suggest that the fibrillation shock criterion should be the fraction of the body current intercepted by the heart. This fraction is proportional to the current density and "effective area" for the heart. Assuming that the fraction of body current intercepted is the dominant criterion, the fibrillation threshold would be about the same for animals of nearly similar geometries but of different sizes and weights."

I personally take the pragmatic view. I take as real what has been measured in most of the experiments. We should not make guesses in this field.

As the experiments of Kouwenhoven et al were carried out on dogs with body-weights between 8 and 16 kg and with heart rates of 180 beats per minute, it is obvious that the results can be applied directly to men including children as proposed by Working Group 4. This concept was corroborated by the results of Green et al who measured fibrillation thresholds directly on human hearts and on dog hearts. These experiments have proved that the results measured on dogs are conservative when applied to the fibrillating characteristics of the human heart. If the results of the numerous measurements of Kouwenhoven on dogs are exploited on the basis of the log-normal distribution, fibrillation threshold curves can be obtained as shown in Figure 9 for 5%, 50% and 95% probability of fibrillation. The safety curve (S in Figure 9) proposed by the experts of WG 4, which is far below the 5% curve must be considered as very conservative. It might even be suggested that for certain safety standards the 5% values are sufficient.

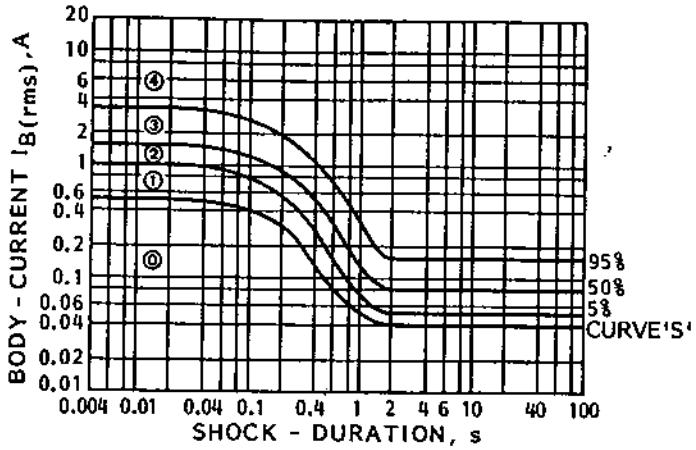

Fig. 9 Fibrillation thresholds

Table 1

Comparison of Young and Grown-Up Pigs
With Regard to Fibrillation Thresholds

Fibrillating thresholds and body weight of pigs (mean values and range in A effective values)	
Ferris et al (1936)	experiments with 9 pigs (grown up) mean body weight 89 kg
Shock duration 3 s	..... 0.24 A (0.17 ... 0.27 A)
Kupfer et al (1981)	experiments with 106 pigs (grown up) mean body weight 105 kg
Shock duration 20 ms	..... 5.1 A
Shock duration 1.5 s	..... 0.38 A
Küttner et al (1982)	experiments with 141 young pigs mean body weight 17 kg (range 11 ... 25 kg)
Shock duration 20 ms	..... 4.6 A (range 3.6 ... 6.0 A)
Shock duration 1.2 s	..... 0.31 A (range 0.24 ... 0.36 A)
Shock duration 4 s	..... 0.17 A (range 0.141 ... 0.21 A)

	Weight of body	weight of heart (Ferris et al)
Dog	22 kg	170 g
Pig	79 kg	300 g
Man (adult)	70 kg	280 g
Man (child 2 years)	9 kg	45 g

KARYAKIN: (interpreted) I would like to give a comment about the fibrillation threshold, and the body weight in general. During the last twenty years we conducted many experiments on dogs and pigs which we consider to be good models for comparison with a human. We tested about a thousand animals, and the study took into account the weight, the threshold of fibrillation and the current duration (from 0.1 to 3 seconds).

GEDDES: Excuse me, what waveform were you using?

KARYAKIN: 50 Hz.

GEDDES: Dr. Karyakin has drawn a graph of the current versus the exposure time for 50 Hz current. In general the curve shows an increased current for fibrillation as the duration of current flow is reduced. Thank you very much. We must move on to the next topic, but before I do, is there anyone here, who would like to address this next question?

LEE: There are really two points on which I would like to speak. The curve which we have just been shown for weight is a simple $y = mx + c$ curve and really very similar to one which Charlie Dalziel and I published in the late 1960's. I think that this is just a first approximation for body weight within species. The second point I wish to make is perhaps not fully in agreement with you and that is we should not stress all the differences. If you look at the papers which have been published on shocks for dogs by Charles Dalziel and I, by Ferris in the 1930's, by Kouwenhoven in the 1950's, by Kiselev in Moscow in 1963 and in my laboratory in Manchester, they all fitted very well. I don't think we should make too much of all this difference. There's a remarkable consistency with these where one picks out things; I will misuse the term as somebody has already misused it, where you pick out the same parameters of experiment.

GEDDES: Good point; the question I want to put before the panel and the audience is as follows. Is more research needed on body-weight scaling? I know my own feeling and I am very biased. But would anyone among the panel members give us the advice now?

BRIDGES: I think the real rationale for this will be more apparent during the panel discussions on the third day. There are critical issues in the design of substations where the surge current can exceed perhaps 100 kA. Under these circumstances the grounding practices that are presently employed may or may not be adequate and a detailed knowledge of how the fibrillation threshold varies with time and possibly with weight is very crucial to the design of the facility.

GEDDES: I am glad you said that. Now do you want to specify something about the transients that we should know more about?

BRIDGES: I think that I may be stealing somebody else's thunder on that; maybe Gary Ford would like to comment.

FORD: In answer to the question, I think that Jack Bridges was talking about 60 Hz or power frequencies and I would agree that it seems to me that it is clear there should be more research. I think you can also say the same for fast transients associated with gas-insulated switchgear. I tend to agree that there is a need for research on this topic in both areas.

GEDDES: Does anybody else on the panel want to speak up for or against research on this topic or setting a priority for it. Apparently nobody wants to make a comment. Let me have a show of hands in the audience who feel that continued research in this area would be useful. Don't be afraid to put your hands up. Could you estimate from where you are panel of whether its 50%. Please raise your

hand high and clear so we can see. Panel, what would you estimate? Looks like about three quarters of you would like more information. Now with that we must move on to the next topic. Dr. Antoni who is the vice-chairman, ought to now have time to exercise his position.

ANTONI: I feel that the electrocution equation should be based on sound biophysical principles which can be understood and it is my belief that it would apply for short pulses. For short pulses one obtains a nice hyperbolic function between current strength and duration. This means that there is constant charge that must be transferred to the membrane to stimulate it. This also holds true as far as we know, for the induction of fibrillation with short pulses. However, if you increase the duration of current flow with alternating current, then there are processes which are purely biologic. A series of extrasystoles is produced and there is an increasing inhomogeneity in the excitatory state and this can hardly be represented by a physical formula. Surely if several constants are used you can adjust a function to such an S-shaped curve; but I think it does not have much validity.

LEE: I would like to make one or two comments on this point, particularly since I have published two electrocution equations with different authors. The first was with Charlie Dalziel and it was shown this afternoon; it was $I = K/\sqrt{t}$. In our studies, we made quite clear that it was not meant to express the complex physiological phenomenon which Prof. Antoni has rightly said was occurring. Our equation was merely an approximation to the data as we knew them at that time. We were careful to limit it to certain durations. Then Prof. Biegelmeier picked up some work which I had performed subsequently and kindly asked me to be a co-author when we published it, not as an equation because you can't publish it as an equation, but as a graph of the z-shaped curve which could be readily understood on simple physiological principles as two or three people pointed out this morning. But again the relation is meant to be a practical guide and no more.

Now then Mr. Chairman, you have asked us to think ahead to what should be done in the future, and here I think we have now accumulated data and I'm sorry to come out with a particularly British point of view, but I think that instead of rushing around trying to collect more data, we ought to stop and think about the data we already have. When we publish this type of data, they represent very much a probability event, and yet we talk about a threshold. Philosophically, these are not compatible and we have to ask what has gone wrong with our thinking. Throughout this morning and afternoon people have talked about threshold and yet these equations, such as they are, are based on probability. I think if you trace back through your retroscope, Mr. Chairman, you will see, if you focus in on the year 1941, that Charlie Dalziel was doing studies of let-go currents and I discussed this with him at length on a number of occasions. I said to him: "Charlie, why did you plot the data on probability paper when you knew perfectly well that there is a threshold at which people can let go?". He said "Because there were some people who could not let go, even after I had switched off the current, and I had to pull out the plug from the wall and show it to them." I'm not presenting this as an after dinner talk; I know it makes a good story, but this is, in fact, an important principle that comes from this work. He said, this is why I had to do it in that way. Now if you analyze what was happening intellectually, he was, in fact drawing a graph, and on the horizontal axis he had current, but on his probability scale he was measuring a physiological effect of stimulation on muscles as well as a psychological effect. It is because he could not separate the physiological from the psychological effect (this is really what was happening in his thinking process) that he had to revert to probability and he picked just conveniently the one in two hundred (0.5%) probability. Now the interesting thing is that if you follow the papers through from that time, you find this one in two hundred and you find that in the ventricular fibrillation, where I don't think there's a great psychological effect present, you still find this one in two

hundred because it got into the literature and got carried through. This is a matter which is not simple, we talk about thresholds, but we have to decide if there is such a thing as a threshold, because if you stick to this probability you're going to say, right, there's a certain probability at 80 milliamps, (I am thinking of the intact human being now) and there is lower probability at 60 milliamps. Are you going to say there's a probability of fibrillation at one milliamp, because if you get away from this threshold and talk about statistics you are. If you do that, you're leading yourself into a further complexity and that is if you don't have a threshold and decide on a fixed threshold you are going to say, who will decide the probability? Is it going to be an electrical engineer? Is it going to be a physician? Is it going to be some sort of committee that's going to decide the risk that other people should take? Now this is the type of a problem that I haven't just dreamed up now, but that we are facing in medicine at the present time when people are exposed to carcinogens, such as an asbestos at work, where there is a threshold, it is a probability and who decides the probability, the engineers, the trade unions or the management? This is the sort of philosophical question that I think we need to stop and think about, as well as collect data.

GEDDES: Thank you for your very good points. I would like a definition of electrocution from the panel because we refer to an electrocution equation, I would like to be sure that we all know what we are referring to. Is it fibrillation? Is it thermal death of the central nervous system? What do we mean by electrocution? I suspect it is ventricular fibrillation? Dr. Lee would you like to comment?

LEE: I must say, when I was talking there, I was talking solely of death from ventricular fibrillation in the intact animal or human being.

GEDDES: I think it is an important point to make because it hasn't been brought up and the reason I brought it up is that it is becoming popular in the United States to electrocute criminals in the electric chair, and although the death may be due to ventricular fibrillation, it is more likely due to thermal coagulation of the central nervous system. Brain temperatures of 140°F have been measured inside an executed criminal's brain. Pathological studies indicate that there are widespread thermal lesions so I don't want to have the two confused within the one term. Dr. Antoni do you want to continue?

ANTONI: Yes. The discussion is now confined to the question "How can we find the boundary where fibrillation may appear in terms of current, time and of other parameters?" Dr. Lee, you have mentioned that you have published two formulas for electrocution, would you comment on them. Perhaps you would like to discuss their validity.

LEE: The first one was with Charlie Dalziel when we elaborated his familiar energy equation. That was limited because our data were limited from 8 ms to 5 s. When we obtained more information, Dr. Biegelmeier, who is here and he must have the credit, spotted that the z-shaped curve fitted these data much better and could also be explained physiologically. That was not taking into account body weight, but only embodied duration and current. But I know I'm quoting Dr. Biegelmeier on that, perhaps he would want to talk if I'm misquoting him at any stage.

ANTONI: Just a short comment. Energy released by the flowing current can be expressed as I^2rt. This expression would indicate that a certain amount of energy can be applied, either with a little current and a long time, or high current and short time. If this amount of energy is supplied, then fibrillation will occur. From your curve, Mr. Chairman, which you showed this morning, it became clear that

there is a u-shaped curve if the threshold is expressed in energy. In this case there cannot be a constant amount of energy to produce arrhythmia.

LEE: You are absolutely right. (Please note, I'm here defending Charlie Dalziel's concept and because he could not be here). The study produced limited data. We stressed that it was not meant to be a physiological explanation but that if you took the data points and drew a line through them, it happened to fit the energy equation, that is all. When more data came along, we saw that the energy equation didn't fit and therefore changed it.

ANTONI: The energy criterion may be valid for short pulses having different shapes and durations between 1 to 10 ms. We have discussed this problem in working group 4 and have gained some new data in Freiburg which points to this, namely rectangular pulses, sinusoidal pulses and capacitor-discharge pulses. If one compares their fibrillatory efficacy it can be stated that a constant amount of energy must be applied to the heart in this small range of duration for any of these impulses to induce fibrillation. I would like to ask whether other members of the panel have a statement concerning this question? Perhaps Dr. Biegelmeier will provide further comments on it.

HART: I would like to make a comment about what I think you said. I^2t is really energy per-unit ohm; is my understanding correct?

GEDDES: I will also point out that the energy depends on where the resistance is located. Because the current density varies throughout a subject, the current will not be uniform and is not as simple as it might appear to state where the energy is deposited.

BIEGELMEIER: When we checked the evaluation by my friends Dr. Lee and Charles Dalziel, on a log-normal distribution basis, we found that a curve would fit the measured values. We have always been very pragmatic, so we took the measured values in Kouwenhoven's paper and we found that if you plot the current against the time up to approximately a tenth of a second, you obtain the fifty percent value of probability for a current in the order of 1.6 A. Then the current decreased according to a log-normal distribution. When one or two seconds duration was reached the curve did not change any more. This is what Dr. Lee proved very precisely with his dog experiments.

GEDDES: Excuse me Dr. Biegelmeier, could you specify the animals and currents?

BIEGELMEIER: Yes, I said it was the Kouwenhoven experiments and it was on dogs of course using 60 Hz; but I think 50 Hz would make no difference, for the 50% probability value. If longer durations, eg, a couple of seconds are used, the threshold doesn't change anymore and remains at about 80 milliamperes. Therefore there is quite a large difference between short and long durations.

Now we do not know what was happening below 10 ms, which is a half cycle, or 8 ms for 60 cycles. Then the results of Dr. Green came from United Kingdom who investigated short-duration pulses. He found that the threshold is fairly constant for durations up to 0.1 or 0.2 s. But when the duration is below 10 ms, then the following is found. If the duration is 10 ms to 5 ms, the threshold is about 1.6 A. When shorter impulses are used, as shown by Green, who sliced waveforms from the 50 Hz cycle which induced fibrillation, the threshold rises with decreasing duration. This was discussed in working group 4 because we are also interested in part 5 of the revision of publication 479. So it was this very significant result from Green that we had accepted. Now we have a curve for fibrillation threshold going from approximately one tenth of a millisecond to ten seconds. I think we are very content about accepting this for the time being. There are much data and the philosophy was based on experiments which were made with dogs (little dogs, 8

to 16 kg). We then applied these data to human beings, with a large safety margin. In addition, Green has conducted very interesting experiments in the human heart and the dog heart with electrodes inserted into the heart. He compared the thresholds of fibrillation and disturbances in pumping actions. He is of the opinion that the values measured on dogs are very conservative for human beings. So this is more or less the philosophy of working group 4. We have similar data from Kouwenhoven down to approximately 8 ms. He used half a wave of 60 cycles. Green studied shorter impulses. At about 4 ms the threshold starts to rise not quite as It; (somewhat between It and I^2t). But we are very pragmatic, just taking the measured values and not inventing any theories. Thank you very much.

GEDDES: Thank you, Dr. Antoni do you want to make a comment?

ANTONI: We have seen many threshold curves this morning, that represent very different conditions. Surely this is one curve which also described empirically what one finds. The question is whether this curve should be, or can be, represented by a formula. This is what I understand by the term electrocution equation. Can we formulate an equation which relates empirical values and what is the advantage of such a measure?

LEE: Well, I might save time and ask Dr. Biegelmeier because I would say this should be done. The lines joining experimental points (and we don't want to try and force these data into an equation) and we don't want to pretend that this provides some new physiological theory. The fact is that present physiological theories happen to fit it. But I wouldn't take it any further than a line joining points which is compatible with present physiological knowledge. Would you agree Friedel? Dr. Biegelmeier agrees for the record.

ANTONI: It seems that the situation is a little different relative to short-duration pulses. The range of short duration is becoming of increasing interest. For instance one should compare a sinusoidal half wave of 50 cycle current of 10 ms duration with a 10 ms square pulse, and with a 100 ms capacitance discharge. If we state that a particular constant charge, or a constant duration must be applied to result in fibrillation, then this will be helpful.

GEDDES: Dr. Antoni has just brought up one of the most important problems in using different waveforms to stimulate. The question is; can one find something about one waveform that makes it equivalent to another waveform? In other words, is a square wave which has a flat top, and an average value equal to the peak value, any different than a half sinusoid of the same duration? How does one compare these two? We are conducting such studies at present. Dr. Antoni, over a drink you and I will probably discuss them. Such work is going on and I want you to be aware of this. If anyone is doing work in this area, I would like to talk to you, because we have found a way of comparing waveforms insofar as myocardial stimulation, pacemaking, and defibrillation are concerned. We were seeking the law of defibrillation. I don't think we have found it yet. But we now can compare the damped sinusoid, half sinusoid, trapezoidal (low tilt and high tilt). We have found a way, but I'm not ready to advertise it as being the golden rule right now.

We must move right along because we will have time only for one more subject. I think the subject we should discuss is the physiological effects of current applied to the body, which is the last question that I asked the panel to address. Would anybody like to offer comments? While you are thinking about it, let me call to your attention a vast literature on electronarcosis and brief-shock or electroconvulsive therapy. With these two techniques, a current is applied to the brain and the spinal cord for the purpose of anesthetizing subjects or convulsing them. We have applied the method to 16 horses and I don't know how many dogs. We have made a motion picture of this research. We thought the method was going to

be a very good substitute for anesthesia. However, the method has some real problems. There is a vast literature that is germane to this particular topic. For example, waveforms are not the critical item if current is applied between the head and the rectum or from forehead to occiput. Depending upon the intensity and rapidity with which you increase the current, you can encounter anything from respiratory arrest, cardiac arrest to tetanic contractions of the thoracic and abdominal muscles and defecation and micturition. It is good practice not to stand near either end of the animal, because they salivate very profusely and eject urine and feces. There's a large volume of literature that may or may not be germane for this audience.

With that as an introduction, I would like the panel to make some comments on their views of the physiological response to the application of current to the body from the viewpoint of this audience which is concerned with power currents and short duration transients.

BRIDGES: I think that muscle contraction is a topic that we discussed early this morning, namely whether we can breathe or whether one has respiratory arrest. The scenario that one encounters in power substation or with power plants is, hand-to-foot or hand-to-hand type of contact. These kinds of physiological effects may be important wherein there is contact between the neck and some part of the chest; that could be part of the scenario. It is not clear to me that in the typical worker scenario one would encounter many of the effects you referred to; but on the other hand, I don't know, and I don't have any literature or background of my own personal knowledge to say that these conditions should not be considered.

GRIFFIN: Speaking from the point of view of an electrophysiologist, I think there are some issues that should be noted. Dr. Jackson, probably more eloquently, if somewhat frustratedly, expressed our opinions. I think there are many fundamental things that we don't know about this subject, including the mechanism by which these currents initiate fibrillation or the mechanism by which fibrillation is maintained once initiated in the intact myocardium. In the area of physiology we have almost everything to learn in terms of some of the most fundamental aspects. I do think there is one area in which we do have good data in a number of scenarios. The myocardium is capable of being profoundly influenced by a variety of factors in terms of measurable fibrillation threshold. Reductions of 50 to 75 percent and elevations in threshold as much as four fold have been recorded by any number of laboratories and different preparations. I think that we can accept that the largest gap in our knowledge is in the area of exact mechanisms, and specific mechanisms of initiation and maintenance of fibrillation.

ANTONI: During the discussion of Dr. Cabanes's paper this morning, I considered a situation when a current is flowing through the body, and there are muscular contractions. The intensity may have the magnitude to cause difficulty in breathing as it is formulated in the document of the working group 4. It is not expressed that there is an arrest of breathing and if you think about the body and the current flowing through it, it will be more on the left side or more on the right side, and there is also the diaphragm which can move. Thus, it may be difficult to breathe if there are muscular contractions in part of the body. But I cannot easily imagine that all muscles which are related to respiration will be contracted the same way.

LEE: Well, Dr. Antoni is working by imagination. We have, in fact, done this one bit of research. I would present three pieces of evidence on this point and I know Dr. Biegelmeier has different views; but this is what makes life interesting. First, way back someone working in a town called at that time St. Petersburg, found that passing current through the chest of a dog caused respiration to stop. I am talking now only of current passing through respiratory muscles and causing their contraction. I am not discussing current through the

respiratory center. We have done this, and we've done it more than once, and published the results. If a current is passed through an upper limb to a lower limb of a dog and gradually raised you will reach a level at which respiration is stopped and the heart continues to beat. The current can be held at this level, and if you measure the partial pressure of oxygen, the acid-base status or any of these other things, you find that these are all abnormal. Then after about 4, 5, or 6 minutes the animal is dead from asphyxiation. The result, is fairly simple to explain on physical principles. It is interesting that the animals do not show pathological signs of asphyxiation with petechial hemorrhages. It's very simple to explain and this may be important when you conduct postmortem examinations on people, because they may die this way and not show that. If you raise the current you can reach a level at which respiration is arrested and fibrillation doesn't occur. I have published a clinical paper about 20 or 30 men who have been in hold-on accidents and they have told me after, "I could not breathe, I could not shout". It wasn't until a number of possible things happened; a colleague came along switched off the current, kicked him away or something like that or the man was able by moving his body weight away from his feet so that he fell and broke the contact, then respiration started again. Now obviously to my mind, this fits with the dog experiments. The man was at such a level of current that it was stopping respiration; but clearly he wasn't fibrillating, otherwise he wouldn't have told me about it.

GEDDES: Dr. Lee, I can verify what you have said. I just want to agree with Dr. Lee, we have done the same experiments in the dog. We have also used the technique of applying intermittent current for artificial respiration with no danger of ventricular fibrillation, by putting an electrode in each axilla. If the current is turned up, the chest muscles and diaphragm are tetanized and the animal cannot breathe. It will stay that way until the current is turned off. There is one human fibrillation accident that has had this happen and the case is in litigation now, so I cannot discuss it with you. But if you turn off the current, the animal will exhale; turning it back on again produces inhalation. The method produces excellent artificial respiration in the dog lab. Now as Dr. Lee stated, apply a tetanic current to the head you can arrest respiration and you can slow the heart by vagal stimulation. But if you reduce the current, an anesthesia-like state exists and respiration will start again. If the current is increased a little, respiration will stop. There are all gradations to centrally applied current. But when current is applied peripherally, motor neurons are stimulated and muscles contract. Do any of the panel members want to give a last comment?

BRIDGES: It seems to me as if we need a better reporting procedure for accidents since this is a potential hazard.

GEDDES: Thank you very much. Thank you panel.

Chapter 3

Body Impedance

NEW KNOWLEDGE ON THE IMPEDANCE OF THE HUMAN BODY

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ABSTRACT

This paper briefly reviews the history of body impedance studies and correlates the earlier work with recent studies. Recent research, including measurements on living persons at power frequency potentials of 15, 25 and 200 V, is described. The results of statistical analysis of all relevant data, which forms the basis for the body impedance values proposed by Working Group 4 of IEC TC 64, are given.

KEYWORDS

Electrical shock; human body impedance

INTRODUCTION

In order to estimate the dangers of electricity in a quantitative manner two problems had to be solved first. The first problem was the determination of the current flowing through the human body if a certain voltage is applied across it from one electrode on one part of the body to an electrode on another part, for instance from hand to hand. For this purpose the voltage - which nowadays is called "touch voltage" - must be divided by the electrical impedance of the human body for the given current-path and therefore this impedance must be known. The other question was the threshold of the current intensity which causes various pathophysiological effects such as perception, let-go and ventricular fibrillation.

EARLY MEASUREMENTS OF THE HUMAN BODY IMPEDANCE

The first measurements were carried out with low voltages and as a consequence the results were influenced to a great extent by the impedance of the human skin which varies to a large extent with contact area, contact pressure, temperature and humidity. For that reason the first measurements also varied and seemed to be contradictory and unreliable. More practical measurements were carried out early in this century in Switzerland which are represented in Figure 1.

The values of Curves 1 and 1a were measured by Weber 1897 when holding copper

wires 6 mm ⌀ with dry and wet hands and the values of Curves 2, 2a and 2b by the Swiss Electrotechnical Association with a brass cylinder 20 mm ⌀. Voltages used were well below 100 V because of the painful effects for the persons holding the electrodes. But data on the impedance for various current paths remained scanty until Freiberger carried out his classical measurements in the thirties of our century.

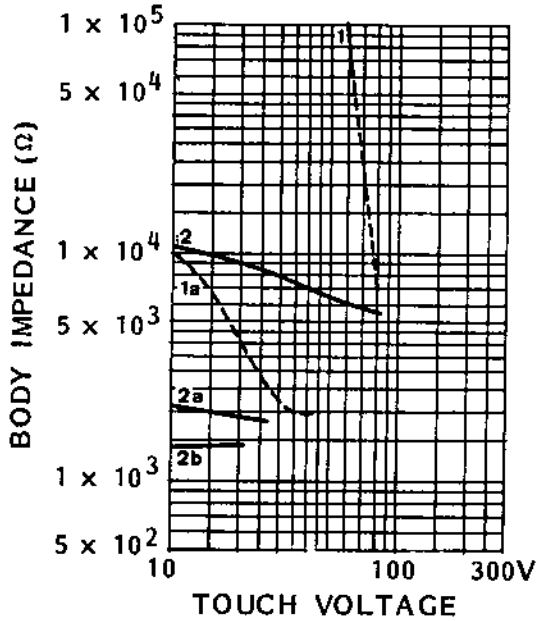


Fig. 1. Remarkable early measurements of the impedance of body of living humans

THE RESULTS OF FREIBERGER'S MEASUREMENTS

Freiberger used for his measurements mainly corpses for voltages up to 5000 V and living persons for voltages up to 50 V. He used in most cases alternating current 50 Hz but also made some measurements with direct current. Measurements with corpses were conducted for various skin conditions (dry or wet) as well as with skin removed prior to measurements. He also used various forms of electrodes which are shown in his original representation in Figure 2.

His results were used by Working Group 4 of IEC TC 64 for the current revision of IEC Report 479, Part 6, which deals with the electrical impedance of the human body:

For defining practical safety requirements by the values of touch voltage as a function of time, certain values for the human body impedance must be taken into consideration. The relation between current and voltage is not linear because the impedance of the human body varies with the touch voltage.

The different parts of the human body - such as the skin, blood, muscle, joints and other tissues - present for the electric current a certain impedance composed of resistive and capacitive components. The values of these impedances depend on a certain number of factors and, in particular, on the current path, the touch voltage, the duration of the current flow, the frequency, the degree of moisture of the skin, the surface of contact, the pressure exerted and on the temperature.

The work done by Freiberger made it possible to produce the circuit-diagram of Figure 3 for the impedances of the human body. As can be seen the impedance consists of three parts - the two impedances of the skin at the electrodes Z_p and the internal impedance Z_i. Total impedance Z_T of the human body is

defined as the vectorial sum of internal and skin impedances. The internal impedance can be considered as mainly resistive. Its value depends primarily on the current path and, to a lesser extent, on the surface of the contact. However, when the surface of the contact is very small - in the order of a few square millimeters - the internal impedance is increased.

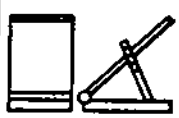
Type	Method of mounting	Dimensions mm	Area mm^2	Shape	Drawings
0,2	screwed by hand	ø 5	20	flat disk	
3	rubber-band	ø 19,5	300	flat disk	
12	rubber-band	ø 39	1 200	flat disk	
5	pressure spring	ø 25	500	flat disk	
10	pressure spring	ø 35	960	flat disk	
10 a	pressure spring	ø 35	1 000	convex disk	
20	pressure spring	ø 50	2 000	flat disk	
FP	strap and leather collar	270x130	35 000	flat plate for feet	
HP	strap	200x120	24 000	convex plate for hands	

Fig. 2. Electrodes used in the experiments of Freiberger

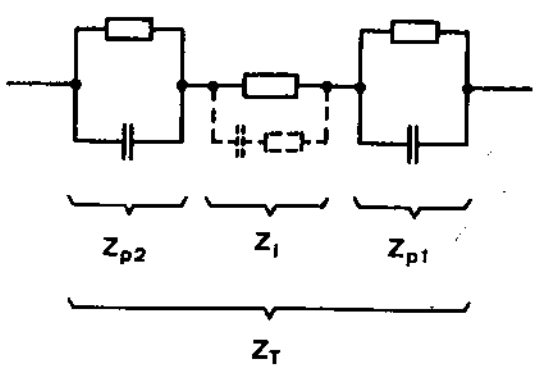


Fig. 3. Circuit diagram for the impedance of the human body

Measurements seem to indicate that the internal impedance also has a small capacitive component (shown in dashed lines in Figure 3). The percentages of the internal impedance of the human body for various current paths in relation to the path from hand to hand was measured by Sam (1968) and is shown in Figure 4.

In series with the internal body impedance are the two skin impedances. The skin impedance can be considered as a network of resistances and capacitances. Its structure is made up of a semi-insulating layer and small conductive elements (sudoriferous ducts) as shown in Figure 5.

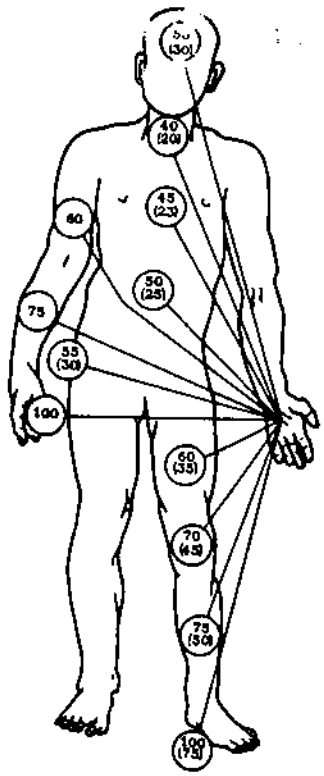


Fig. 4. Internal impedance of the human body as a function of the current path

The numbers indicate the percentage of the impedance for the path concerned, in relation to the path hand-hand.
The numbers not in brackets refer to the current paths from one hand to the part of the body in question. The numbers in brackets refer to current paths between two hands and the corresponding part of the body.

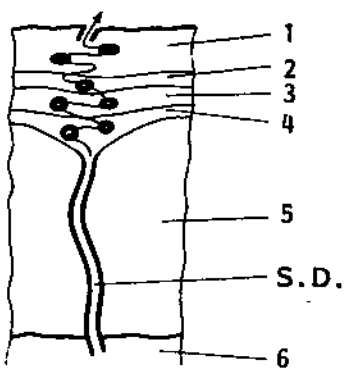


Fig. 5. Diagram showing the structure of the human skin

1...4 partly isolating layers (epidermis)
(1...stratum corneum, 2...stratum lucidum, 3...stratum granulosum, 4...stratum germinativum)
5...conductive dermis (corium)
6...conductive tissue with sudoriferous glands
S.D. ..., sudoriferous ducts, diameter approximately 20 μ

The skin impedance falls when the current is increased. Sometimes current marks are observed. The formation of current marks depends on the current-density and the duration of the current. The effects have been described by Wagner (1961) and are shown in Figure 6.

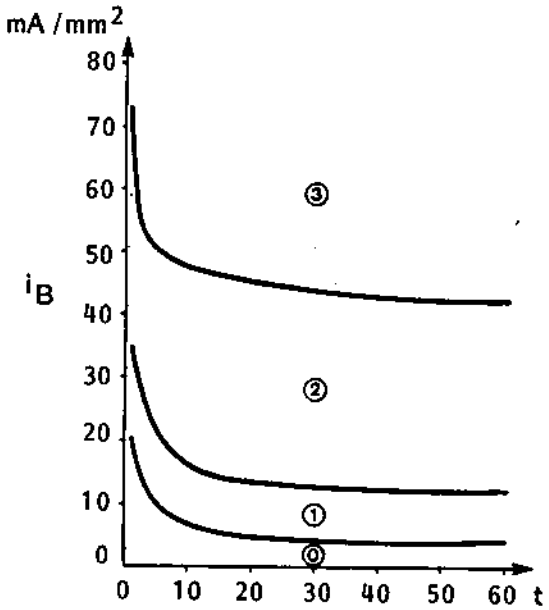


Fig. 6. Pathological changes of the human skin in function of current-density and duration

0 ... no changes
1 ... first changes, formation of swellings round the electrode
2 ... full current marks, blisters
3 ... carbonisation

The pathological changes and a theory of the human skin impedance have been described by Biegelmeier and Miksch.

The value of the skin impedance depends on the voltage, frequency, duration of the current flow, surface of contact, pressure of contact, the degree of moisture of the skin and the ambient temperature. For touch voltages up to some tens of volts the value of the skin impedance varies widely with contact area, temperature, respiration etc., even for one person. For higher touch voltages above 50 to 100 V the skin impedances decrease considerably and become negligible when the skin breaks down. As far as the influence of frequency is concerned, the impedance of the skin decreases when the frequency increases.

For a rough estimation and current paths between the extremities, the percentages given in Figure 4 for internal impedances Z_i are also valid for the total impedances of the human body Z_T. As for practical purposes the impedances can be assumed to be located in the extremities of the body and a simple circuit diagram can be given for the total impedances of the human body.

From Figure 7 it can easily be understood that the impedance for a current-path one hand to both feet is 75%, from both hands to both feet 50% and from both hands to the trunk of the body 25% of the impedance from hand to hand (100%).

In the first moment when the touch voltage is applied capacitances in the human body are not charged and have zero impedances. If follows from Figure 3 that in this case the skin impedances are zero because the resistances in the skin are

bridged by the skin capacitances. The resistance measured under these conditions is called initial resistance of the human body R_I. It is approximately equal to the internal impedance of the human body Z_I.

R_I limits the current peaks of short impulses, for instance in the case of shocks from electric fence controllers.

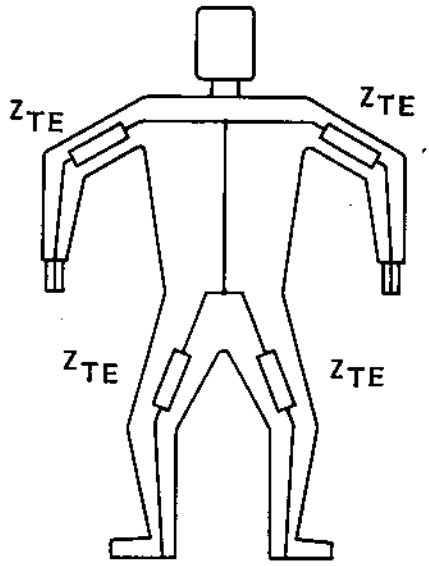


Fig. 7. Simplified diagram for the impedances of the human body. Z_{TE} impedance located in the extremities of the human body.

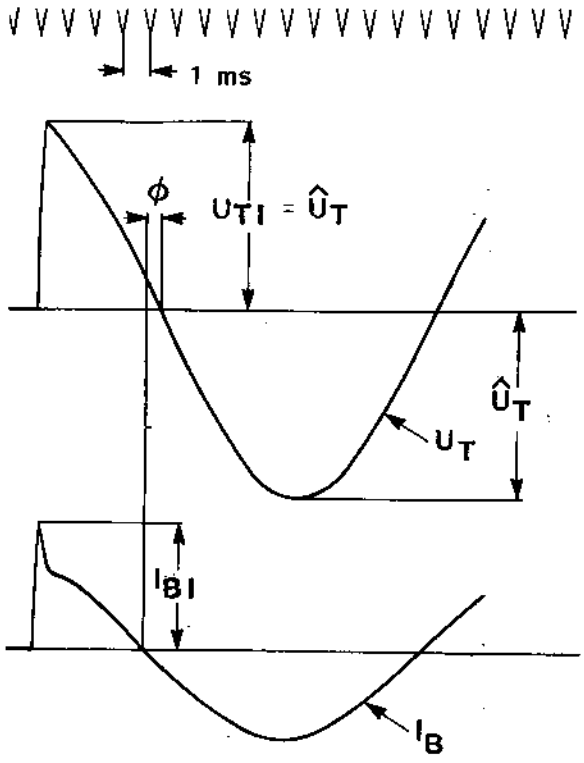


Fig. 8. Touch voltage and body-current when the contact is made at the peak of an AC voltage

When a human being is touching electrodes and a certain voltage is suddenly applied, the current through his body has a form which is in principle shown in Figure 8.

The oscillogram gives the body current when the contact is made at the peak of the voltage.

The following correlations exist:

Total body impedance $$Z_T = \frac{U_T}{I_B}$$

Initial body resistance $$R_B = \frac{U_{TI}}{I_{BI}}$$

with I_B = Stationary r.m.s. value of body current

I_{BI} = Peak value of body current at contact making

U_T = Stationary r.m.s. value of touch voltage

U_{TI} = Instantaneous value of touch voltage at contact making

RECENT MEASUREMENTS ON LIVING PERSONS WITH TOUCH VOLTAGES OF 15 V AND 25 V ALTERNATING CURRENT 50 Hz

Freiberger has measured impedances on living persons with touch voltages up to 30 V AC and 50 V DC and compared the values found with those of corpses measured under similar conditions. The values measured on corpses proved to be considerably higher with a cos ϕ much lower than those measured on persons alive (Table 1).

TABLE 1 Comparison of Impedances and Cos ϕ of Corpses and Living Persons

Subject	Touch Voltage AC 50 Hz (V)	Current (mA)	cos ϕ	Impedance (kΩ)	Current-Path
dead	20	1.62	0.48	12.345	hand-foot
alive	20.7	5.28	0.914	3.920	hand-hand (x)
alive	27.4	7.15	0.94	3.830	hand-hand (x)
(x) impedances from hand to foot and hand to hand at approximately the same touch voltage ought not to differ much.					

This difference can only be explained by the fact that the skin of corpses at voltages of some ten volts has a much higher impedance than the skin of living persons. In order to find statistically reliable values for the impedance at low touch voltages a larger number of living persons were measured in Austria and in Switzerland. The subjects firmly grasped cylinder electrodes with the left and the right hands in a test circuit similar to that described later. The duration of the current flow was limited to 0.1 s.

(a) Measurements of 100 Persons at 25 V

Eighty male and 20 female subjects were measured. The values between male and female subjects showed little difference. The weights of the persons measured was between 53 and 102 kg, their ages were between 25 and 68 years.

The measurements had the following results:

Average total body impedance	Z_{TC} = (3517 ± 1397) Ω
Average initial body resistance	R_{BC} = (781 ± 114) Ω
Range of total body impedance	1547 ... 9118 Ω
Range of initial body resistance	530 ... 1101 Ω

(b) Measurements of 52 Persons at 15 V

Thirty male and 22 female subjects were measured.

The measurements had the following results:

Average total body impedance	Z_{TC} = (3717 ± 1181) Ω
Average initial body resistance	R_{BC} = (637 ± 98) Ω
Range of total body impedance	2020 ... 7193 Ω
Range of initial body resistance	375 ... 875 Ω

RECENT MEASUREMENTS ON A LIVING PERSON WITH TOUCH VOLTAGES UP TO 200 V AC, 50 Hz

On a person volunteering for these experiments measurements of the impedance were carried out with voltages up to 200 V AC, 50 Hz. It was also the aim of these experiments to investigate the functioning characteristics of differential residual current-operated circuit breakers (ground-fault interruptors) for the purpose of additional protection against direct contact with live parts.

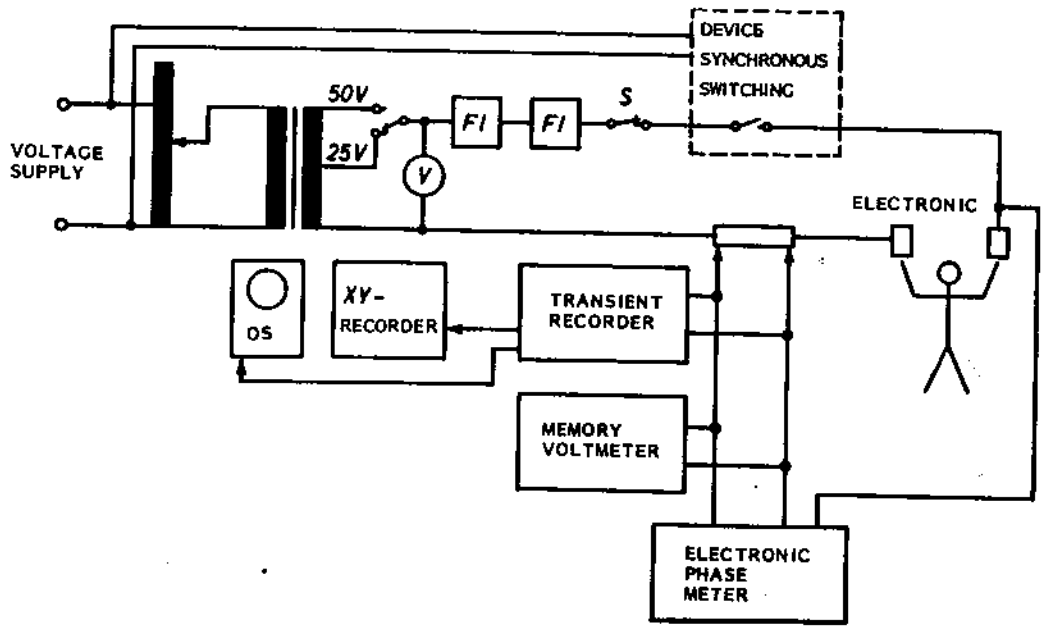


Fig. 9. Improved circuit for measurements of the impedance of the human body

These first measurements were made with an electromechanical oscillograph and an auxiliary switch which permitted initiation of the touch voltage at its peak value. The current path was hand to hand and brass cylinder electrodes were used (100 mm long, 80 mm diameter) which were firmly grasped. In this way a situation was simulated which would correspond to a serious electrical accident. Four ground fault interruptors were connected in series - two with a rated tripping fault current $I_{\Delta N}$ of 30 mA and two with $I_{\Delta N}$ = 100 mA. At the moment of contact a steep rise of current was observed, which the electromechanical oscillograph could not register properly and it was replaced during later experiments by a cathode ray storage oscilloscope and a transient recorder which displayed its readings on an x-y recorder. The phase shift was first recorded by another cathode ray oscilloscope and later by an electronic measuring device. The later arrangements are shown in Figures 9 and 10.

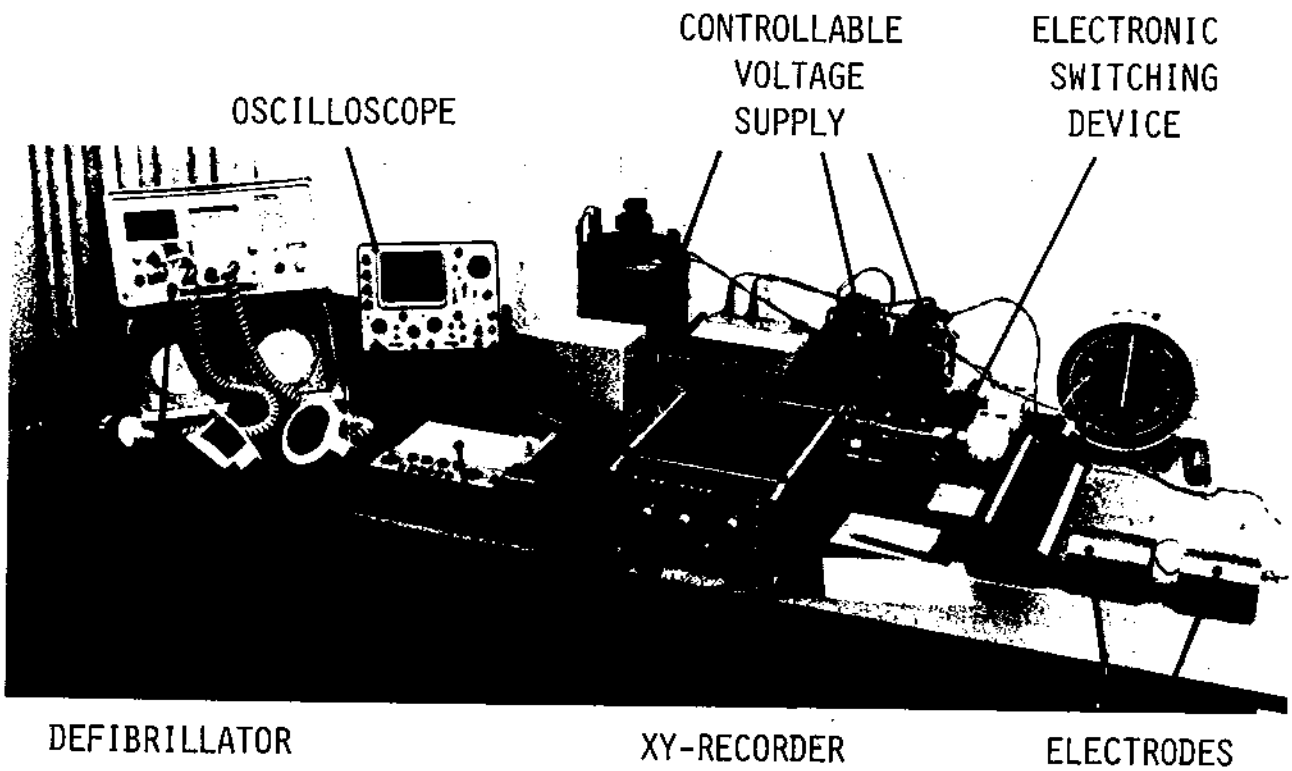


Fig. 10. Experimental apparatus

The duration of the shock was limited by an electronic device to approximately 0.1 s. In the case of the tripping of the GFI's the duration was limited to approximately 10 ms due to the tripping time of the circuit breaker. Below 50 V some experiments were made with shock durations up to 0.5 s or longer. The touch voltage was raised in steps beginning with 75 V, the voltages up to 50 V having been investigated thoroughly before. At each voltage six shocks were executed with intervals of 3 min between the shocks, the shocks being distributed at random within the cardiac cycle. The results of the measurements are shown in Table 1. Of special importance seem the following facts:

During the above-mentioned experiments the following maximum currents were withstood by one person six times. The shocks were initiated randomly within the cardiac cycle.

approximately 400 mA	as peak-impulse current with a time constant of approximately 0.2 ms
approximately 100 mA	r.m.s. value as half wave AC-impulse 50 Hz, beginning at current peak, shock duration approximately 10 ms
approximately 50 mA	r.m.s. value for 100 ms

One shock was executed with approximately 100 mA r.m.s. value for 100 ms. No irregularities in the heart were observed. No after-effects of the many shocks executed on the subject were observed.

The following results are also of interest:

a) Ground fault interruptors tripped and protected the person against electrocution and harmful after-effects of the shocks. The breakers with a tripping sensitivity of 30 mA started to operate at touch voltages over 50 V, the 100 mA breakers started to operate at touch voltages over 175 V.

b) At touch voltages over 100 V the influence of the impedance of the human skin decreases rapidly. Therefore at touch voltages near 200 V contact area and humidity have little influence on the body current.

c) For touch voltages of some ten volts the total body impedance of hands wetted in normal water is not much lower than that of dry hands. The influence of temperature is as important as humidity. Even rapid respiration changes the impedance. Conductive solutions however change the total body impedance significantly in this voltage range.

d) The initial body resistance apparently does not depend on touch voltage, wave form, frequency or humidity.

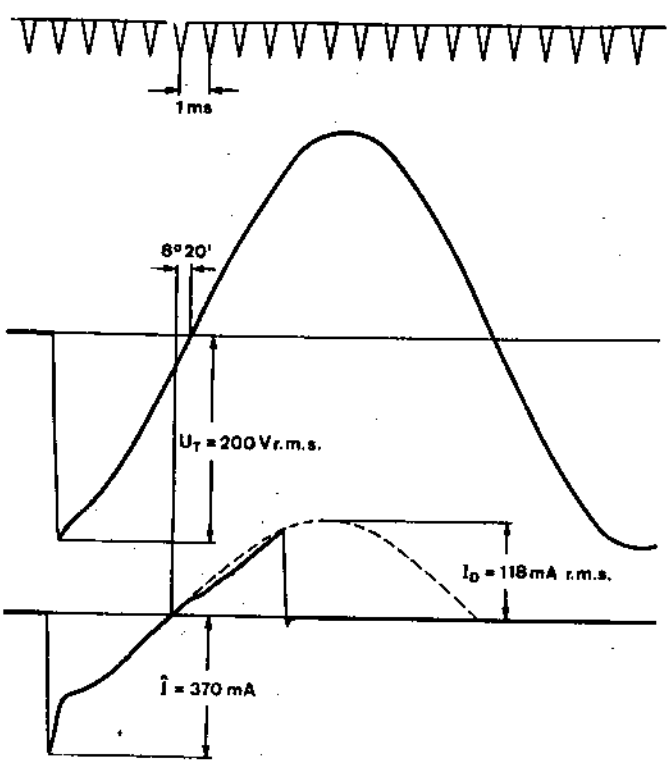


Fig. 11. Oscillogram of touch voltage and body current for a touch voltage of 200 V and shock duration of 10 ms

Attention is drawn to the fact that the experiments were carried out with a current path from hand to hand and with initiation at peak voltage. It is intended to carry out experiments with initiation at zero voltage crossover point and with a current path from left hand to both feet. The oscillogram at 200 V touch voltage is given in Figure 11 in which the typical leading peak current due to the capacitances of the impedance of the human body can distinctly be seen. Some measurements were carried out up to a voltage of 150 V without GFI's, the shock duration being limited by means of the electronic device to 0.1 s. Figure 12 shows the body current of 98.5 mA (touch voltage 150 V, A.C. 50 Hz) flowing from hand to hand for 0.1 s. Strong muscular effects were felt; however, without any harm to the test person.

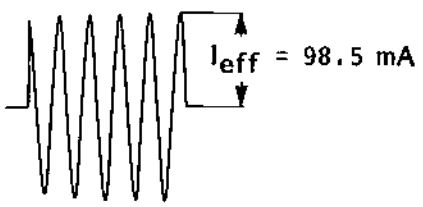


Fig. 12. Oscillogram of a body current of 98.5 mA flowing at a touch voltage of 150 V AC, 50 Hz for 0.1 s

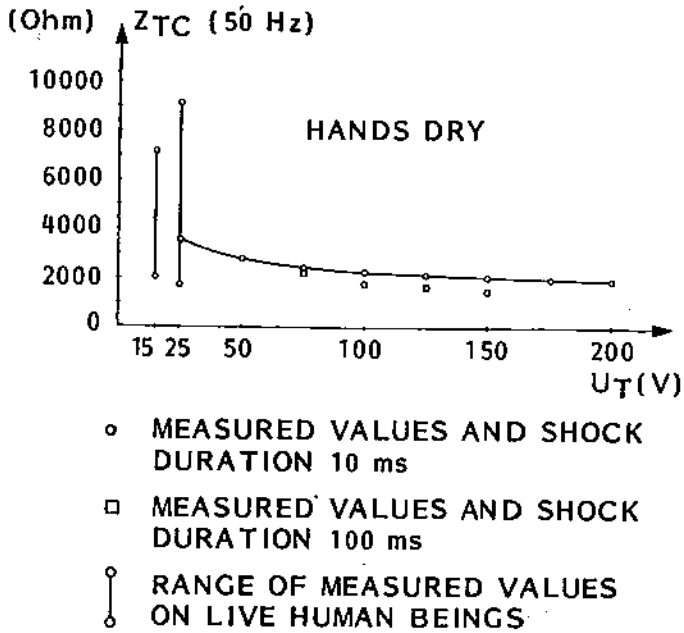


Fig. 13. Total body impedance Z_T as a function of touch voltage

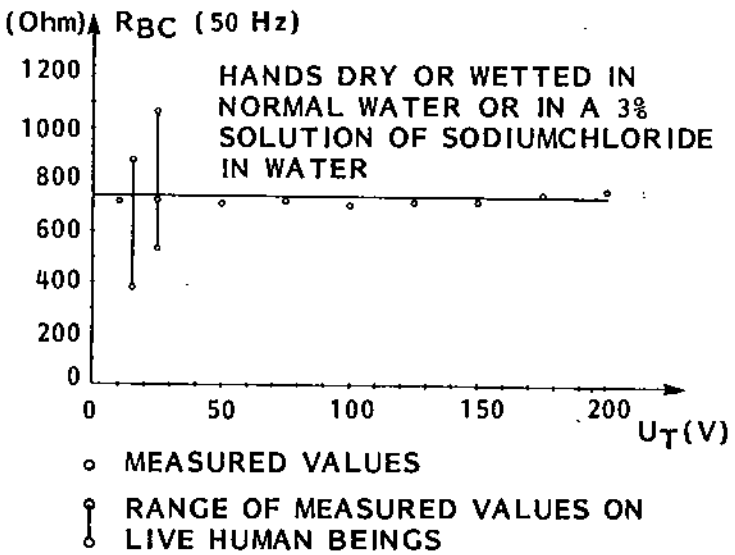


Fig. 14. Initial body resistance R_B as a function of touch voltage

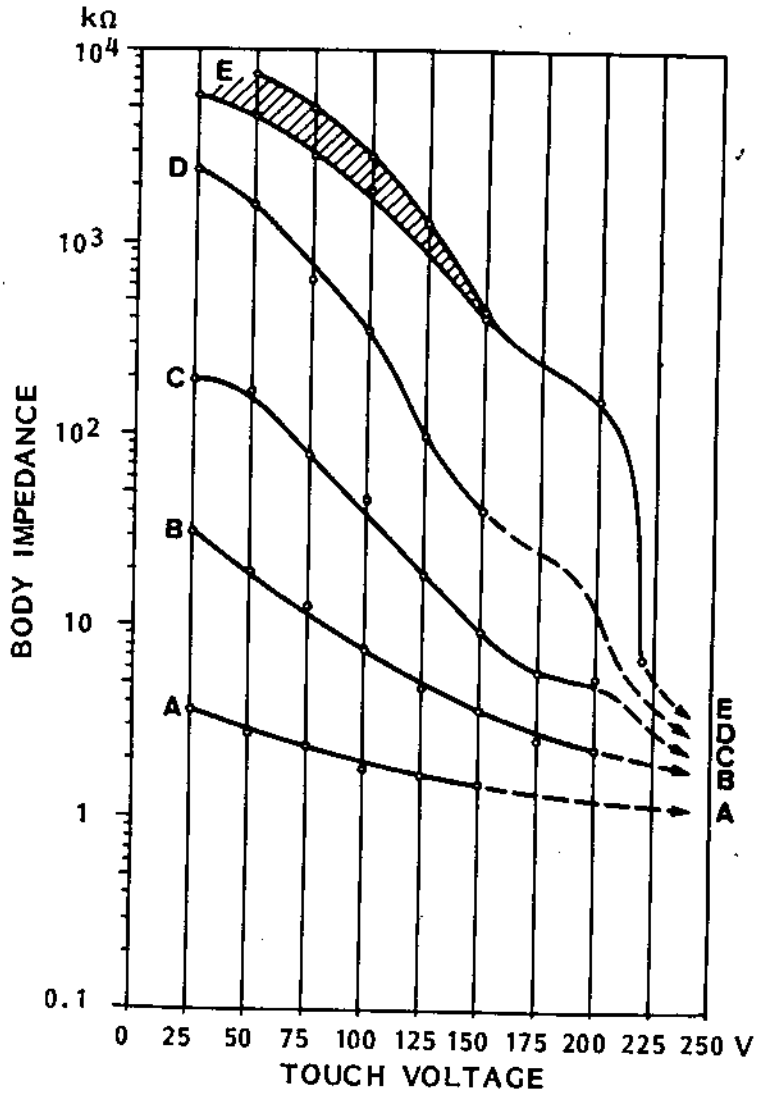


Fig. 15. Body Impedance as a Function of Touch Voltage for Various Contact Areas

A ...	contact	area	electrode	Z-80	8200 mm²
B ...	"	"	"	Z-12	1250 mm²
C ...	"	"	"	Z-1	100 mm²
D ...	"	"	"	Z-0.1	10 mm²
E ...	"	"	"	Z-0.01	1 mm²

The results of the measurements at 15 V and 25 V in their full range and the single points measured on one person are plotted as a function of touch voltage in Figure 13 for the total body impedance and in Figure 14 for the initial body resistance.

Figure 15 shows the total body impedance as a function of touch voltage for various contact areas. The Figure indicates clearly how the large difference amongst the curves A to E decreases when the touch voltage surpasses 200 V. This phenomena is caused by elimination of the skin impedance at higher voltages.

STATISTICAL EXTRAPOLATION OF THE RESULTS OF THE MEASUREMENTS OF BODY IMPEDANCES CARRIED OUT ON CORPSES AND LIVING PERSONS

In order to apply the values measured on corpses at higher touch voltages to living persons the following assumptions are made:

a) For touch voltages up to some hundred volts values measured on corpses are too high to be applied for impedances of living persons.

b) For touch voltages over 700 V the values measured by Freiberger three seconds after application of the voltage i.e., after the breakdown of the skin impedance, are taken as valid for living persons.

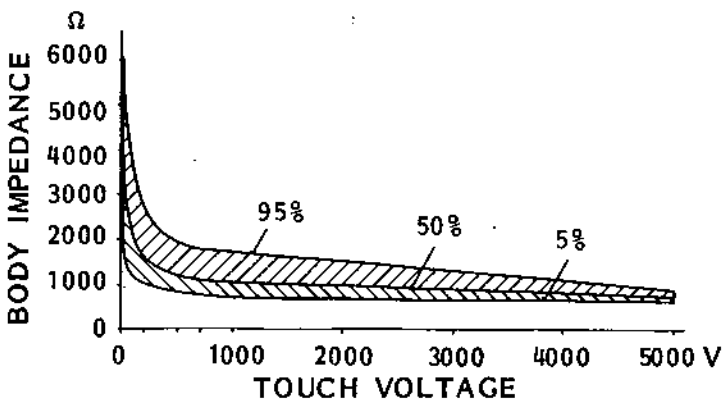


Fig. 16. Range of total body impedances for the current path hand to hand or hand to foot, for touch voltages up to 5000 V and live human beings

In order to derive the most acceptable values for the impedances of living persons for the full voltage range up to 5000 V, the curves must therefore be lowered at the low voltage end to the values measured at 25 V on living persons. In this way Figure 16 was derived by Working Group 4 of IEC TC 64 after analyzing with modern statistical methods all measurements made by Freiberger up to touch voltages of 5000 V and on the population of 100 living persons at 25 V. This statistical exploitation had the results shown in Table 2.

TABLE 2 Statistical Values for the Total Body Impedances for a Current Path From Hand to Hand and Large Contact Areas

Touch Voltage (V)	Values for the Total Body Impedances (Ω) that are not Exceeded for a Percentage (Percentile Rank) of the Population			Number of Measurements	Subject
	5%	50%	95%		
25	1750	3250	6100	100	alive
25	6400	9600	14500	9	dead
75	5450	8200	12400	6	dead
100	2300	5700	14000	4	dead
125	2100	4150	8250	9	dead
220	1300	2200	3750	20	dead
700	710	1100	1600	9	dead
2000	660	1100	1800	15	dead
5000	700	760	820	3	dead

The values of Table 2 were measured for a current path from hand to hand with large contact areas. Taking into account the values measured by Freiberger for a current path from hand to foot, which differed only little from the values of Table 2, Working Group 4 arrived at values for the total body impedance Z_i, shown in Table 3, by adapting the curves - as said above - to the 25 V-values measured on living persons at the low voltage end.

TABLE 3 Values for the Total Body Impedances Z_T Chosen by Working Group 4 of IEC TC 64 for a Current Path Hand to Hand or Hand to Foot for Large Contact Areas (80 cm^2 ... 100 cm^2) for Living Human Beings Including Children

Touch Voltage (V)	Values for the Total Body Impedances (Ω) that are not Exceeded for a Percentage (percentile rank) of the Population		
	5%	50%	95%
25	1750	3250	6100
50	1450	2625	4375
75	1250	2200	3500
100	1200	1875	3200
125	1125	1625	2875
220	1000	1350	2125
700	750	1100	1550
1000	700	1050	1500
Asymptotic Value	650	750	850

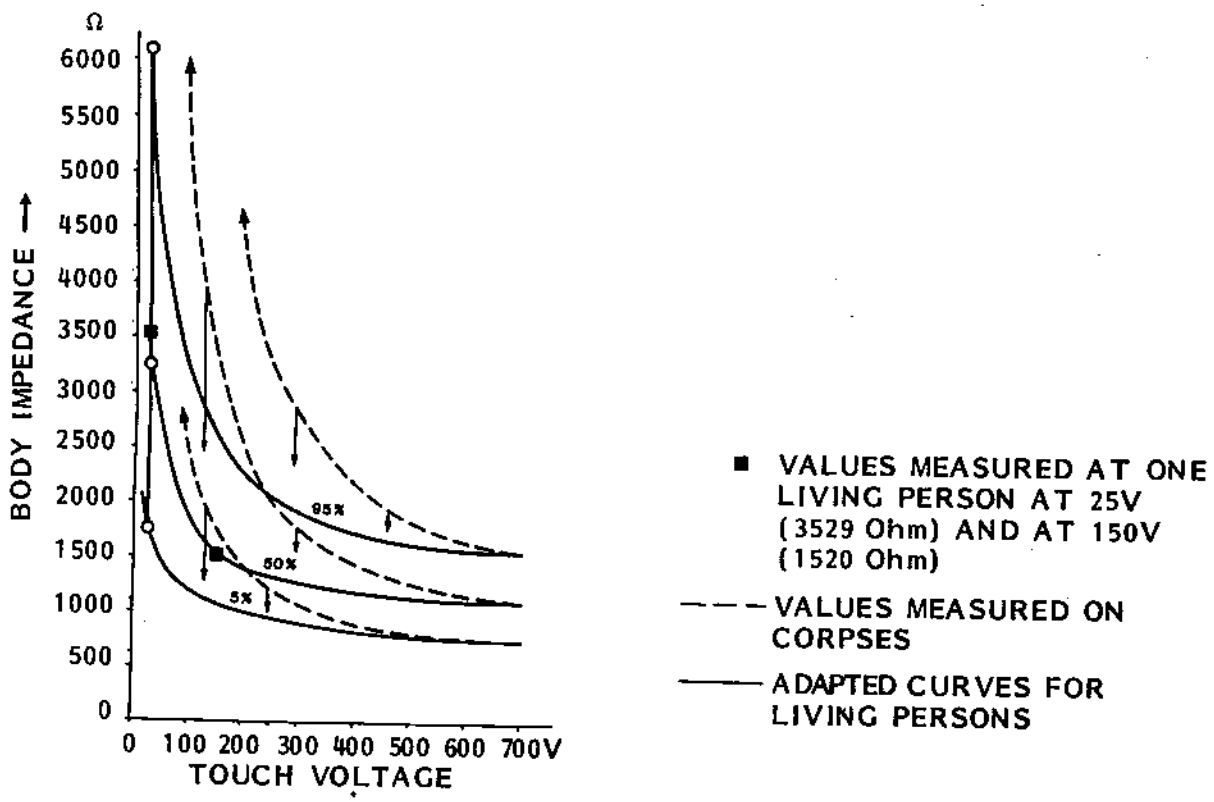


Fig. 17. Derivation of total body impedances for living persons by adapting values measured on corpses at low touch voltages to those measured at the same voltage on living persons

Figure 17 shows the values of Table 3 and indicates the means by which the curves for the corpses were adapted to the values measured on living persons at 25 V touch voltage. The measurements carried out on one person at 150 V after 0.1 s (98.5 mA) giving an impedance of 1500 Ω is also indicated in Figure 17 and, by chance, fits well into the curve for the 50% percentile rank. The same person was measured at 25 V with an impedance of 3529 Ω, again being very near the same 50% curve. The data represented in Figure 16 and Table 3 is thought to be the most recent knowledge on the impedance of the human body.

Though most of the measurements have been made on adults the values given may also be applied to children. This follows from a simple consideration on the resistance of the extremities of the body. The length of the extremities of children is certainly shorter than those of adults but the cross-sectional area is smaller so that no increase of impedance is to be expected for children. Some measurements should however be carried out in that respect.

SUMMARY

After a short representation of the results of early measurements of the impedance of the human body, the experiments of Freiberger which were carried out in the thirties but are still the basis of our knowledge on the impedance of the human body are discussed in detail. The circuit diagram for the impedance of the human body derived by Freiberger has been confirmed by recent measurements carried out on living persons. Therefore the impedance of the human body consists of three impedances viz: two skin impedances, with large capacitive components at low voltages, and an internal body impedance which can be considered as mainly resistive.

At the first moment of making contact, the current is limited by the initial body resistance which results from all resistances located in the body when the capacitances are unloaded and may therefore be considered as shortcircuited.

Recent measurements carried out on living persons with touch voltages of 15 V and 25 V AC, 50 Hz allowed a statistical analysis and the calculation of the 5%, 50% and 95% percentile rank for the body impedances at these voltages.

As is well known in statistics, the 50% values are the most reliable data, statistical reliability decreasing towards the lower or higher percentile ranks. The 5% and 95% values are therefore deemed to be the best basis for setting limits from the point of view of Standardization.

Self experiments carried out with one person allowed, for the first time, some orientation about impedances of living persons for touch voltages up to 200 V AC 50 Hz and a statistical exploitation of the experiments of Freiberger delivered the 5%, 50% and 95% percentile ranks for the impedances of corpses for touch voltages up to 5000 V. Taking all data it was possible for Working Group 4 of IEC TC 64 to propose values for the impedances of living persons for touch voltages up to 5000 V which represent the best knowledge of today in this difficult field.

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DISCUSSIONS

NILES: In Dr. Cabanes' paper yesterday, heart factors were given and you mentioned these factors also. What is the heart factor for the foot-to-foot current path? Secondly, was there any difference in the contact pressure when seating or standing?

BIEGELMEIER: The book of Freiberger contains ratios of current magnitude flowing through the heart for various current paths to total body current. For the current path foot-foot the ratio is 0.1%, compared with several percent for current path hand-feet; so the danger in this situation for the current path foot-foot is much less than for the current path hand-foot.

NILES: The contacts for the Swiss and Austria touch tests were cylinders firmly grasped. Would there be a difference if a non-firm contact is made such as a "brush" contact? Could the results of Fig. 15 be used to estimate a brush contact (assuming a "brush" contact has a smaller contact area)? Would the capacitance involved with a brush contact influence the impedance?

BIEGELMEIER: If the contacts are grasped only slightly there would certainly be an increase in the measured values. We have determined the real contact in the experiments with coloured probes, so if grasped only slightly coloured probes could show the smaller contact area and Figure 15 could be used to calculate the increased impedances. I do not think that this would influence the capacitances measured.

SHERMAN: You described a decrease in skin resistance with increase in applied voltage. Was there any visible change in skin morphology? Can you speculate on the mechanisms involved in this reduction in skin resistance.

BIEGELMEIER: In most of the experiments with larger contact areas no change of the skin was observed. With small contact areas of the order of 1 mm^2 the skin was punctured. In other cases the decrease in the skin impedance seemed to be reversible.

BEATTIE: There exists a potentially dangerous situation surrounding ground rods conducting fault current. Very large voltage gradients exist in the immediate vicinity of the rod so that several thousand volts could be encountered over a distance of one metre. The impedance behind this voltage is negligible. Thus several amperes of current could pass from foot-to-foot. Although the current pathway may not involve the heart a severe burn could ensue.

BIEGELMEIER: This is of course true, it was just mentioned that for a current path foot-foot the current through the heart is much smaller than for a current path hand-foot.

REILLY: The internal body impedance is a very important parameter because it defines a lower limit on total body impedance for conditions in which skin impedance is low. Prof. Biegelmeier infers this quantity from measurements of the magnitude of the initial current spike. The accuracy of measurement of this spike will depend on the dynamic response of the measurement systems, as affected by system

bandwidth, inductance, and stray capacitances. Would Dr. Biegelmeier please comment on the rise time of his measurements, and the possibility of artifacts due to oscillations or overshoot in the initial current spike.

BIEGELMEIER: It is not easy to measure that spike. I used a memory voltmeter which registered within 1 microsecond the spike of the current. So of course for the touch voltage there was no problem. To calculate the initial body resistance, you divide the instantaneous values of the voltage by the instantaneous values of the current. In my opinion it is important to measure this value because it is the lowest value you can measure and it is important for instance in the case of lightning strokes. If a person is hit by lightning it is a very short impulse and so, of course, in the moment of the strike the capacitances are not loaded so the resistance which limits the current through the body is the initial body resistance. We have investigated that by experiments with pigs. We exposed pigs to lightning strokes in a high voltage laboratory and the physics is like this: the lightning stroke goes through the body but of course the current of the lightning stroke does not go through the body because it is a very high current. Immediately following the high voltage you get a flashover over the body so the voltage is determined by the arcvoltage of the flashover and the length of the arc. When someone is hit by lightning the voltage of about 2000 V hangs on the body for a couple of microseconds and these 2000 V give a very short current which is determined by 2000 V divided by the initial body resistance. This is the importance, in my opinion of the initial body resistance.

BERNSTEIN: With voltages to ground in Europe nominally being 240 V, why did you select 200 V as the highest voltage for your tests?

BIEGELMEIER: The normal voltage to ground in Europe is 220 V (only in UK-240 V). I used 200 V because in practical accidents there is always some voltage lost in the line or in the ground. Apart from that the series were long and painful enough.

HART: I have a comment concerning discussion on internal body resistance. Steady-state measurements of internal body resistance at frequencies up to 1 MHz indicate values of approximately 400 Ω from hand-to-hand and 450 to 500 Ω from one hand to one foot.

BIEGELMEIER: Though these values seem to be rather low compared with our measurements they are very near to the Swiss results. A standard value of 500 Ω could be realistic.

BAISHIKI: Figure 17 of your paper represents the derivation of total body impedances for living persons by adapting values measured on corpses at low to medium voltages to those measured at the same voltage on living persons. The text indicates that this curve is an all encompassing curve to represent all human beings: men, women and children.

1. Could the author offer any insight to the approximate range for the child? The low value is usually associated with men and the higher value is roughly valid for women.

2. Could the author offer any insight to the distinction between hand-to-hand as compared to hand-to-feet impedance values? Could the original data be similarly analyzed to produce two curves instead of just one?

3. Do we still represent the upper portion of the curve or the 95% curve for dry contact conditions and the lower curve for wet contact conditions?

BIEGELMEIER

1. There is little data available for children. The question was discussed in working Group 4 of IEC TC 64 and it is thought that the values are applicable also for children. They have shorter extremities but the cross-sectional area of the extremities is also smaller. Further research is needed.

2. There is no need for a distinction between hand-hand and hand-foot. There will be of course some difference but the range encountered in practice is so great that these differences are of no practical importance.

3. The values are for dry conditions. For wet conditions the values at lower touch voltages (about 25 to 100 V) will be somewhat lower, if water is used.

LAMBERT: Would you comment on the effect of a high impedance in series with the body on the demonstrated decrease of body impedance with increasing touch voltage (Fig. 15).

BIEGELMEIER: This would represent a constant current source, so, that the body impedance would become a function of the imposed current and decrease with rising current.

HOYLE: With reference to Figure 15, Curve 'D' (for contact areas of approximately 1 cm^2) is very representative of the type of contacts that occur in the home, e.g., bare spots on a wire, finger in a light socket, or contact during fuse replacement. The curve shows clearly a ratio of body impedances of about 100:1 for 120 V versus 240 V (to ground) systems. The former system therefore, is significantly safer in practice.

BIEGELMEIER: That is quite true from the point of view of body impedances.

TARCHALSKI: Since the application of current was random, how many applications coincided with the vulnerable period. Current flow times of 10 and 20 ms are short in comparison with the heart cycle. The statement that the experiment verified the effectiveness of GFCI's is partly true. The question as to what happens when the current is below the tripping value of GFCI (such as 90 mA for 100 mA device) is yet to be answered. In practice the total resistance is not only body resistance (which itself is variable) but may include series resistance such as that of the shoes etc.

BIEGELMEIER: The ECG showed that a large number of shocks in the order of 15-75% fell into the vulnerable period. The 100 mA breakers offer in addition to the protection against indirect contact a limited protection against direct contact. In Europe normally breakers with IAN - 30 mA are used; it has to be pointed out that these breakers cannot limit the current through the body.

HOUSTON: Based on your ECG recordings, do I understand correctly that only a single cardiac extrasystole was produced during each shock, no further cardiac rhythm abnormality was noted?

BIEGELMEIER: We could not even be sure of the single extrasystole you mention. There was no cardiac rhythm abnormality noted. Only a few seconds after the shock the heart rate went slightly up.

BODY IMPEDANCE OF NONHUMAN PRIMATES UNDER CONSTANT VOLTAGE SHOCK CONDITIONS

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ABSTRACT

Tests were conducted on two Rhesus monkeys to determine the range of variation in body impedance under constant-voltage, low-source-impedance shock conditions. Shock voltages ranged from 10 to 240 volts for various hand-electrode conditions including dry hands, hands wetted with saline water, and mixtures of saline water and detergents. The duration of exposure was limited by ground fault current interrupters to prevent fibrillation during the tests. Considerable data resulted and representative summaries of these data are presented in two groups: (1) dual trace oscillographs of applied voltage and current; and (2) plots of the instantaneous relationship between voltage and currents for several different body paths, such as hand-to-hand, foot-to-foot, and hand-to-foot.

One important development during these tests was the identification of a precursor current spike. This spike was significantly larger than the follow current. The plots of the instantaneous relationship between applied voltage and body currents showed a high degree of nonlinearity and time dependence. For example, at low voltages, the body impedance was strongly capacitive, whereas at higher voltages it became largely resistive. In one animal test, the high-impedance skin broke down, resulting in much lower body impedance. Such phenomena as the precursor current spike or the breakdown of the high-impedance skin could be unnoticed factors which aggravate the electrical shock hazard.

KEYWORDS

Electric shock; fibrillation threshold; body impedance; electrical safety; constant voltage shock; body resistance; electrical resistance of nonhuman primates; impedance of human body.

BACKGROUND

The safe current thresholds criteria presently in use are not directly applicable to the constant-voltage, low-impedance shock hazard conditions normally found in the home. These thresholds are inappropriate because of the range of variation in

body resistance, which determines the body current under constant-voltage, low-source-impedance conditions. Data on apparent body impedance measured at constant voltages from 30 to 120 volts, are sparse, however, and come from only a few experiments. Such data must be adequately developed before the problem of electrical safety levels can be resolved.

For example, third-wire grounds, if ideally installed, have been assumed to provide adequate protection against fatal shock. Closer scrutiny of the third-wire grounding system, however, reveals the presence of an obscure and perhaps serious hazard inherent in the basic design. Under certain conditions of insulation failure, the exposed metal enclosure attached to the third-wire ground may be briefly connected to the energized conductor side of the line. In such a case, the voltage drop in the grounding system is sufficient to place the metal shell at 60 to 110 volts with respect to the earth ground. A person grasping such an enclosure would be exposed to this voltage until the fuse or circuit breaker opened. Sixty volts or more, when applied to humans even for a few seconds, particularly under wet conditions, appear to be near or just over the safety criteria which are deemed potentially lethal in published data.

To obtain some preliminary information about such faults, a cursory laboratory evaluation was undertaken using Rhesus monkeys to provide estimates of body impedance under the types of constant-voltage, low-source-impedance shock conditions that might be found in the home (Bridges and co-workers, 1977).

EXPERIMENTAL PROTOCOL

The live animal experiments were conducted in the biological test and evaluation facilities of IIT Research Institute in compliance with NIH requirements. Five Rhesus monkeys were used as experimental subjects, but only two were used for the tests reported here. The subjects were identified by number and weighed as follows:

Subject	Weight, lb
7407	14.8
7506	19.0

All animals were given phencyclidine hydrochloride, which produces an effect similar to anaesthesia. The drug is not a barbiturate.

Various hand-electrode contact conditions were used: dry hands, and hands wetted with normal saline water, saturated saline water, a mixture of ECG cream and saline water, and a mixture of saline water and detergents.

The apparatus used for all the tests is diagramed in Fig. 1. A variable auto-transformer controlled the applied 60-Hz line voltage, and voltages from 15 to 120 volts were applied to the test subjects by activating the mercury exposure switch. A ground fault circuit interrupter (GFCI) limited the duration of the exposures to ensure the survival of the test subject. A dual trace oscilloscope monitored the initial ten cycles of the applied voltage and resultant current waveforms. An additional oscilloscope monitored the long-term envelope of the current waveform. Digital ammeters and voltmeters provided backup. An ECG monitor was also used for some of the tests.

The apparent body impedance under constant voltage conditions was measured in two separate types of tests. In the first test, a limited duration shock, as governed by the GFCI, was applied to subjects 7407 and 7506. This was done for various

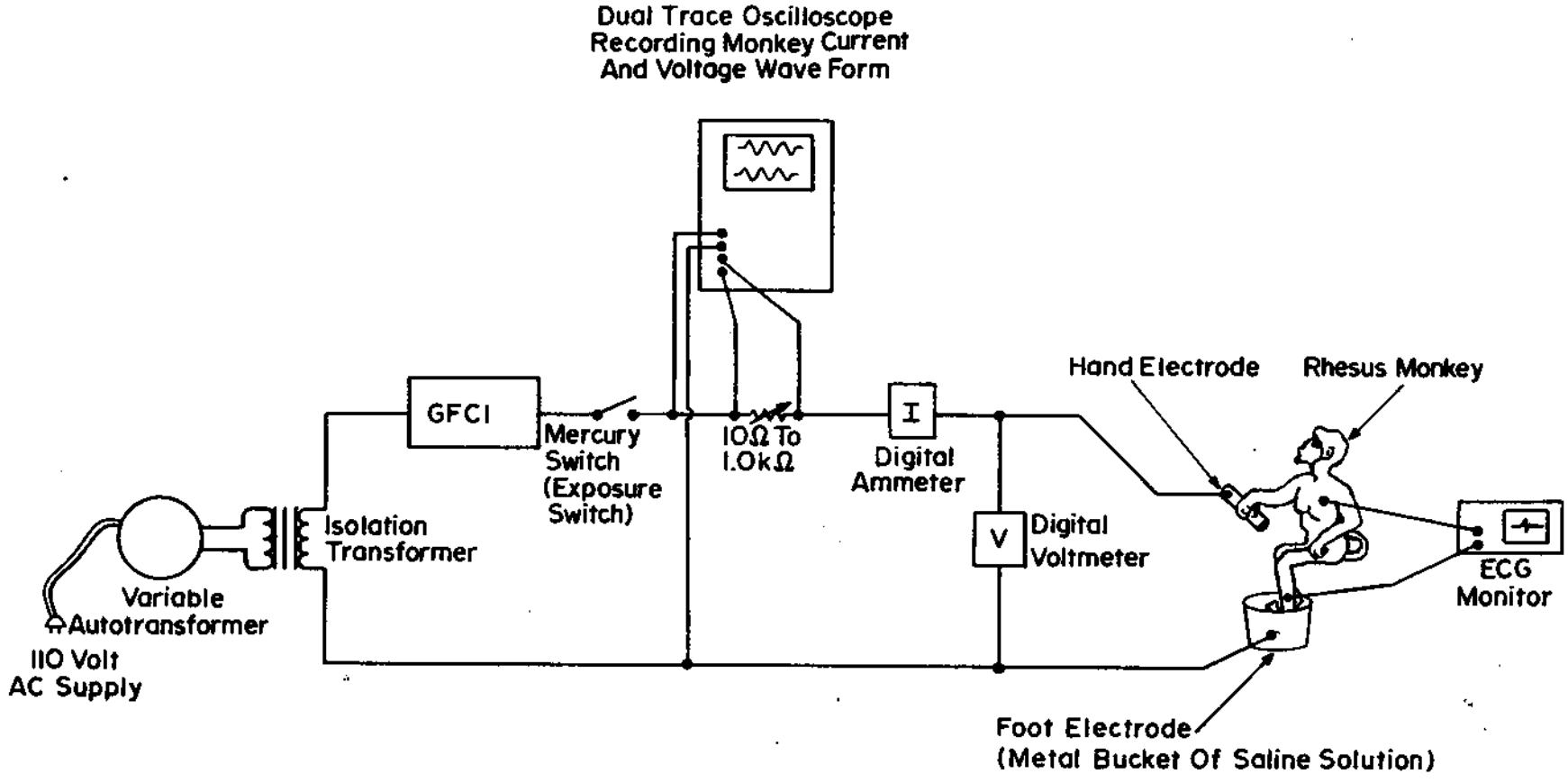


Fig. 1. Apparatus for body resistance and constant voltage shock tests.

hand and electrode combinations such as dry plate, dry cylinder, cylinder wet with normal saline, cylinder wet with saturated saline, and cylinder wet with ECG electrode cream. For the first of these tests, a subcutaneous electrode was placed in the foot. In the second series of tests, also of limited duration, the apparent body impedance measurements were made between hand and both feet, hand-to-hand, and foot-to-foot for various electrode surface conditions and skin conditioning.

RESULTS OF SHORT-DURATION SHOCK TEST

A series of short-duration shock tests was conducted to determine the electrical behavior of the body of the monkeys under constant-voltage source conditions. The exposure was limited by the GFCI to prevent fibrillation during the tests. Representative summaries of the data that resulted are presented in two ways: (1) photographs of dual trace oscilloscope waveforms which show the applied body voltage and current as a function of time; and (2) plots which draw upon data recorded in similar oscilloscope traces and show the relationship between the instantaneous currents and voltages for various conditions of dry or wet skin.

Figures 2, 3, and 4 are photographs of the oscilloscope traces indicating the voltage and current waveforms for the short duration shock tests. A phase difference can be seen between the current and voltage waveforms for the lower values of applied body voltage. Of great interest in all of these recorded waveforms is the short-duration current spike which occurs as the voltage is suddenly applied to the subject.

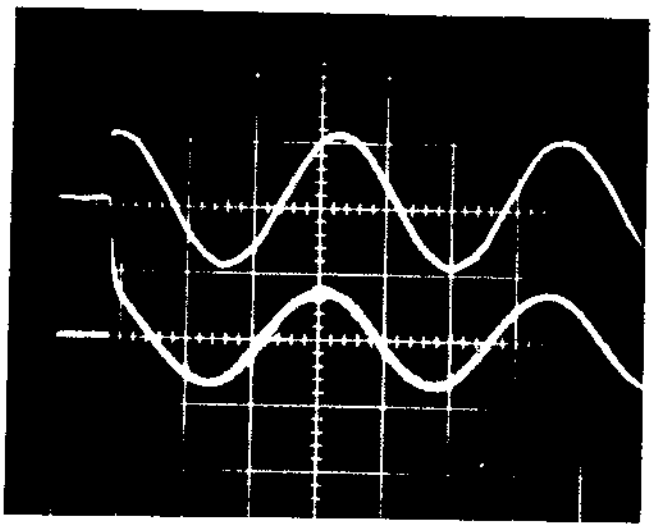
Figures 5, 6, 7, 8, and 9, are simultaneous plots of the instantaneous voltage and current which appear in similar dual-trace oscilloscope photographs taken during the second series of tests. Also included as a point of reference is a similar plot for a simple resistor which would give about the same ratio of the peak voltage to the peak current.

DISCUSSION

The Precursor Current Spike

The most important development of these quick-look tests is the identification of a precursor current spike, shown in Figs. 2, 3, and 4. Since this current spike was unexpected, the recording equipment did not capture the peak value with any degree of accuracy and the actual values may be much higher than indicated. The observed peak spike current for the 20-volt rms applied voltage was about four times the average rms current which followed. In the case of a higher voltage (approximately 100 volts), the peak of the spike was clearly at least one and one-half times the average rms follow current. The test circuit might also have limited the peak value of this precursor spike.

In the past, the constant current test methods used to evaluate fibrillation thresholds did not simulate many actual shock conditions. They also did not consider the charging or precursor current spike in combination with a longer duration follow current. In addition, under the constant current test conditions of the earlier tests, the capacity of the body to exhibit a capacitive input impedance tended to integrate the applied waveform, thus suppressing spikes. On the other hand, a constant voltage source, which has very low impedance, might drive the peak value of the spike to the ampere level.

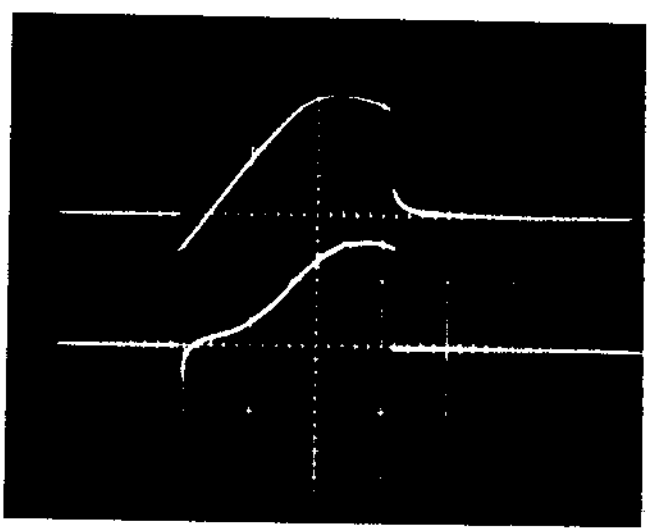


(a)

Horizontal Scale
t = 5 ms/Div.

Top Trace
V = 20 volts/Div.

Bottom Trace
I = 2.5 ma/Div.



(b)

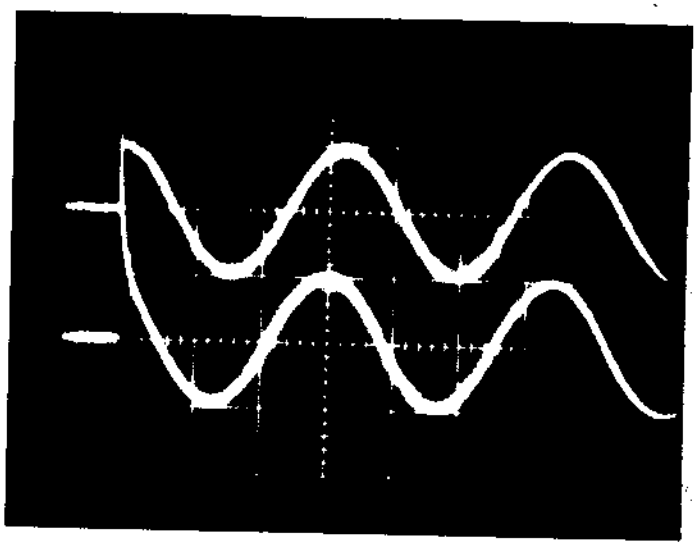
Horizontal Scale
t = 2 ms/Div.

Top Trace
V= 100 volts/Div.

Bottom Trace
I = 50 ma/Div.

NOTES:
Subject 7506
Weight 19 lbs.
Right hand on dry plate, both feet on dry plate.

Fig. 2. Short duration shock test (dual trace body voltage and current waveforms showing current spike).

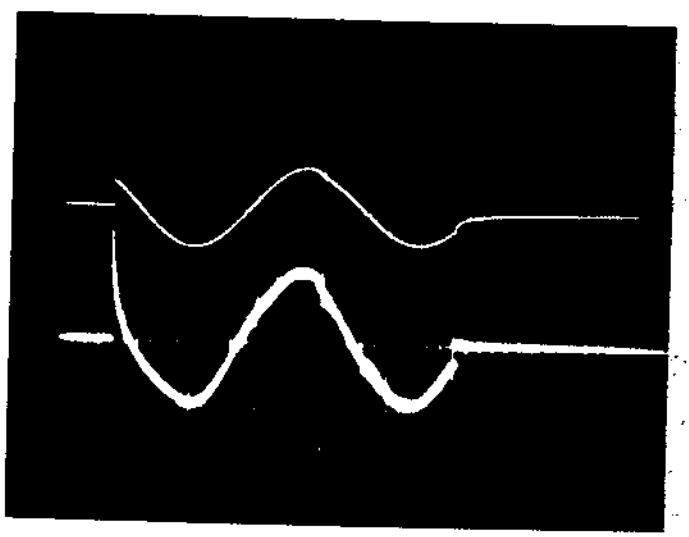


(a)

Horizontal Scale
t = 5 ms/Div.

Top Trace
V = 20 volts/Div.

Bottom Trace
I = 5 ma/Div.



(b)

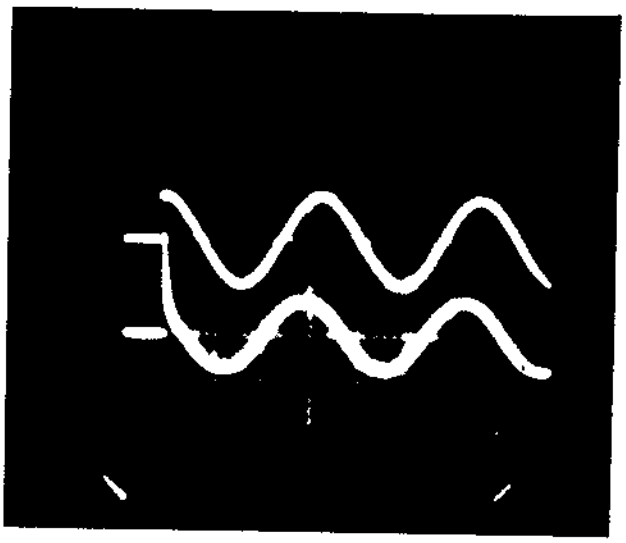
Horizontal Scale
t = 5 ms/Div.

Top Trace
V = 100 volts/Div.

Bottom Trace
I = 20 ma/Div.

NOTES:
Subject 7506
Weight 19 lbs.
Right hand on metal cylinder wetted with normal saline, both feet in metal beaker containing normal saline solution.

Fig. 3. Short duration shock test (dual trace body voltage and current waveforms showing current spike).

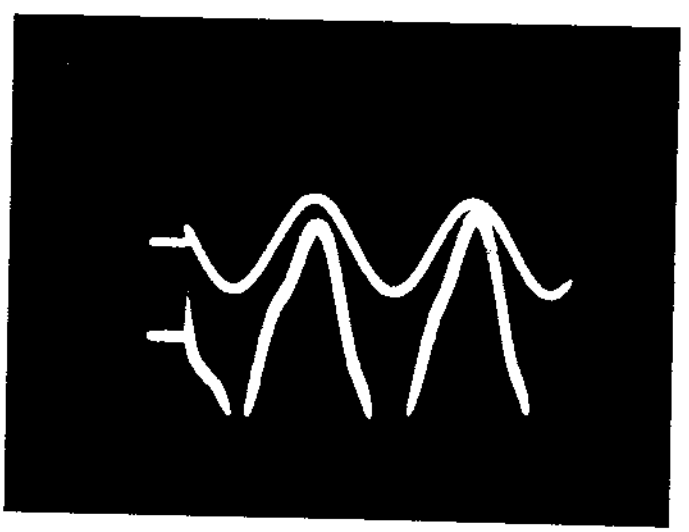


(a)

Horizontal Scale
t = 5 ms/Div.

Top Trace
V = 20 volts/Div.

Bottom Trace
I = 1 ma/Div.



(b)

Horizontal Scale
t = 5 ms/Div.

Top Trace
V = 50 volts/Div.

Bottom Scale
I = 2 ma/Div.

NOTES:
Subject 7407
Weight 14.8 lbs.
Right hand on dry plate, both feet on dry plate.

Fig. 4. Short duration shock test (dual trace body voltage and current waveforms showing current spike).

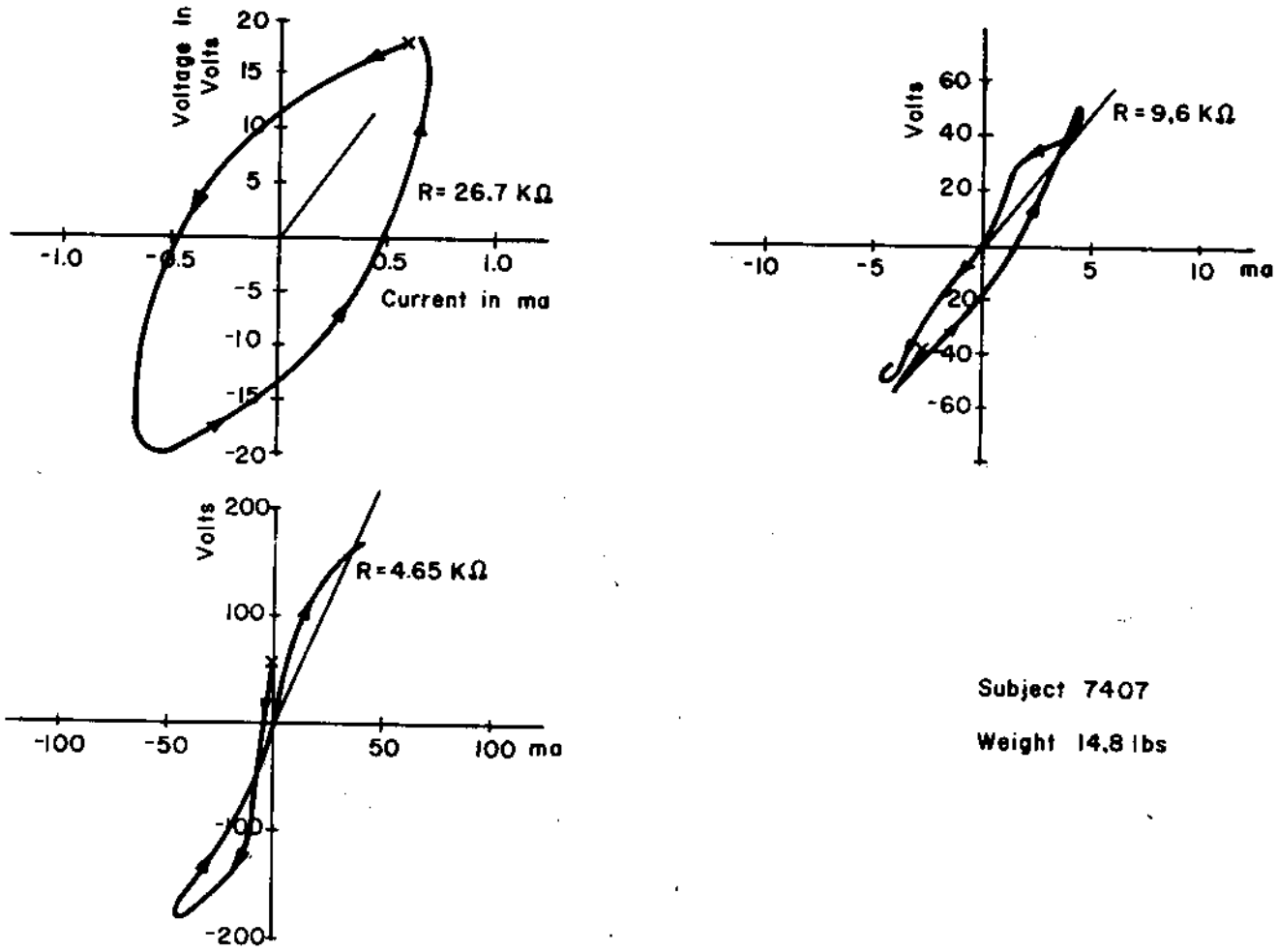


Fig. 5. V-I curve, short duration shock test, dry plate on hand, subcutaneous electrode in foot.

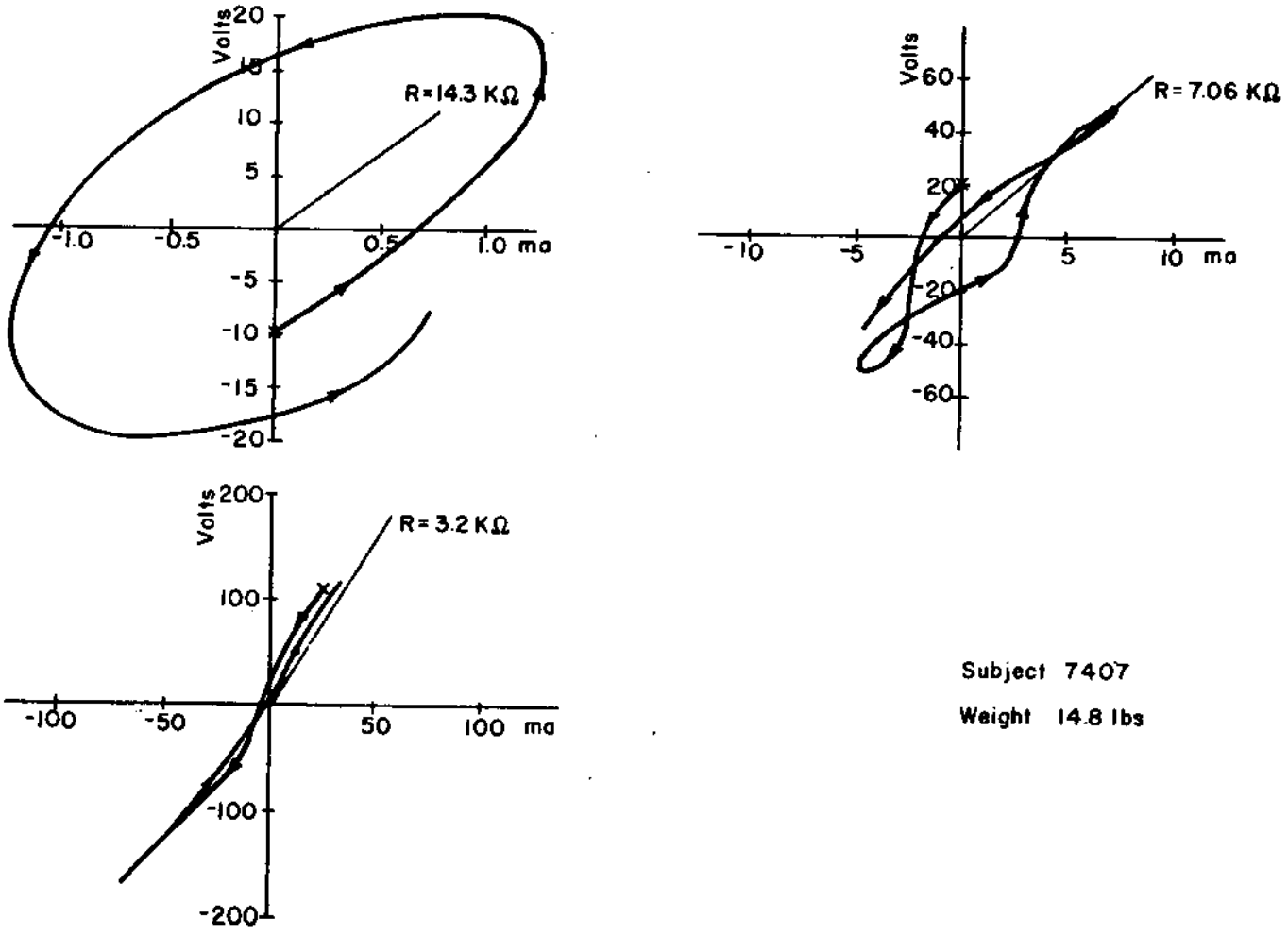


Fig. 6. V-I curve, short duration shock test, dry cylinder clasped in hand, subcutaneous electrode in foot.

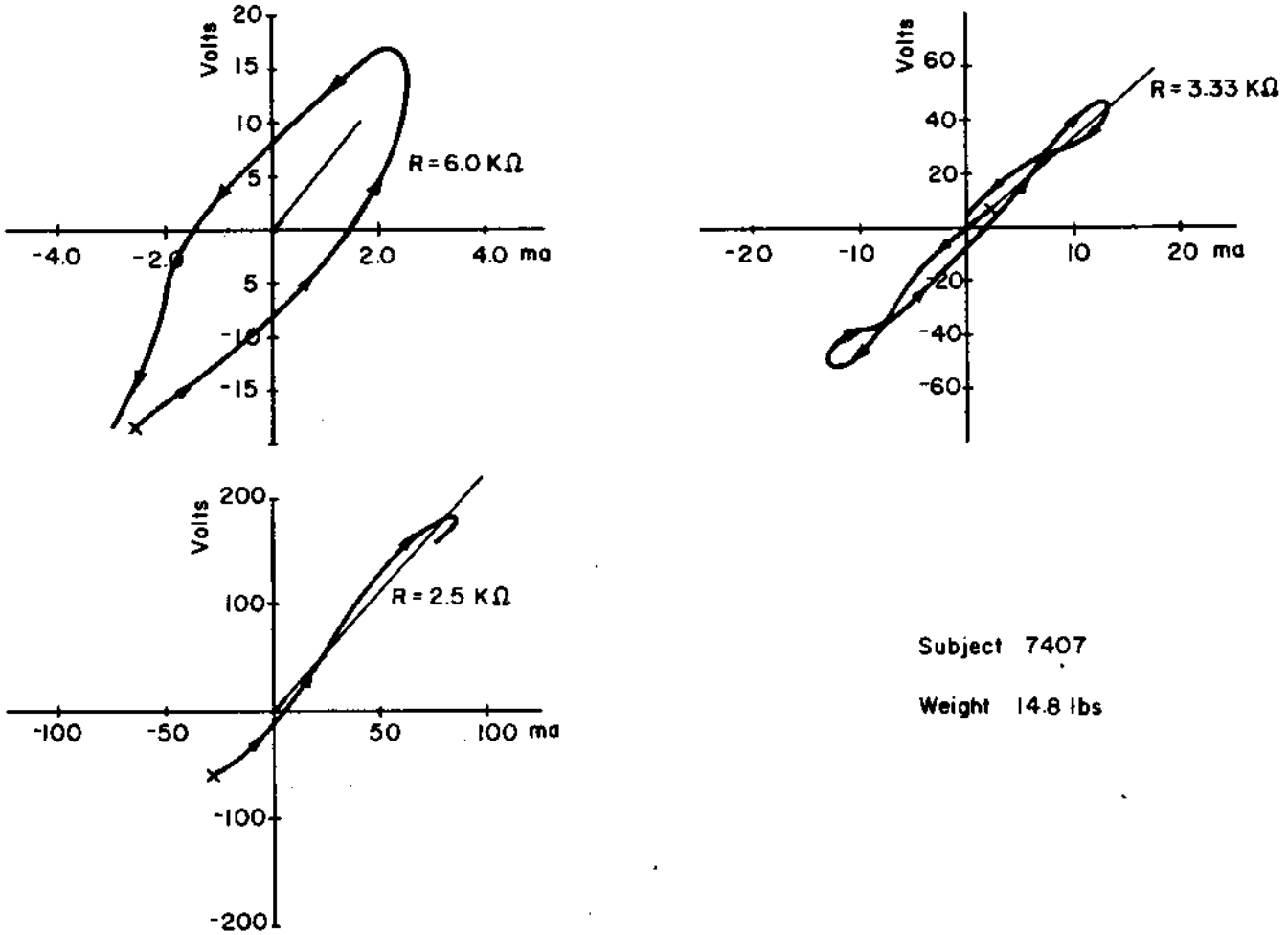


Fig. 7. V-I curve, short duration shock test, normal saline wetted cylinder clasped in hand, subcutaneous foot electrode.

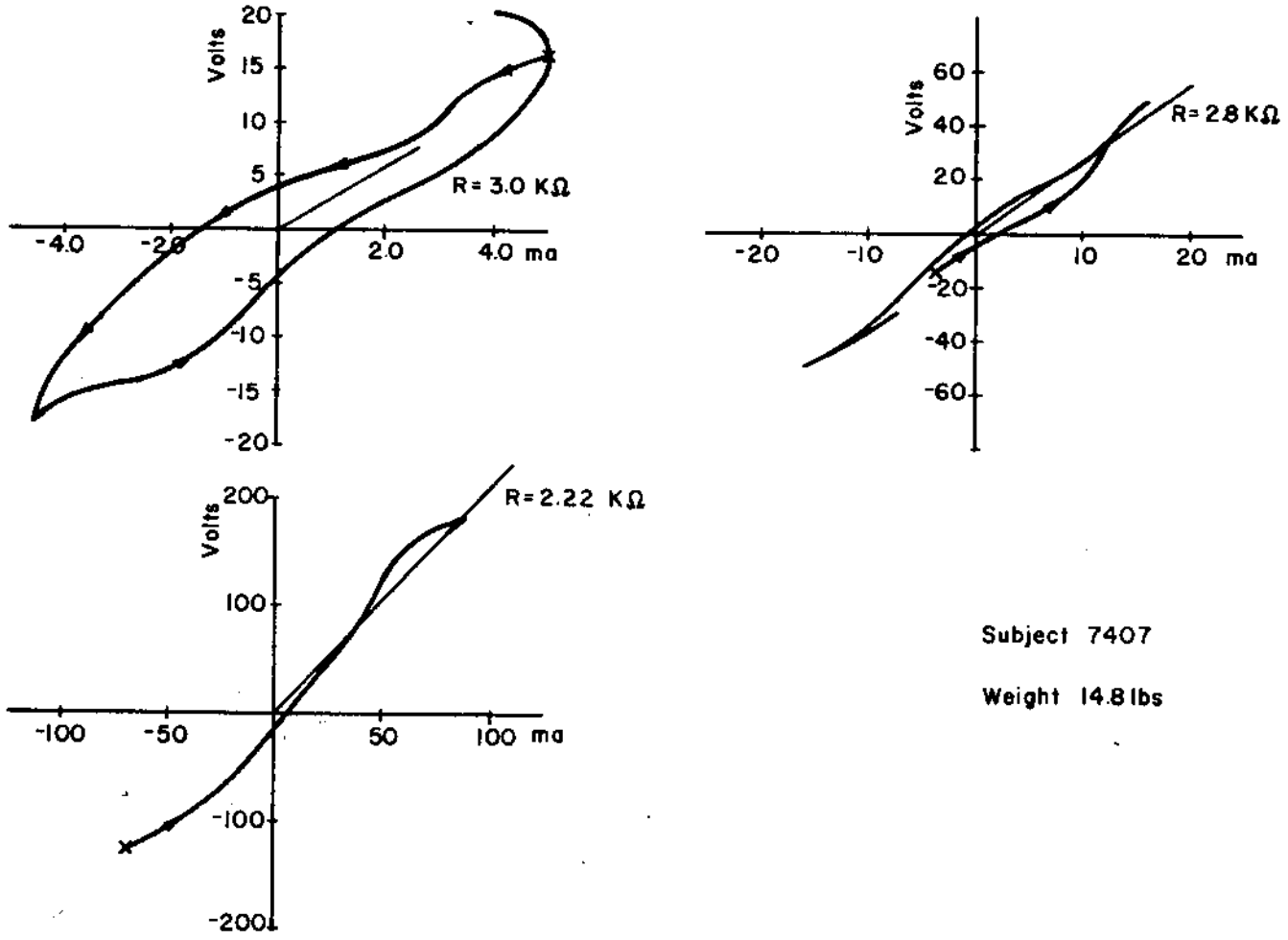


Fig. 8. V-I curve, short duration shock test, saturated saline wetted cylinder clasped in hand, subcutaneous electrode in foot.

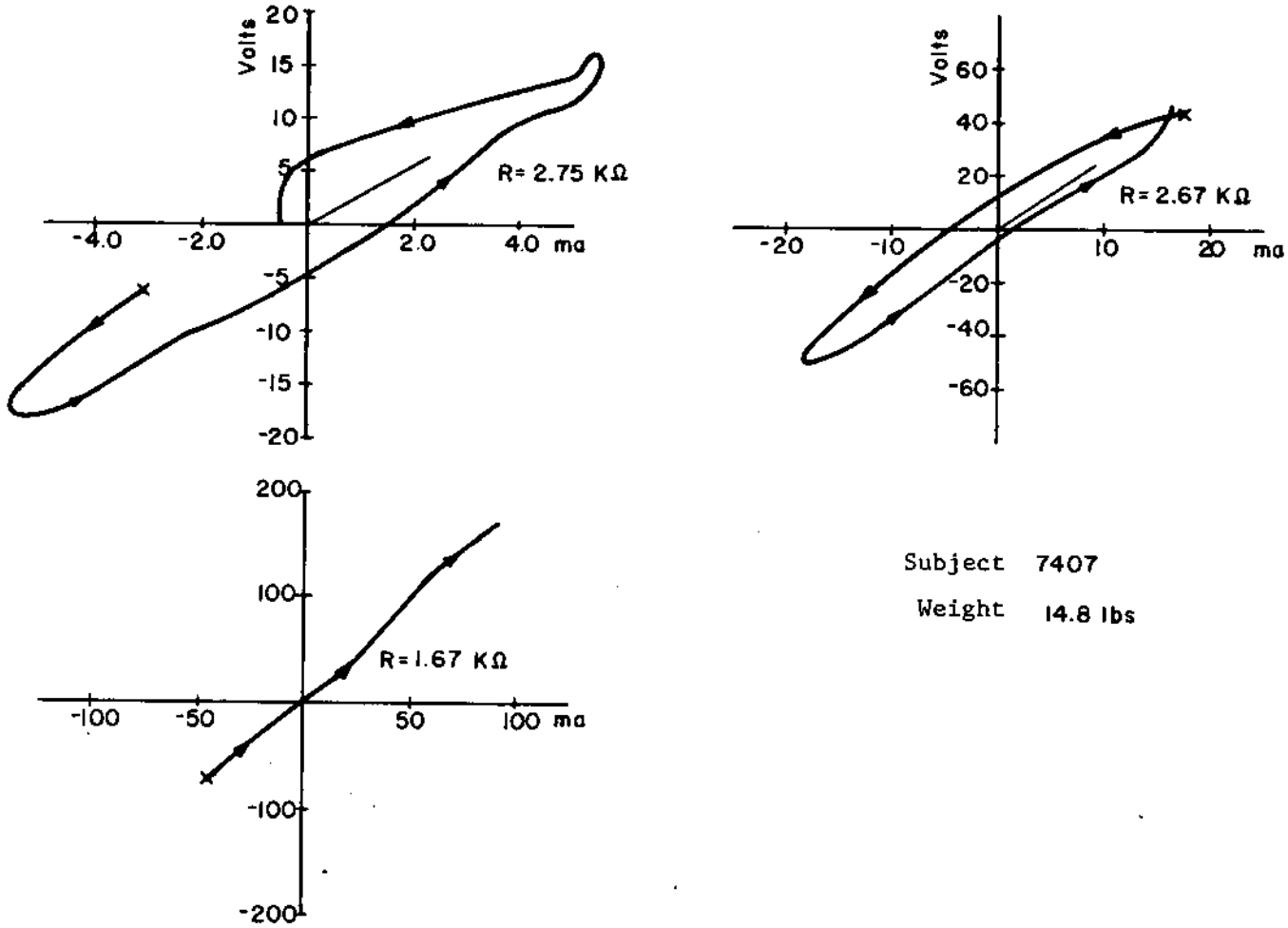


Fig. 9. V-I curve, short duration shock test, ECG cream coated cylinder clasped in hand, subcutaneous electrode in foot.

Staff at Johns Hopkins University recently conducted tests on human subjects exposed to very brief, capacitor-type spark discharges (Reilly and co-workers, 1982). The test results indicate that the "apparent body impedance" (the instantaneous applied potential divided by the body current) could be as low as 120 to 300 ohms depending on the area of the contact. Substantial precursor spike currents could therefore flow in humans who are suddenly exposed to constant-potential, low-impedance voltage sources. The amplitude of the precursor current spike for a large-area contact, based on the Johns Hopkins data, approaches 0.5 ampere if the shock was suddenly delivered from an exposed, low-source impedance, 120-volt conductor.

Shocks from 120-volt, low-impedance sources can be demonstrated to be lethal to humans based on the current knowledge of fibrillation thresholds (Dalziel, 1972; Draft IEC Revision) and apparent body impedances (Carter and Morley, 1969; Freiberger, 1934). Such demonstrations are possible, however, only if the lower percentile ranges of fibrillation thresholds and the lower values of apparent body impedances are used. Other mechanisms may exist which could escalate an almost hazardous shock condition to a highly lethal one. Such an exacerbation could be the largely unnoticed precursor current spike.

Skin Impedance Failure

A number of investigators, such as noted in the Johns Hopkins study (Reilly and co-workers, 1982), have demonstrated that the bulk of the "apparent body impedance" resides largely in the epidermis or skin. The apparent impedance of the subject, either nonhuman or human, can be drastically reduced if the contacting metallic surfaces, or electrodes, either deliberately or inadvertently bypass this high-resistance layer. As discussed earlier, this high-resistance layer is bypassed by the capacitive or displacement currents associated with a very short-duration impulsive or spark-over type exposure. If tests are conducted on nonhuman subjects, another method to bypass these layers is to use electrodes placed beneath the skin (subcutaneous electrodes). The result is apparent body impedance levels of a few hundred ohms for long-duration exposures.

The possibility of the high-resistance skin layer being punctured or bypassed also has to be considered. For example, when a Rhesus monkey (subject 7407) was exposed to shocks, as limited by the GFCI, the apparent body impedance did not fall below 2670 ohms for 45-volt peak exposures (see Fig. 9). Subject 7407 was exposed (in a parallel study not discussed in detail here; Bridges and co-workers, 1977) to a series of longer duration shocks at progressively increased levels of voltage from a low impedance source. This subject, while holding a saline-metal cylinder in the right hand and with both feet in a saturated saline solution, experienced fibrillation after exposure to a 45-volt rms low impedance source. During this exposure, we found that the apparent body impedance had dropped to between 700 and 461 ohms from the previously measured value of about 2800 ohms, as noted in Fig. 8, for comparable conditions. A careful visual inspection of 7407 revealed no cuts or burns on the hands.

Although few definitive conclusions can be drawn from this one example, one explanation of the observed results is that the apparent skin impedance broke down or was otherwise negated.

The possibility that the current limiting effects of the relatively high apparent impedance of the skin can be negated somehow may also explain where the shock hazard for humans is exacerbated.

Contact Geometry

The Johns Hopkins study on the effects of very short duration shocks (Reilly and co-workers, 1982) also demonstrated some rather contradictory pheonomena which are supportive of the above discussion. For example, the study demonstrated that the apparent body impedance of human subjects decreases substantially for very small area contacts as the applied voltage is increased. In contrast, the apparent body impedance remains largely constant for large area contact surfaces. This suggests a "breakdown" or current avalanching type of phenomenon which could be augmented by the high electric field gradients associated with small area electrodes.

Definition of Impedance

The concept of impedance itself causes further difficulties, inasmuch as it is defined rigorously only for steady-state, single-frequency, sinusoidal waveforms. Under many shock conditions, the voltage is applied as a step waveform and the resulting current in the early period behaves as an exponentially decaying transient current spike. The concept of impedance therefore cannot be rigorously used to characterize the voltage-current behavior of the Rhesus monkeys, and quite possibly humans. A rigorous characterization would define a relationship in terms of a network of capacitors and resistors with nonlinear and possibly time-dependent parameters, as has been suggested by Stephans (1963).

CONCLUSIONS

Data have been developed on the transient voltage and current relationship for low-voltage, low-impedance shock applied to Rhesus monkeys. These data show the existence of a large precursor current spike which is much larger than the follow current. Since such spikes are not generated if constant current sources are used, the physiological effects of these spikes have yet to be considered in definitive experiments. The possibility that the high-impedance skin layer could exhibit electrical breakdown or electron avalanching was also noted in one of the animal tests. Such precursor current spikes or high-impedance skin breakdown phenomena are relatively unnoticed factors in aggravating shock hazards for humans.

ACKNOWLEDGMENT

This work was sponsored by the Consumer Product Safety Commission under the direction of William King and L. A. Ilzetzki. The author acknowledges the assistance of Raymond A. Zalewski and Kent Kogler in conducting the electrical portion of the tests, and Drs. Maurline Preache and Curt Port in the biological aspects.

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DISCUSSIONS

HART: I would like to suggest areas in which further research is needed.

1. Effects on people and methods to measure leakage currents from mixed frequency sources such as mains leakage mixed with signal leakage or switching power supply leakage currents.

2. Safe voltage levels for frequencies above 100 Hz and for non-sinusoidal waveforms. Examples of concern are:

   a. Let-go levels have been shown to be at lower voltage levels at 1 kHz than at 50 Hz.

   b. Square waves are more severe at 50 Hz than are sine waves.

   c. Voltage levels for burns above 100 kHz are not well defined.

DOLAN: The current pathway strongly influences the effect a shock will have on the heart for example. This is because the current distribution through the organs of the body can vary widely depending on position of the external electrodes. In the heart, current density variations of as much as 40:1 have been determined using a model we have developed. This means that one part of the heart could have 40 A/m^2 going through it and another part only 1 A/m^2. A different electrode position produces an entirely different current distribution in the heart.

BRIDGES: I quite agree; as Dr. Geddes has pointed out, the heart is especially sensitive to an electrode placed in the immediate vicinity of the heart. The IEC 64 in their proposed standard considers either increasing or decreasing the threshold depending on the pathway.

BERNSTEIN: Does your study of body impedance help explain reports of low voltage, such as 12 V, ac electrical shocks that have caused deaths?

BRIDGES: Of the unusually low-voltage shock fatalities that I am familiar with, all of these have either involved a current pathway from contact points on the chest or where the skin had been punctured physically, such as a cut. It is conceivable that small area contacts may have been involved in which case the beneficial effect of skin impedance is negated. This could be of interest for voltage sources of 25 V and upwards.

MADER: Regarding the origin of the precursor spike, is it possible to explain this on the basis of pathological or biological data for living tissue? In this light:

1. Is there a correspondence between time constant of the spike and steady-state phase shift?

2. Is the same spike observed with dead subjects?

3. Can cell reactions account for the phenomenon?

4. What is the effect of the capacitance of the leads and equipment between the mercury switch and the subject?

BRIDGES: In response to (1), we have not correlated any relationships between the spike time constant and the phase angle of the flow current. In the case of (2), we have not investigated current-flows in dead subjects, (3) some form of cell reaction could conceivably account for the spike; however, it may be more of an electrochemical or electrophysical-phenomenon, since the skin surface is composed largely of dead tissue, (4) our equipment was not designed to record or apply fast transients.

BEATTIE: (1) Comment: Bridges stated that humidity/moisture plays a small role in determining body resistance at high voltages. Experience in our experiments indicates that moisture has a very strong effect if the electrode area is small.

(2) Question: Can you draw any conclusions concerning fibrillation levels from the electrocution reported in your presentation, given the known characteristics of your ground fault interrupters and measured currents?

BRIDGES: In response to (1), assuming that water-saturated footwear is not considered, both Dr. Biegelmeier's and my results show that as the touch voltage is increased, the difference between wet and dry conditions (in terms of body impedance) is small. In response to (2), for the electrocution studies, we removed the GFCI (Ground Fault Current Interrupter) and applied progressively increasing levels of 60 Hz shocks. Each exposure was separated in time by about 1 to 2 hours. Prior to the electrocution test, the subject had sufficient body resistance to preclude fibrillations at 45 Vrms. As noted during the 45 Vrms application, the body current increased significantly and abruptly, so that the body impedance decreased to 500 Ω.

KANODE: I have a question concerning an avalanche effect identified with small contact areas under increased voltage conditions. Have there been any tests made that consider the possibility of skin heating effect causing a sharp increase in current density in a small contact area as the voltage level is increased.

BRIDGES: The possibility that the abrupt breakdown of skin impedance under shock conditions could be further aggravated by thermal effects should be investigated.

VAINBERG: Could you please indicate if there is a difference in measured fibrillation threshold levels and body impedances for various experimental conditions (body laying down versus standing)? If there is a difference, what would be the implication in applying these experimental data to real life situations?

BRIDGES: I have observed shifts in the position of the heart when the test animal lies down. Therefore lab test protocols relating to fibrillation shock data may have to be refined. Also the scenario for possible shock accidents in real-life situations is important. Limb-to-limb shock data has been emphasized at this conference, but other current paths are plausible in certain work situations, e.g., through the chest or chest to rump or thighs. These paths will cause much higher susceptibility to electrical shock hazards by reducing body impedance and increasing current through the heart.

SANCES: Did the author determine the potential distribution within the body, with depth probes?

BRIDGES: We did two things, first of all we had a catheter implanted into the heart which was led out by an insulated lead. We measured the differential resistance for a potential drop across the baboon using subcutanteous probes. They were just needles that we inserted. Therefore the skin resistance does not enter in.

SANCES: But you didn't go inside to measure muscle or bone or tendon or anything of that sort.

BRIDGES: No, the only thing that was really deeply implanted was the catheter in the heart.

SHERMAN: (1) Does the zero potential line obtained in the experiments on baboons indeed indicate zero potential, or is there a potential difference below the resolution limit of your equipment? If so, what is it? (2) Which factors determine the position of zero potential line. (3) Would body weight scaling versus fibrillation threshold be accurately described by 2/3 power relationship if fat mass is subtracted from total body weight.

BRIDGES:

(1) A battery operated telemetry system was used to pick up the body potentials; the signal transmitted was filtered after reception. The bandwidth of the filter was about 0.8 Hz. This filtering, applied body current of about 10 to 30 microamperes and related signal levels allowed a signal to noise ratio of about 10,000 to 1, with the noise signal level being in the nanovolt region. The filter also removed the ECG, stray 60 Hz (the excitation signal was ~64 Hz) and fluorescent lamp noise. The use of a floating telemetry system is essential to remove ground current effects.

(2) The position of the zero-potential line is controlled by the vector direction of the current density and the spatial distribution of the conductivity. For hand-to-hand current, the assymmetrical position of the heart (and the included higher blood conductivity tilts the zero-equipotential line to the left.

(3) The 2/3 power relationship was developed on the basis of a homogeneous body. Departures from homogeneity and similarity could alter this relationship.

VAINBERG: Could you please comment on the influence of the sources used in experiments (current versus voltage sources) on the ventricular fibrillation thresholds? Could you also comment on applicability of experiments to real situations existing on transmission line rights-of-way and at substations where one encounters sources with very high levels of voltage and current?

BRIDGES: Most of the fibrillation data has been developed using sinusoidal current sources. However, when a person touches a low-impedance voltage source, the initial current is in the form of a spike followed by a more or less sinusoidal current waveform. This spike and following current may or may not be important. The applied current waveform in real life are also influenced by the output impedance of the source and the way in which the skin breaks down in impedance. These factors are discussed in Prof. Biegelmeier's and my papers included in the session on body impedance.

WILSON: Do you know at what electric field strength (V/m) from a 60 Hz HV line interference with any type of commercial pacemaker will occur.?

BRIDGES: In the case of a patient walking beneath a power line, 5 kV/m or upwards can cause reversion of an implanted pacemaker to the asynchronous mode. This reversion takes place whenever the patient touches a household electrical appliance or walks into a high intensity field. This reversion is not regarded as hazardous for short periods.

ANALYSIS OF CROSS-BODY IMPEDANCE AT HOUSEHOLD VOLTAGE LEVELS

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ABSTRACT

This paper presents an investigation of cross-body impedances involved in electrical burn injuries at household voltage levels. The purpose of the study was to investigate the relationship between cross-body impedance and geometry of contact surface, and to quantify the cross-body impedance as a function of duration of contact. A set of nine circular and elliptical stainless steel electrodes, ranging in area from 0.8 cm^2 to 20.0 cm^2 and in circumference from 1.6 cm to 28.0 cm, was used in the study. 100 Volts AC (60 Hz) was applied with a constant pressure across the hind quarters of anesthetized hogs, between an electrode and a 40 cm by 60 cm ground plate. Each hog, weighing approximately 70 kg, received 5 to 10 applications with a single electrode. Prior to application, the hind quarters of the subjects were shaved and no conducting medium was applied between the electrode and the skin. The resultant current - time relationships, with a constant applied voltage, are composed of three distinct phases: 1) an initial marked increase, 2) a period of gradually increasing current, and 3) a sharp fall-off in current. The minimum cross-body impedance occurs immediately before the fall-off in current, and delineates the second and third phases. The averge minimum cross-body impedance was 241.5 ohms (S.D. = 10.6) with the smallest electrode and 64.4 ohms (S.D. = 5.8) with the largest electrode. The average duration of current flow, from onset to cessation, was 23.8 seconds (S.D. = 5.6) with the smallest electrode and 308.8 seconds (S.D. = 123.8) with the largest electrode. The average applied energy over the duration of current flow was 761.5 joules (S.D. = 200.4) with the smallest electrode and 40,253.2 joules (S.D. = 15,730.4) with the largest electrode. The average applied power was 40.4 watts (S.D. = 1.7) with the smallest electrode and 131.3 watts (S.D. = 6.2) with the largest electrode. The study produces a qualitative assessment of the relationship between cross-body impedance and geometry of contact surface. An increase in electrode area, while maintaining a constant electrode circumference, resulted in a negligible change in minimum cross-body impedance. However, an increase in electrode circumference, while maintaining a constant electrode area, resulted in a decrease in minimum cross-body impedance. The results indicate that the circumference at the contact surface is more significant than the area of contact in establishing the minimum cross-body impedance. These results are supported by electrode studies in a saline tank, and theoretically in the literature.

KEY WORDS

Electode, geometry, stainless steel electrodes, 60 Hz, 100 VAC, current-time relationship, cross-body impedance, hogs, total applied energy, electrical burns, burn severity

INTRODUCTION

Electrical burn injuries continue to be an extremely serious world problem (Sances, 1979, Wu, 1979). Skoog reported that 7 percent of all burn injuries encountered at University Hospital in Uppsala, Sweden between 1951 and 1970 were electrically induced (Skoog,1970). The National Center for Health Statistics estimates that 4 percent of the burns in the United States were directly caused by electricity in the years 1974 to 1976 (Wu, 1979).

Traditionally, investigators have included contact area as the only important geometrical property involved in the electrical burn injury (Carter, 1969a, Carter, 1969b, Hunt, 1976, Skoog, 1970, Wu, 1979). Studies in recent years have shown theoretically that the current density is greatest at the edge of a circular electrode (Newman, 1966, Overmeyer, 1979). Saline tank studies utilizing circular and elliptical electrodes support these findings, showing that for circular electrodes, the resistance is inversely proportional to the electrode diameter, and that circumference and area must both be considered in determining the resistance of an elliptical electrode (Sances,, 1981). Also, previous studies have identified a triphasic current-time relationship in the electrical injury (Carter, 1969a, Carter, 1969b, Hunt, 1976, Sances, 1981). Studies of amputated human limbs showed that the current-time relationship involved an initial sharp rise, followed by a much slower rise, and then finally a rapid fall in current flow (Carter, 1969b). However, this characteristic relationship between current and duration of contact has not been quantitatively investigated at household voltage levels.

This study was conducted to analyze the impedance across the hind quarters of a hog, as a function of geometry and duration of contact. The study was also designed to determine the energy to produce a given tissue burn severity as a function of electrode geometry.

METHODS

Eighteen hogs weighing 60 to 90 kilograms were used in this experiment. Each of the hogs was sedated with an initial dose of 15.0 mg/kg of Ketamine hydrochloride mixed with 0.75 mg/kg Acepromazine. Nembutal was administered as necessary to sustain a surgical level of anesthesia. The hogs were positioned on an insulated table with a 40 x 60 centimeter ground plate under the hind quarter. Both hind quarters were shaved and no conducting medium was applied.

Circular and elliptical stainless steel electrodes, 1 millimeter in thickness, were used. The circular electrodes ranged in diameter from 1.0 to 5.0 centimeters. The elliptical electrodes were constructed so that, for a particular circular electrode, one elliptical electrode was of the same area but different circumference, and another elliptical electrode was of the same circumference but different area. This variety of electrode configurations allows the assessment of the effects of changes in electrode geometry. The dimensions of the electrode set are shown in Table 1.

Table 1 Description of the Stainless Steel Electrode Set

Electrode Number	Electrode Configuration	Major/Minor Radius (cm)	Electrode Area (cm^2)	Electrode Circumference (cm)
1	Round	0.50/0.50	0.79	3.14
2	Round	0.61/0.61	1.17	3.83
3	Round	1.30/1.30	5.31	8.17
4	Elliptical	1.70/0.55	2.94	7.94
5	Elliptical	3.15/0.55	5.44	14.21
6	Round	2.55/2.55	20.43	16.02
7	Elliptical	3.37/1.06	11.22	15.70
8	Elliptical	6.21/1.04	20.29	27.97

One hundred volts rms (60 Hz) was applied across the hind quarters between an electrode and the ground plate. The electrode was held in place with a constant pressure, which was maintained with a spring scale at 0.1 kg/cm. This was the minimum pressure necessary to ensure uniform contact between the electrode and the skin. Each hog received 5 to 10 applications with a single electrode. Application sites were separated by at least 10 centimeters to minimize interactions between burns. The electrode was brought into contact with the skin before the voltage was established to observe any time delay between the application of voltage and the initial flow of current. This procedure also ensured a uniform contact over the entire application time. Previous studies have shown that the current-time relationship is the same regardless of whether voltage or contact is established initially (Carter, 1969a). The voltage was applied until a cessation of current was observed. The voltage and current waveforms were recorded with a Honeywell Visicorder Model 1858. The current was measured by monitoring the voltage across a 1 ohm resistor in series with a single-phase 60 Hz variable transformer, capable of supplying potentials from 10-500 volts rms.

From the recorded voltage and current waveforms, the following parameters were calculated: 1) time to falloff - the total time of current flow, from onset to cessation, 2) minimum cross-body impedance - the impedance at the time of maximum current flow, 3) total applied energy - the area under the current-time curve multiplied by the applied voltage, and 4) average power - the total applied energy divided by the time to falloff. A least squares linear regression curve fitting routine was used to identify trends between these derived parameters and the electrode geometry.

RESULTS

The wound associated with each application site was composed of several distinct regions (See Figure 1). The perimeter of the contact area was distinguished by a ring of charred tissue approximately 1 millimeter wide. A brownish-gray burned region encompassed the entire contact area and extended concentrically approximately 0.75-1.0 centimeters beyond the perimeter of contact. The portion of the burned region outside of the contact area was predominantly covered by blistering. A whitish-yellow ischemic region, 0.75-1.0 centimeters wide, surrounded the burned area. Concentric with the contact area and 1.5-2.0 centimeters distant, was a dark ring, approximately 0.5 centimeters wide, of hemorrhage and thrombosis. All animals survived the experiment.

In 85 percent of the applications, the time delay between the application of voltage and the initial flow of current was less than 0.10 seconds. In the remainder of applications, the maximum time delay was 1.7 seconds and the average delay was 1.1 seconds.

The phase angle between the voltage and the current was less than 3 degrees for all applications. The applied voltage remained constant over the entire application interval. A representative current-time waveform, which consists of three phases, is shown in Figure 2. In the first phase, there was a tonic contraction of the entire hind end as the current increased to 50 percent of

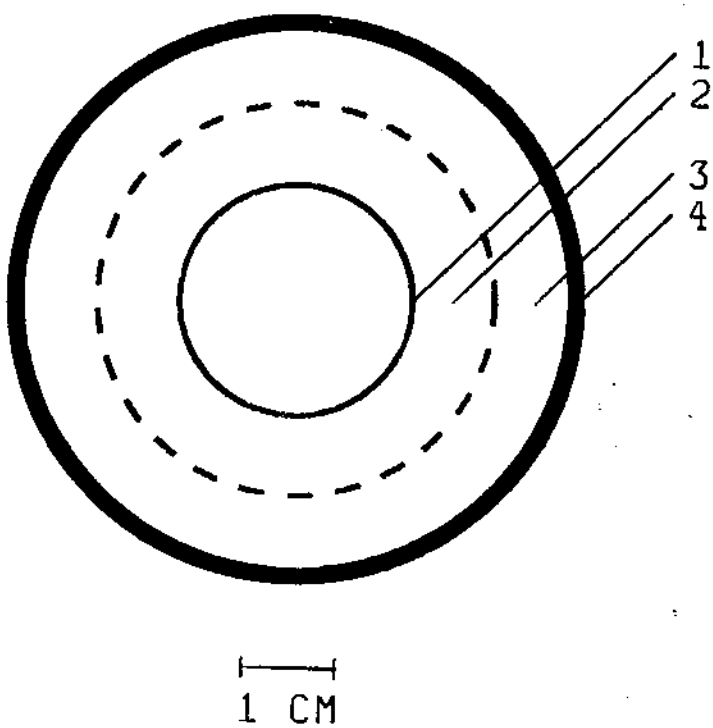

Figure 1: Diagram of a representative injury location. The wound consists of four zones: (1) A ring of charred tissue marks the perimeter of the contact area, (2) A Brownish-gray burned area encompassing the area of contact, (3) A whitish-yellow ischemic region, and (4) A dark region of hemorrhage and thrombosis.

the maximum value. The average duration of the first phase over all subjects was 1.5 seconds (s.d. = 1.2 seconds). Generally, the length of this initial phase increased with electrode size. The second phase is characterized by sustained contraction and a gradual increase in current flow. The second and third phases are delineated by the time of maximum current flow (minimum cross-body impedance). In the third phase, the current rapidly decreased following sparking and tissue charring at the perimeter of the electrode. The muscular contraction diminished as the current flow decreased. The current reduction of the third phase lasted approximately three to four times as long as the initial current increase of the first phase.

The derived parameters for all subjects are listed in Table 2. The largest values for total applied energy, minimum cross-body impedance, and time to falloff were found in the application sites located most caudal or dorsal. The lowest values of these parameters corresponded to the most ventral application sites. From the values determined for electrodes 3, 4, and 5, a change in electrode area while maintaining a constant circumference produced a negligible change in cross-body impedance and average power. However, an increase in electrode circumference, while maintaining a constant area, resulted in a significant decrease in cross-body impedance and increase in average power. The values associated with electrodes 6, 7, and 8 were not sufficiently consistent to conclusively identify similar trends. The cross-body impedance varied more with electrode circumference than with area, as shown in Figure 3. The least squares linear regression routine produced the following relationships, using the data from all subjects.

Relationship	Correlation Coefficient
Resistance $\propto$ Area $^{-0.32}$	0.9557
Resistance $\propto$ Circumference $^{-0.51}$	0.9369
Power $\propto$ Area $^{0.33}$	0.9399
Power $\propto$ Circumference $^{0.54}$	0.9420
Energy $\propto$ Area $^{1.08}$	0.9660
Energy $\propto$ Circumference $^{1.73}$	0.9649
Time $\propto$ Area $^{0.73}$	0.9555
Time $\propto$ Circumference $^{1.17}$	0.9523

where area = electrode area (cm^2), circumference = electrode circumference (cm), resistance = minimum cross-body impedance (ohms), power = average power (watts), energy = total applied energy (joules), time = time to falloff (seconds).

DISCUSSION

The resulting burns observed in this study are similar to those reported elsewhere (Artz, 1979; Carter, 1969a; Carter, 1969b; Hunt, 1976; Wu, 1979). The whitish-yellow ischemic region surrounded by a ring of hemorrhage and thrombosis is indicative of vascular occlusion and necrosis. These effects have been shown to occur at the time of electrical (Artz, 1979; Hunt, 1976) and thermal (Moritz, 1947) injury. The occurrence of charring only at the perimeter of the electrode indicates that the current density is highest in this region. This agrees with previous theoretical (Newman, 1966; Overmeyer, 1979) and saline tank (Sances, 1981b) electrode studies. Previous hog studies utilizing the same electrode set demonstrated that the temperature beneath the dermis at the edge of the electrode is 15-20 C higher than at the center (Sances, 1981a).

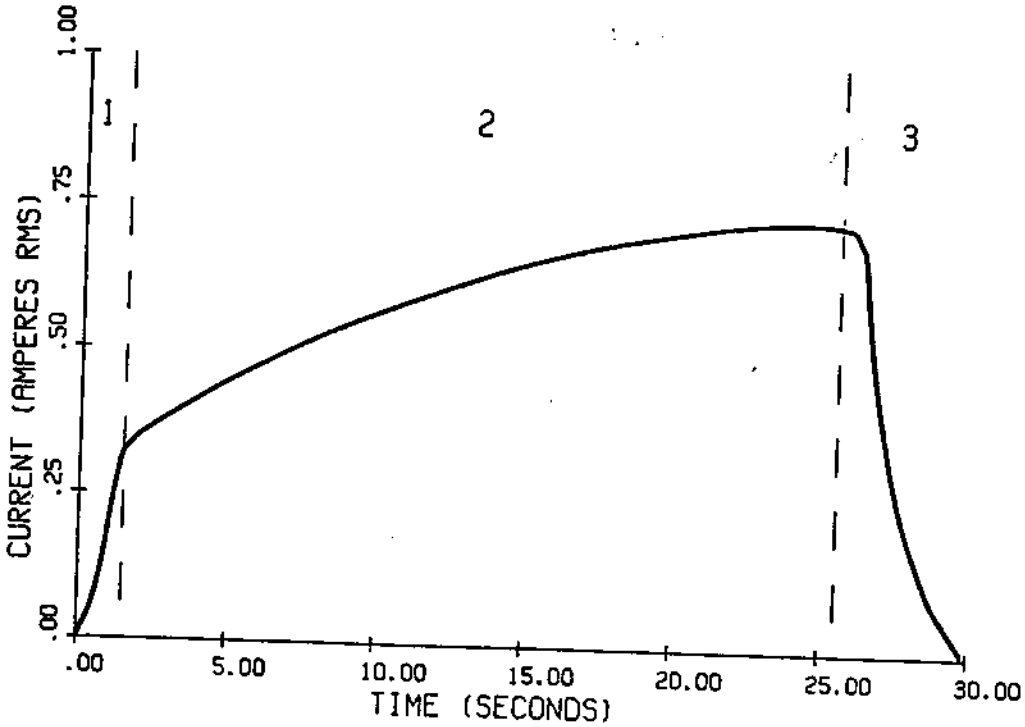

Figure 2: Representative current vs. duration of contact for electrode 2, at an applied potential of 100 volts rms.

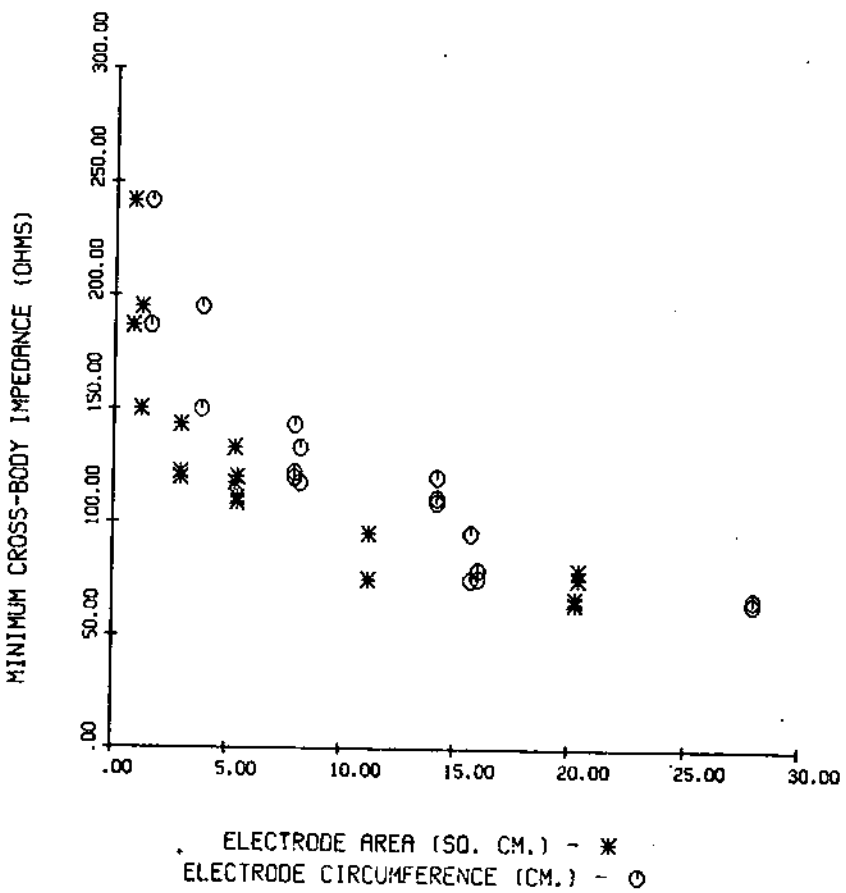

Figure 3: Minimum cross-body impedance vs. electrode area/circumference for all subjects.

Table 2 Derived Parameters for All Subjects with Applied Voltage of 100 V rms

Values listed are mean/standard deviation

Electrode	Hog	Minimum Cross-Body Impedance (ohms)	Total Applied Energy (Joules)	Time to Falloff (seconds)	Average Power (watts)
1	1	186.68	1157.25	26.63	42.51
		15.96	418.48	7.28	5.49
	2	241.52	761.50	23.75	40.39
		10.60	200.44	5.64	1.69
2	3	149.85	1454.50	26.05	55.54
		20.37	389.91	6.45	6.96
	4	194.87	1341.75	33.00	40.60
		16.47	461.84	10.54	3.04
3	5	132.92	6165.33	103.50	59.10
		6.87	1651.84	24.02	3.07
	6	117.34	5890.50	84.13	70.54
		13.14	2009.26	28.78	8.75
4	7	143.15	4279.33	72.38	57.35
		9.96	2387.10	30.43	10.76
	8	119.64	7865.67	108.22	74.68
		11.42	2450.76	41.13	7.91
	9	121.96	7664.22	115.72	67.22
		12.54	3413.89	53.24	6.14
5	10	108.79	13586.25	138.58	97.91
		7.35	4395.42	43.93	5.71
	11	119.92	14906.22	166.00	89.76
		9.52	5275.24	58.53	8.80
	12	110.72	6717.63	89.00	75.41
		11.71	1975.01	23.82	7.26
6	13	75.30	28149.57	206.00	134.60
		7.54	14735.25	96.49	13.03
	14	78.91	33922.33	326.42	107.13
		11.81	12420.16	133.85	17.33
7	15	74.76	16353.75	152.38	108.95
		8.55	3927.62	42.59	10.74
	16	95.18	15082.50	178.50	86.31
		16.36	3016.11	48.26	12.00
8	17	66.67	37017.60	301.00	124.44
		7.45	9580.97	90.47	10.42
	18	64.44	40253.17	308.75	131.28
		5.78	15730.38	123.76	6.19

This study also shows that the relationship between the current flow and the duration of contact is triphasic in nature, as indicated by others using excised human cadaver skin (Carter, 1969a), amputated human limbs (Carter, 1969b), and hogs (Sances, 1981b). The skin initially acts as an insulator to the flow of current. Generally, less than 0.1 seconds were required to overcome the initial skin resistance, enabling the current to flow freely through the internal tissues. Thus, the first phase involves a breakdown in the resistance of the skin. The gradual increase in current of the second phase is probably caused by several factors. Joulean heating will cause the underlying tissue temperature to rise in proportion to the resistance of the particular tissue and the square of the current flow through the tissue. Studies in the hog have shown that tissue resistivity decreases with increasing temperature (Sances, 1981a). Also, studies of thermal injury have shown a marked increase in capillary permeability in the area of the injury (Artz, 1979; Moritz, 1947). The resulting extravascular increase in body fluids will also tend to decrease the overall body impedance, since the resistivity of body fluids is considerably less than the resistivity of muscle or fat (Sances, 1981a, Sances, 1983). In the third phase, the sharp decrease in current flow is probably due to the drying out of the area under the electrode. Vascular occlusion prevents the dissipation of heat by the blood flow. Consequently, the heat vaporizes the local body fluids, causing a drying of the tissue. This culminates with the charring of tissue at the perimeter of the electrode.

The results from electrodes 4, 5, and 6 demonstrate that the cross-body impedance is more significantly affected by changes in electrode circumference than by changes in electrode area. This is also shown, though not as conclusively, by electrodes 6, 7, and 8. The intense muscular contractions caused by the initial flow of current can result in a non-uniform contact over the electrode surface, especially the relatively large electrodes. The relationships described by the least squares linear regression analysis indicate that all of the derived parameters vary more rapidly with electrode circumference than with electrode area. These results show that whereas traditionally only the surface area of contact was considered important, actually the entire electrode geometry, both area and circumference, must be taken into consideration when evaluating the severity of an electrical injury.

This study also showed that the traditionally accepted value for body impedance of 500 ohms is probably considerably high. The smallest electrodes in this study produced cross-body impedances of only approximately 200 ohms.

All of the resulting burns in this study were pathologically similar. However, depending on the electrode size and the duration of contact, the energy required to produce this level of burn severity, at 100 volts, varied from approximately 1000 Joules to 40,000 Joules. The marked increase in energy for the large electrodes is probably due to the increased surface to be burned. Additionally, this results in increased time to burn which indicates the contributions of other factors such as conduction and convection of heat.

Acknowledgment

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DISCUSSIONS

OSMAN: In some electrosurgical procedures, burns took days to appear after the operation. How long did it take for the burns to appear in your experiments?.

PRIETO: The resulting burns were completely established when the electrode was removed except for the ring of hemorrhage and thrombosis which developed over several minutes following the insult.

WILLS: Clinical experience indicates that some workers in hand-to-hand electrical contacts with high voltage lines (2400 - 4800 V) characteristically have: (i) respiratory difficulties (ii) devastating burns (iii) but no ventricular fibrillation. Why is this? What current would the heart see?

PRIETO: It is often observed that low currents produce fibrillation while high currents cause severe burns. The reason usually given for this effect is that the high current cause the entire heart to contract, following which it may be able to resume a normal rhythm.

KNICKERBOCKER: Regarding the previous question as to why high voltage shocks, which lead to serious burns, do not result in fibrillation; it is widely appreciated that a high current tends to contract all fibres of the heart and in fact, for a period of time a shock of some 5 amperes through the chest of a fibrillating victim seemed effectively to defibrillate the heart.

PRIETO: Thank you for the comment.

MADER: Isn't this phenomenon simply the well-known "skin effect" of alternating current? If so, the degree of skin effect will depend on frequency. For a given frequency it will be possible to remove the centre of a disk electrode thus forming an annular electrode without substantially altering the resistance. However, the equivalence will not apply to the same degree between a disk and elliptical electrode of the same circumference. Would the authors care to comment?

PRIETO: Round and elliptical electrodes were used in these studies for several reasons. First, these electrode configurations simulate actual injury contacts very well. Secondly, annular electrodes were used in preliminary studies, as well as wire rings. The preliminary results do not conflict with the circular/elliptical electrode results. An annular electrode produced a lower cross-body impedance than a circular electrode of the same outside circumference, which has been attributed to the additional circumference. However, the results of the annular electrodes have not been completely analyzed and further studies have been planned. Also, annular electrodes involve two edges of contact rather than a single contact edge as seen in the circular/elliptical electrodes and typical injury contacts.

NEW EXPERIMENTS WITH REGARD TO BASIC SAFETY MEASURES FOR ELECTRICAL EQUIPMENT AND INSTALLATIONS

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ABSTRACT

This paper describes new measurements carried out to determine the body impedance of living persons for current paths hand to hand, left hand to feet and foot to foot. Some of the measurements have been carried out in wet conditions. The measurements have been carried out for touch voltages up to 200 V and form the basis for a document which will be sent to ACOS/IEC in order to promote the safe application of electric energy.

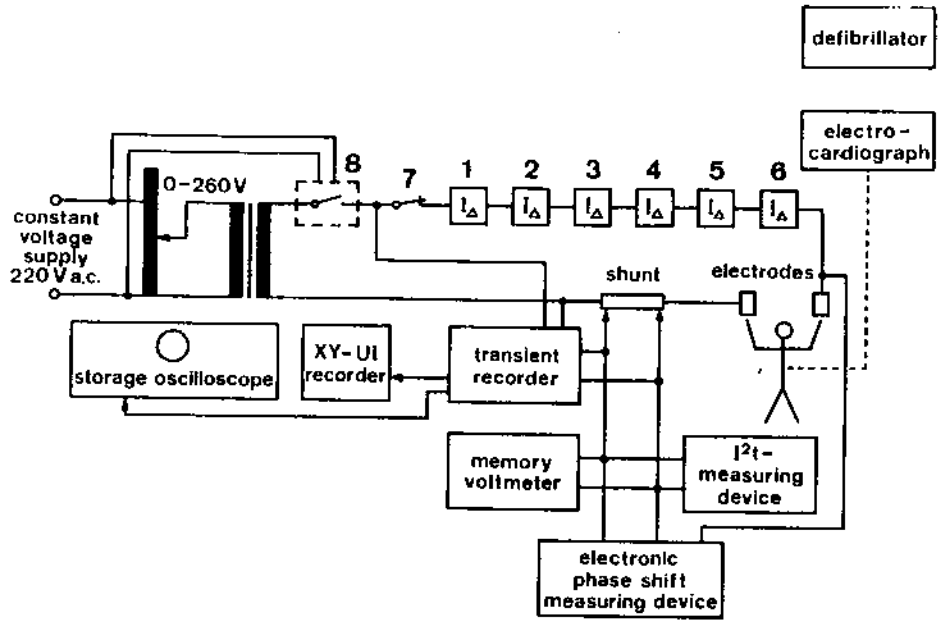
KEYWORDS

Electric shock, ground fault interruptors, human body impedance

INTRODUCTION

In order to promote the safe application of electric energy IEC has always followed certain principles of protection namely: protection against indirect contact, protection against direct contact, additional protection against direct contact by means of ground fault interruptors, hereinafter called RCCBs, double insulation, and so forth. In this context the conditions in the installations with regard to humidity, body impedance, likeliness of insulation faults, etc, must also be considered. This has led to considerable difficulties in the discussions in IEC Technical Committees. The main reason for these difficulties was shortage of information on the limits of danger of body currents and the influence of the various conditions on the current flowing through the body, such as humidity, contact area, current path, etc.

At the same time doubts persist regarding the effectiveness and reliability of protective measures, especially with regard to RCCBs. In order to clarify the most important problem which is the effectiveness of RCCBs, large series of experiments have been carried out which have provided important new results. The results of these experiments are described in detail in the next part of this paper.



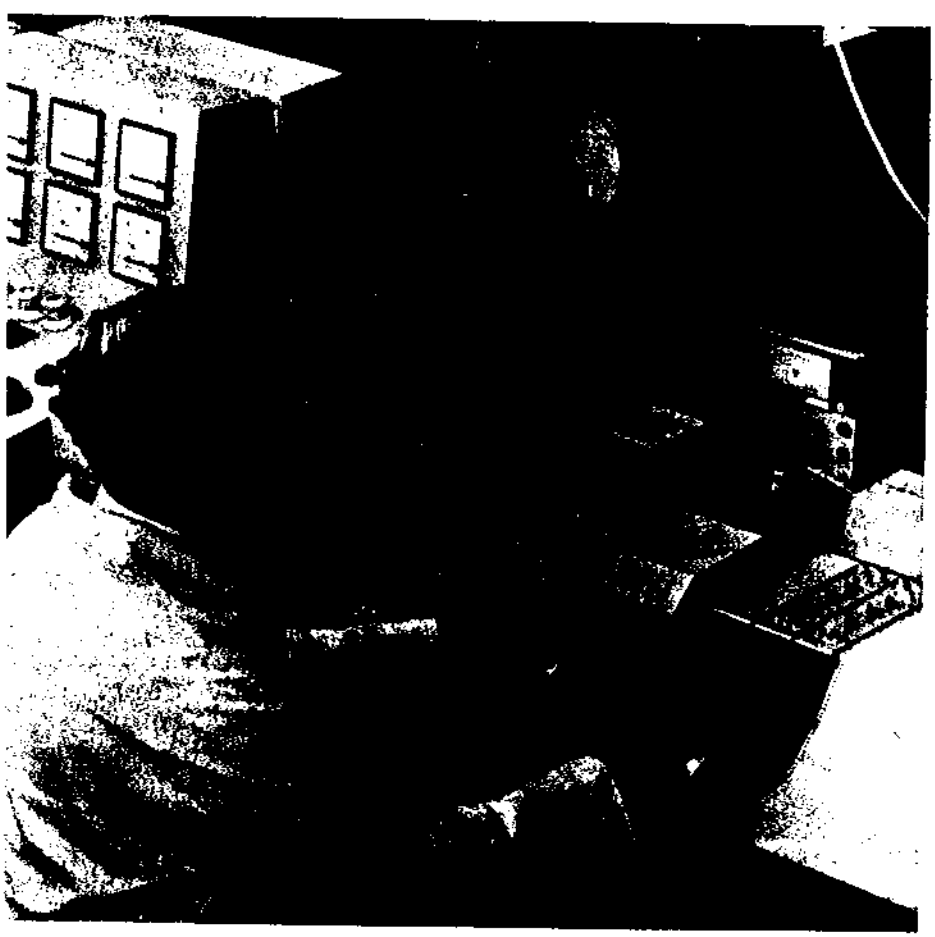


Figure 1: Experiments with test person for a current path hand to hand .

1a... Circuit-diagram of the test arrangement.
1b... Test person grasping hand-electrodes.

PURPOSES OF EXPERIMENTS, MEASURING ARRANGEMENT AND TEST PROGRAM

Additional measures of protection against electrical accidents depend to a large extent of the tripping characteristic of RCCBs. Furthermore investigations of such acccidents require the knowledge of the impedance of the human body as a function of the tough voltage for various current paths and forms of contact. The experiments described in this paper were carried out with the following purposes.

1. To prove the effectiveness of RCCBs to protect a person in case of direct contact with touch voltages up to 200 V ac.

2. To prove that this protection is given without any harmful after-effects of the shocks.

3. To describe current intensities and forms of rise of current after contact making at various touch voltages.

4. To describe the influence of contact area and humidity of the skin at various touch voltages up to 200 V ac.

5. To measure the body impedance at various touch voltages up to 200 V ac for a current path hand to hand, left hand to feet and foot to foot.

6. To describe the physiological effects felt by the test person for various shock intensities.

7. To determine the I^2 x t-values of the shock impulses received by the test person.

8. To measure the current peaks and the phase angle caused by the capacitances of the human body.

Though the experiments were carried out with 50 Hz ac, the results are deemed to be also applicable to 60 Hz ac. Compared with earlier measurements more sophisticated electronic equipment was used in the circuit for the present measurements. Figure 1a shows the arrangement in which an electrocardiograph registered the moment of contact making with regard to the cardiac cycle. At each voltage, six shocks were executed at random within the cardiac cycle. The ECG proved that during the experiments the shocks fell frequently within the vulnerable period.

The volunteering test person (age 59, weight 85 kg, normal condition of health) grasped brass cylinder electrodes (100 mm long, 80 mm diameter) for the current path hand to hand firmly. For the current path left hand to feet and foot to foot a copper foil 0.1 mm thickness was inserted into the shoes, using the same hand electrode as described above (Figure 1b). In this way a situation was simulated which would correspond to a serious electrical accident.

Six RCCBs were connected in series at lower touch voltages being removed one after another until in some cases two 100 mA-RCCBs remained as the only protective means at touch voltages of 175 V and 200 V. For all measurements except test-series 4 and 7 RCCBs

were common electro-mechanical types with non-polarized tripping relays and the following tripping ranges:

1	$I_{\Delta N}$ =	10 mA,	tripping range	8.2 - 8.8 mA
2	$I_{\Delta N}$ =	10 mA,	tripping range	7.9 - 8.5 mA
3	$I_{\Delta N}$ =	30 mA,	tripping range	22.8 - 25.5 mA
4	$I_{\Delta N}$ =	30 mA,	tripping range	20.1 - 21.3 mA
5	$I_{\Delta N}$ =	100 mA,	tripping range	74 - 81 mA
6	$I_{\Delta N}$ =	100 mA,	tripping range	71 - 76 mA

For test-series 4 and 7 other RCCBs were used; 30 mA and 100 mA breakers having polarized tripping relays and 10 mA breakers having tripping circuits with electronic amplification, the function of which depends on the line voltage. These breakers had the following tripping ranges:

1'	$I_{\Delta N}$ =	10 mA,	tripping range	6.7 - 7.1 mA
2'	$I_{\Delta N}$ =	10 mA,	tripping range	6.3 - 7.1 mA
3'	$I_{\Delta N}$ =	30 mA,	tripping range	21 - 23 mA
4'	$I_{\Delta N}$ =	30 mA,	tripping range	20 - 21 mA
5'	$I_{\Delta N}$ =	100 mA,	tripping range	78 - 82 mA
6'	$I_{\Delta N}$ =	100 mA,	tripping range	71 - 73 mA

The test circuit was electronically switched on and off and contained a further safety switch which was manually operated. The test program consisted of six series, namely:

Series 1: Current path hand to hand, full electrode area, touch voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V, six exposures at dry conditions at each touch voltage, contact making at the peak of touch voltage (Appendix 1).

Series 2: Current path hand to hand, full electrode area, touch voltages 25, 50, 75, 100, 125, 150, 175 and 200 V, six exposures at dry conditions at each touch voltage, contact making at zero point of touch voltage (Appendix 2).

Series 3 Current path left hand to feet, full electrode area, touch voltages 25, 50, 75, 100, 125, 175 and 200 V, six exposures at dry conditions at each touch voltage, contact making at zero point of touch-voltage (Appendix 4, Figure 2).

Series 5 Current path hand to hand, full electrode area, touch voltages 25, 50, 75, 100, 125 and 200 V, one exposure with hands wetted for one minute in water of the public water supply system (resistivity ρ ~3500 Ω) (series 5-1), and one exposure with hands wetted for one minute in a 3% solution of sodium chloride (resistivity ρ~20 Ω) (series 5-2), contact making at zero point of touch voltage (Appendix 5).

Series 6 Current path foot to foot, full contact area, touch voltages 25, 50, 75, 100, 125, 150, 175 and 200 V, six exposures at dry conditions at touch voltages up to 150 V, one exposure at 175 V and 200 V, contact making at zero point of touch voltage (Appendix 6).

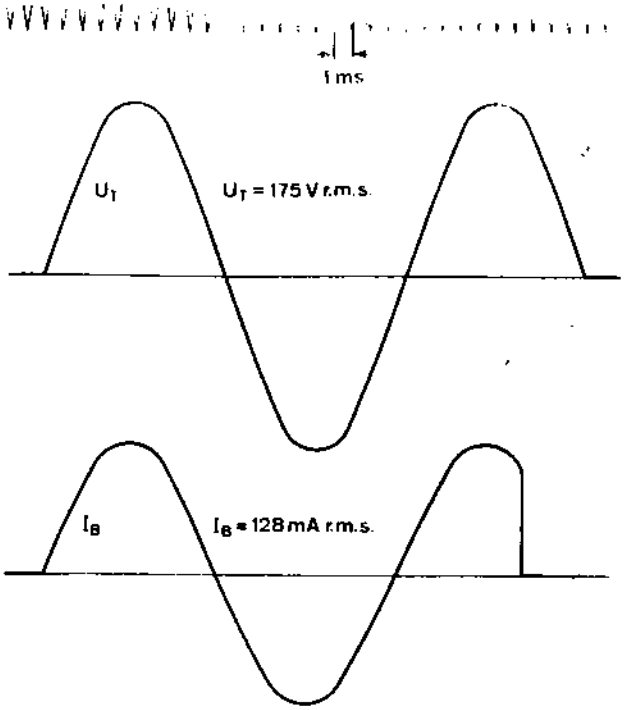


Figure 2: Body current and touch voltage at 175 V rms, current path left hand to feet, dry conditions, full electrode area, contact making at zero point of touch voltage, contact breaking by RCCB after three half waves.

This shock started within the vulnerable period of the cardiac cycle. Painful muscular reactions ($I^2 \times t = 525\ \mu A^2 s$), no irregularities of heart observed.

Due to the tripping of the RCCB's, the shock duration was limiting to less than 30 ms. In case of contact making at the peak of touch voltage and for breakers working with electronic amplification (breakers No 1' and 2') the shock duration was usually limited to less than 10 ms. In case of contact making at the zero point of touch voltage, the breakers with non-polarized tripping relays usually limited the shock duration to less than 20 ms, the breakers with polarized tripping relays to less than 30 ms.

SUMMARY OF TEST RESULTS

During the experiments described in this paper several hundred electric shocks have been executed on the test person without detrimental after-effects from the electro-pathological point of view. The ECG after the experiments showed no change when compared with the ECG which was taken before the shocks.

As a summary, the following results and conclusions should be especially mentioned:

1. The following currents as average values out of six measurements distributed at random within the cardiac cycle were withstood:

1.1 For a current path hand to hand (heart current factor 0.4)

420 mA as a peak impulse current with a time constant of approximately 0.2 to 0.4 ms

125 mA rms value as half wave or nearly fully wave ac-impulse 50 Hz, shock duration up to 20 ms,

50 mA rms value for a shock duration of 100 ms.

1.2 For a current path hand to feet (heart current factor 1.0)

480 mA as a peak impulse current with a time constant of approximately 0.2 to 0.4 ms.

190 mA rms value as half wave or nearly full wave ac-impulse 50 Hz, shock duration up to 20 ms.

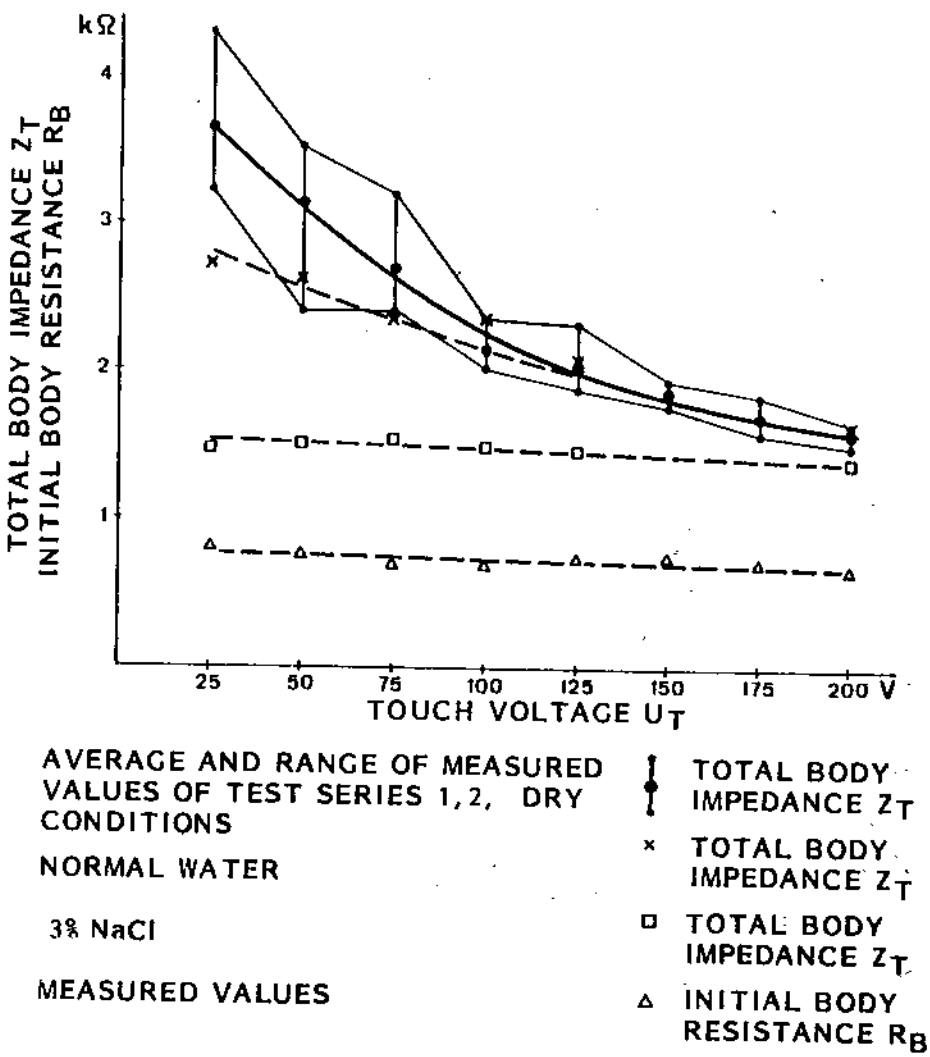


Figure 3: Total body impedance Z_T and initial body resistance R_B in function of touch voltage at contact area for dry and wet conditions and a current path hand to hand.

2. During the experiments the dependancy of the total body impedance Z_T and the initial body resistance R_B on the touch voltage up to 200 V have been measured. The results for a current path hand to hand are shown in Figure 3, for a current path left hand to feet in Figure 4 and for a current path foot to foot in Figure 5.

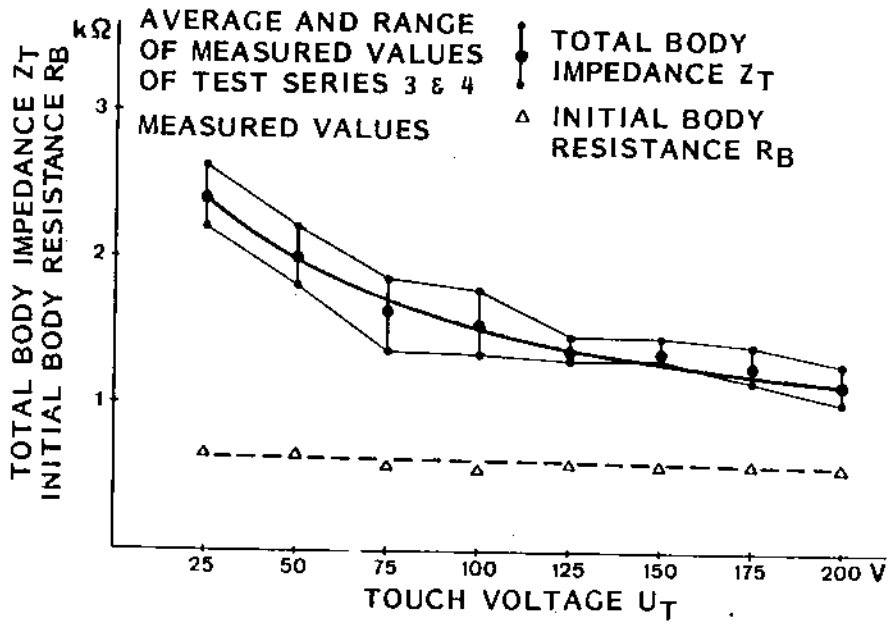


Figure 4: Total body impedance Z_T and initial body resistance R_B in function of touch voltage at full contact area, dry conditions and a current path left hand to feet.

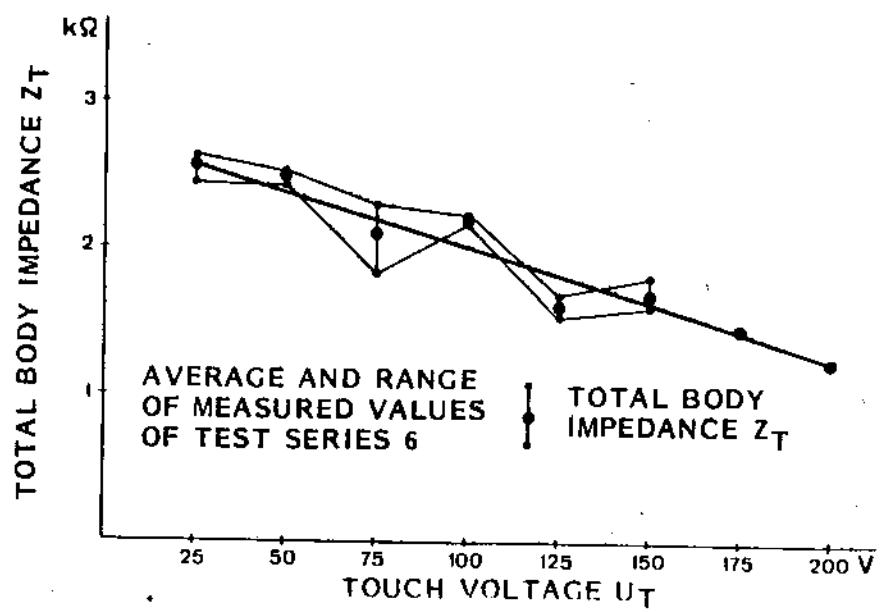


Figure 5: Total body impedance Z_T in function of touch voltage at full contact area, dry conditions and a current path foot to foot.

3. Under the conditions mentioned under 1.1, one measurement was carried out at touch voltages of 25, 50, 75, 100, 125 and 200 V with hands wetted for one minute in water of the public water supply (resistivity approximately 3500 Ω) and in a 3% solution of sodium chloride in water (resistivity approximately 20 Ω). The results of these measurements are shown in Figure 3.

4. Under the same conditions one further measurement was carried out at a touch voltage of 150 V with dry hands and a shock duration of 100 ms and a body current of approximately 100 mA rms.

5. Under the conditions mentioned under 1.2 one further measurement was carried out at a touch voltage of 175 V and a shock duration of 30 ms and a body current of approximately 130 mA rms (see Figure 2).

APPENDICES:

Appendix 1:	Test-series 1:	Current path hand to hand, dry conditions, full contact area, contact making at peak of touch voltage.
Appendix 2:	Test-series 2:	Current path hand to hand, dry conditions, full contact area, contact making at zero point of touch voltage.
Appendix 3:	Test-series 3:	Current path left hand to feet, dry conditions, full contact area, contact making at peak of touch voltage.
Appendix 4:	Test-series 4:	Current path left hand to feet, dry conditions, full contact area, contact making at zero point of touch voltage.
Appendix 5:	Test-series 5-1 and 5-2:	Influence of humidity, full contact area
Appendix 5-1:	Test-series 5-1	Hands wetted in normal water of the public supply, contact making at zero point of touch voltage.
Appendix 5-2:	Test-series 5-2	Hands wetted in a 3% solution of sodium chloride, contact making at zero point of touch voltage.
Appendix 6:	Test-series 6:	Current path foot to foot, dry conditions, full contact area, contact making at zero point of touch voltage.

APPENDIX 1-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's,
IN CASE OF DIRECT CONTACT AND MEASUREMENTS
OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 1: Current-path hand to hand,
Touch-voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V,
Six exposures at dry condition at each touch-voltage,
Contact making of the peak of touch-voltage.

Results: Measured values are averages out of 6 measurements.

Touch-voltage U_T(V)		25	50	75	100	Touch-voltage U_T(V)		125	150	175	200
Body-current $I_B(mA_{rms})$		7.6	18.2	28.5	47.5	Body-current $I_B(mA_{rms})$		66.6	82	106	129
Body-current $\hat{I}_B$(mA) peak		42.8	91.9	152	206	Body-current $\hat{I}_B$(mA) peak		237	283	350	420
Total body impedance $Z_B(\Omega)$ (x)		3356	2757	2651	2106	Total body impedance $Z_B(\Omega)$ (x)		1937	1838	1647	1546
Initial body resistance R_B (Ω) (x)		817	765	695	687	Initial body resistance R_B (Ω) (x)		743	747	708	666
Phase angle ϕ(°)		16.1	16.2	14.7	11.7	Phase angle ϕ(°)		8.5	7.9	6.4	6.2
Shock duration (ms)		<20	<20	<20	<20	Shock duration (ms)		<20	<20	<20	<20
Physiological effects		light cramp in fingers	light cramp in fingers and joints of hands	cramp in fingers, joints of hands and arms	cramp in fingers, joints of hands, arms, and shoulders	Physiological effects		cramp in fingers, joints of hands, arms and shoulders, light lifting of upper body	as 125 V but stronger, slight pain	as 150 V but stronger, painful	as 175 V but stronger painful lifting of body
Functioning RCCB	10 mA	--	++	taken out	taken out	Functioning RCCB	10 mA	--	++	taken out	taken out
	30 mA	--	--	+-	++		30 mA	--	--	+-	++
	100 mA	--	--	--	--		100 mA	--	--	--	--

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

APPENDIX 2-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's,
IN CASE OF DIRECT CONTACT AND MEASUREMENTS
OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 2: Current-path hand to hand,
Touch-voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V,
Six exposures at dry condition at each touch-voltage,
Contact making at zero voltage-point of touch-voltage.

Results: Measured values are averages out of 6 measurements.

Touch-voltage U_T(V)		25	50	75	100	Touch-voltage U_T(V)		125	150	175	200
Body-current $I_B(mA_{rms})$		6.3	15.4	27.5	45.8	Body-current $I_B(mA_{rms})$		59.6	80.3	100.7	124
Body-current $\hat{I}_B$(mA) peak		--	--	--	--	Body-current $\hat{I}_B$(mA) peak		--	--	--	--
Total body impedance $Z_B(\Omega)$ (x)		3968	3546	2751	2188	Total body impedance $Z_B(\Omega)$ (x)		2103	1870	1738	1610
Initial body resistance R_B (Ω) (x)		--	--	--	--	Initial body resistance R_B (Ω) (x)		--	--	--	--
Phase angle ϕ(°)		22.7	18	12	10.2	Phase angle ϕ(°)		12	8	6	5
Shock duration (ms)		<20	<20	<20	<20	Shock duration (ms)		<20	<20	<20	<20
Physiological effects		stronger as in test-series 1				Physiological effects		stronger as in test-series 1			
Functioning RCCB	10 mA	--	++	++	taken out	Functioning RCCB	10 mA	taken out	taken out	taken out	taken out
	30 mA	--	--	+-	++		30 mA	++	++	+-	++
	100 mA	--	--	--	--		100 mA	--	+-	++	++

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

APPENDIX 3-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's, IN CASE OF DIRECT CONTACT AND MEASUREMENTS OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 3: Current-path left hand to feet
Touch-voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V,
Six exposures at dry condition at each touch-voltage,
Contact making at the peak of touch-voltage.

Results: Measured values are averages out of 6 measurements.

Touch-voltage U_T(V)		25	50	75	100	Touch-voltage U_T(V)		125	150	175	200
Body-current $I_B(mA_{rms})$		10.5	25	45	73	Body-current $I_B(mA_{rms})$		91	112	145	189
Body-current $\hat{I}_B$(mA) peak		52	107	183	250	Body-current $\hat{I}_B$(mA) peak		291	355	412	480
Total body impedance $Z_B(\Omega)$ (x)		2383	2005	1669	1375	Total body impedance $Z_B(\Omega)$ (x)		1376,	1333	1201	1057
Initial body resistance R_B (Ω) (x)		667	658	578	564	Initial body resistance R_B (Ω) (x)		605	597	598	587
Phase angle ϕ(°)		18.7	15.1	12.3	9.4	Phase angle ϕ(°)		9	8.7	6.5	5
Shock duration (ms)		20	20	20	20	Shock duration (ms)		20	20	20	20
Physiological effects		light cramp in fingers, no reaction in legs	cramp in fingers, joints of hands and arms. In legs light cramp in tendons.	cramp in fingers and in arm, light lifting of legs	cramp in arm and shoulder and legs	Physiological effects		strong cramp in arm and shoulder, cramp in legs	stronger than 125	strong reactions in arm and legs, light lifting of body	lifting of body, pain in arm, strong reaction in legs
Functioning RCCB	10 mA	++	+	taken out	taken out	Functioning RCCB	10 mA	taken out	taken out	taken out	taken out
	30 mA	--	+	+	++		30 mA	++	++	++	++
	100 mA	--	-	-	+-		100 mA	+-	+-	+-	+-

APPENDIX 4-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's, IN CASE OF DIRECT CONTACT AND MEASUREMENTS OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 4: Current-path left hand to feet
Touch-voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V,
Six exposures at dry condition at each touch-voltage,
Contact making at zero point of touch-voltage.

Results: Measured values are averages out of 6 measurements.

Touch-voltage U_T(V)		25	50	75	100	Touch-voltage U_T(V)		125	150	175	200
Body-current $I_B(mA_{rms})$		10.3	25	47	58	Body-current $I_B(mA_{rms})$		91	107.5	130	161
Body-current $\hat{I}_B$(mA) peak		--	--	--	--	Body-current $\hat{I}_B$(mA) peak		--	--	--	--
Total body impedance $Z_B(\Omega)$ (x)		2436	1997	1614	1721	Total body impedance $Z_B(\Omega)$ (x)		1372	1396	1348	1239
Initial body resistance R_B (Ω) (x)		--	--	--	--	Initial body resistance R_B (Ω) (x)		--	--	--	--
Phase angle ϕ(°)		--	--	--	--	Phase angle ϕ(°)		--	--	--	--
Shock duration (ms)		<10	<10	10, 20 and 30	10 and 30	Shock duration (ms)		10	10..30	10..30	10
Physiological effects (xx)		light sensation in ankles and fingers	sensation in hand and ankles	sensation up to elbow and knees, lifting of heels	sensation up to shoulder, lifting of heels	Physiological effects (xx)		sensation up to shoulder and legs, lifting of heels, pain in joint of hand	sensations at shock duration 30 ms much stronger than at 10 ms	painful in arm and legs	somewhat stronger than 175 V
Functioning RCCB (xxx)	10 mA	++	++	taken out	++ (o)	Functioning RCCB (xxx)	10 mA	++	taken out for 2 shocks	taken out for 1 shock	++
	30 mA	--	--	++	-- (++)		30 mA	--	+-	+-	--
	100 mA	--	--	--	--		100 mA	--	+-	+-	--

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122
(xx) effect depends on shock duration 10, 20 or 30 ms
(xxx) rapid operation of 10 mA breakers prevents tripping of 30 mA and 100 mA breakers
(o) taken out for one shock for tripping the 30 mA breakers (++ 30 ms - shock)

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122
(xx) effect depends on shock duration 10, 20 or 30 ms
(xxx) rapid operation of 10 mA breakers prevents tripping of 30 mA and 100 mA breakers

An oscillogram at 175 V touch-voltage with a shock duration of approximately 10 ms is shown in Figure 3.

APPENDIX 5.1-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's,
IN CASE OF DIRECT CONTACT AND MEASUREMENTS
OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 5-1: Current-path hand to hand
Touch-voltages, 25, 50, 75, 100, 125 and 200 V,
One exposure after hands wetted for 1 minute in normal water of public supply (resistivity ρ = 3500 Ωcm),
Contact making at zero point of touch-voltage.

Results:

Touch-voltage U_T(V)		25	50	75	100	125	200
Body-current I_B(mA_{rms})		9.2	19	31.8	42.4	60.1	123
Body-current $\hat{I}_B$(mA) peak		--	--	--	--	--	--
Total body impedance Z_B(Ω) (x)		2720	2631	2358	2358	2080	1626
Initial body resistance R_B (Ω) (x)		--	--	--	--	--	--
Phase angle ϕ(°)		20	--	12.6	12	--	6
Shock duration (ms)		16	5	18	18	7	6.5
Physiological effects		as in test-series 2				as in test-series 2	
Functioning RCCB	10 mA	++	++	taken out	taken out	taken out	taken out
	30 mA	--	--	++	++	++	++
	100 mA	--	--	--	--	--	++

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

APPENDIX 5.2-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's,
IN CASE OF DIRECT CONTACT AND MEASUREMENTS
OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 5-2: Current-path hand to hand,
Touch-voltages, 25, 50, 75, 100, 125 and 200 V,
One exposure after hands wetted for 1 minute in solution of NaCl (3%) in water (resistivity (ρ ~20 Ωcm),
Contact making at zero point of touch-voltage.

Results:

Touch-voltage U_T(V)		25	50	75	100	125	200
Body-current I_B(mA_{rms})		17	33	48.8	67.2	86	145
Body-current $\hat{I}_B$(mA) peak		--	--	--	--	--	--
Total body impedance Z_B(Ω) (x)		1470	1515	1536	1488	1453	1380
Initial body resistance R_B (Ω) (x)		--	--	--	--	--	--
Phase angle ϕ(°)		9	7.5	--	4	12	6
Shock duration (ms)		6	15	7.5	7	17	10
Physiological effects		light cramp in fingers and joints of hands	cramp in fingers, joints of hands and arms	cramp in fingers, joings of hands, arms and shoulders	as 75 V but stronger	strong reaction of muscles up to shoulders	heavy shock, lifting of whole body
Functioning RCCB	10 mA	++	++	taken out	taken out	taken out	taken out
	30 mA	--	--	++	++	++	++
	100 mA	--	--	--	--	+-	+-

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122

APPENDIX 6-1

EXPERIMENTS CONCERNING THE FUNCTIONING OR RCCB's, IN CASE OF DIRECT CONTACT AND MEASUREMENTS OF THE IMPEDANCE OF THE HUMAN BODY

Test-Series 7: Current-path foot to foot
Touch-voltages, 25, 50, 75, 100, 125, 150, 175 and 200 V,
Six exposures at dry condition at each touch-voltage,
Contact making at zero point of touch-voltage.

Results: Measured values are averages out of 6 measurements.

Touch-voltage U_T(V)		25	50	75	100
Body-current $I_B(mA_{rms})$		9.8	20	36	45.5
Body-current $\hat{I}_B$(mA) peak		--	--	--	--
Total body impedance $Z_B(\Omega)$ (x)		2560	2496	2098	2190
Initial body resistance R_B (Ω) (x)		--	--	--	--
Phase angle ϕ(°)		--	--	--	--
Shock duration (ms)		<20	<10	<10	<10
Physiological effects		light sensation in ankles	light sensation in ankles and calfs	stronger than at 50 V and lifting of heels	slight pain in both feet, lifting of heels
Functioning RCCB (xxx)	10 mA	++	++	++	++
	30 mA	--	--	+-	--
	100 mA	--	--	--	--

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122
(xx) effect depends on shock duration 10, 20 or 30 ms
(xxx) rapid operation of 10 mA breakers prevents tripping of 30 mA and 100 mA breakers

Touch-voltage U_T(V)		125	150	175	200
Body-current $I_B(mA_{rms})$		77.4	89.1	120	162
Body-current $\hat{I}_B$(mA) peak		--	--	--	--
Total body impedance $Z_B(\Omega)$ (x)		1616	1684	1458	1234
Initial body resistance R_B (Ω) (x)		--	--	--	--
Phase angle ϕ(°)		--	--	--	--
Shock duration (ms)		<10	<10	<10	<10
Physiological effects (xx)		sensation with slight pain in both feet, lifting of heels	pain in both feet, lifting of heels	stronger than at 150 V, light lifting of body	pain in legs, lifting of body
Functioning RCCB (xxx)	10 mA	++	++	++	++
	30 mA	--	--	--	--
	100 mA	--	--	--	--

-- both breakers not tripping
++ both breakers tripping
+- one of the two breakers tripping

(x) see Revision of IEC-Report 479, Part 6, Document 64 (Central Office) 122
(xx) effect depends on shock duration 10, 20 or 30 ms
(xxx) rapid operation of 10 mA breakers prevents tripping of 30 mA and 100 mA breakers

DYNAMIC ASPECTS OF BODY IMPEDANCE

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ABSTRACT

This paper describes a group of experiments conducted on humans to determine physiological factors that attend the onset of electrical shock sensation including how body resistance varies as a function of the potential and frequency of an applied voltage. The unique test setup employed is fully explained and diagrammed, experimental techniques are described, and several X-Y plots, where each point on the resultant curve represents instantaneous body resistance, are included. Data from this investigation suggests that: 1) for some portions of the human body, impedance is a function of both applied voltage level and the duration of its application; and 2) at a particular voltage level there is an apparent sudden decrease in skin impedance (increase in current) coincident with the onset of (the sensation of) electrical shock.

KEYWORDS

Electric shock; body impedance.

INTRODUCTION

From many studies of electric shock, we know that the perception threshold for electric shock is about 0.5 milliampere. And, from other sources, we know that the resistance of the human body is in the range of 1500 to 2000 ohms.

Applying these facts to Ohm's Law, we would predict that the human body should percieve an electric shock from potentials as low as 1 volt.

However, every day we handle batteries, toy trains, doorbell and garage door circuits, calculator power supplies and innumerable other low voltage circuits without any sensation associated with electric shock. Clearly, we have no perception of electric shock at these low voltages.

This lack of sensitivity of the human body to low voltages is reflected in various national and international safety standards. These standards typically allow low voltages to be accessible. For higher potentials the standards specify that the current must be less than a limit value - typically 0.5 milliampere.

These anomalies and seemingly contradictory statements are depicted in Fig. 1.

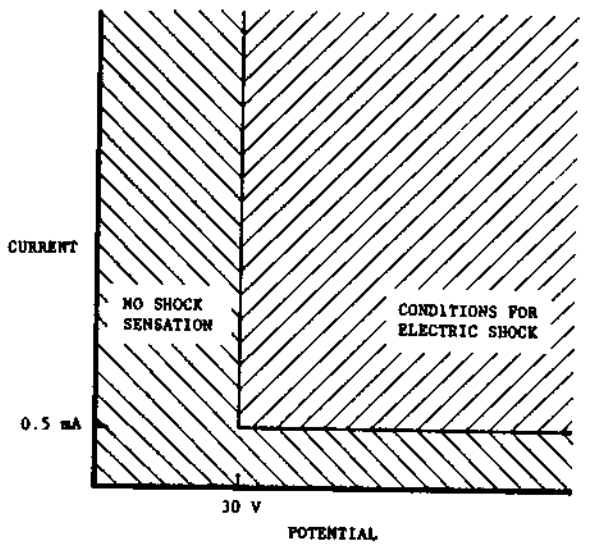


Fig. 1. Discontinuous nature of electric shock criteria.

The only reasonable explanation is that the body impedance changes with applied voltage.

BACKGROUND

Stevens and others have investigated some aspects of change of skin voltage when subjected to constant current pulses. These studies assumed that body capacitance did not change with time or voltage. These studies also suggested that skin resistance varies with the instantaneous magnitude of voltage across the skin.

More recently, Bridges presented the applied voltage and current as X-Y plots, derived point-by-point from voltage-time and current-time oscillograms. These plots, of course, depicted the instantaneous body resistance for any voltage and current. This data confirmed a change in body impedance with voltage and suggested a method of measurement.

None of these studies actually observed the body impedance changing.

IMPEDANCE MEASUREMENT TECHNIQUE

Bridges' voltage-current plots provided the key to a technique for directly observing changes in body impedance. A dynamic oscilloscope voltage-current display provides all of the information from which resistance, capacitance, and impedance can be calculated. The Appendix details the display parameters and the calculation of resistance and reactance, assuming the body impedance is comprised of a parallel resistance-capacitance circuit. (This technique can also be applied to series circuits and circuits with inductive elements.) Fig. 2 shows the basic measurement set up. This set up became more complex when time was identified as a significant parameter affecting the change in body impedance.

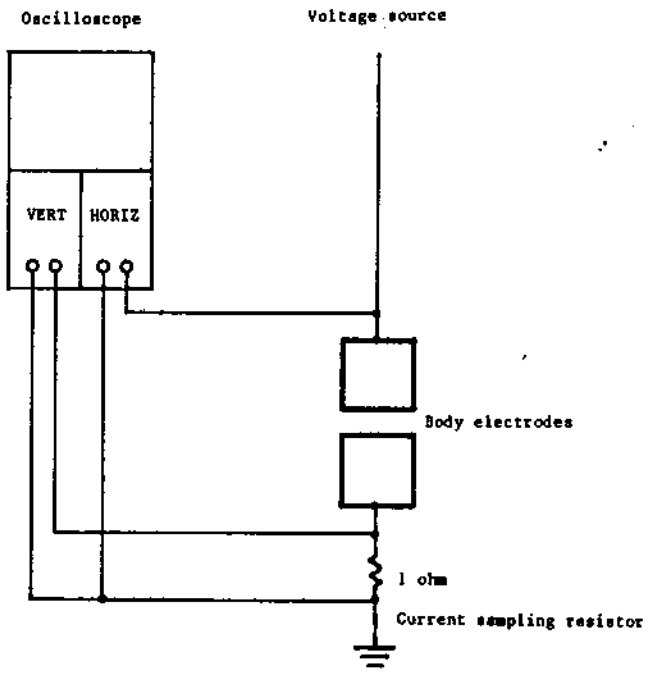


Fig. 2. Basic measurement set-up.

Certain conditions surrounded the measurements. First, the subjects were volunteers. Second, care had to be taken to assure that the body portion of the test circuit only included the arm and hand. Third, for safety, the voltage source must not exceed 40 volts peak. Furthermore, the volunteers were allowed to let go at any time.

The electrodes were ordinary brass, with no special treatment. This was to simulate ordinary contact with common conductive parts. The electrodes were rectangles about 4" x 6" placed about 1/8" apart. The subject was asked to place his palm or his forearm across the electrodes. The current through the palm was transverse, while the current through the forearm was longitudinal.

It is known, however, that electrode material affects impedance measurement. This was ignored because, in electric shock incidents, the electrode impedance is a part of the circuit.

A voltage source was used for these impedance measurements. It is believed a current source would have given similar results.

Three different waveforms were used: triangular dc, triangular-modulated monopolar ac, and triangular-modulated bipolar ac. (Monopolar ac is an ac waveform where the rate of change changes sign, but the absolute magnitude - polarity - does not.) The waveforms start from zero, increase at a uniform rate to the value in Table I, and return to zero. The ac frequency was 60 Hertz.

TABLE I Peak Applied Voltages

Waveform	Palm Voltage	Forearm Voltage
triangular dc	+30	+20
triangular-modulated monopolar ac	-30	-30
triangular-modulated bipolar ac	±40	±40

Tests were conducted across the same kind of skin, either the palm or the fleshy part of the forearm. In earlier experiments it was found that the different kinds of skin affected the measurement. When tests were made between forearm and palm, the electric shock sensation was always on the forearm. When tests were made down the forearm or across the palm, the sensation was equal at both electrodes.

RESULTS, dc HAND TEST

The dc hand test showed virtually no change in resistance with applied voltage. Subjects reported no sensation or a very slight sensation. The maximum potential was 40 volts. Even one subject who was very frightened and perspired profusely on the palm had no sensation at 40 volts and about 9 milliamperes. Resistances ranged from 16 kilohms to 6.5 kilohms.

RESULTS, dc ARM TEST

The dc arm test showed a dramatic change in resistance at the onset of sensation. As experience was gained it was possible for the observer to know both the onset of sensation and the degree of severity from the oscilloscope display. Initially the resistance is on the order of 100 kilohms; at the onset of sensation the resistance drops to less than 10 kilohms.

In most cases, the change of resistance did not occur until the voltage reached 15 volts. In two subjects, the resistance change did not occur until after the triangular voltage wave had passed the peak voltage and was decreasing. This suggests that body resistance is not only a function of voltage, but also a function of the time the voltage is applied.

The change of resistance was quite fast - less than one-half second.

The dc arm test was repeated on several subjects within about 10 minutes of the first test. The second trial showed essentially a constant resistance equal to the final resistance of the first test. This suggests some sort of physiological body change caused by the electric energy, a change which does not immediately reverse. When the dc arm test was repeated a week later, the body again exhibited the change in resistance as observed in the first trial.

Figure 3 shows the typical forearm response to a 20-volt triangular wave. The upper trace is current as a function of time. The lower trace is current as a function of applied voltage (horizontal deflection). The current remains close to zero until the voltage reaches about 15 volts; then the current rapidly increases and thereafter is more or less linear.

RESULTS, MONOPOLAR ac HAND TESTS

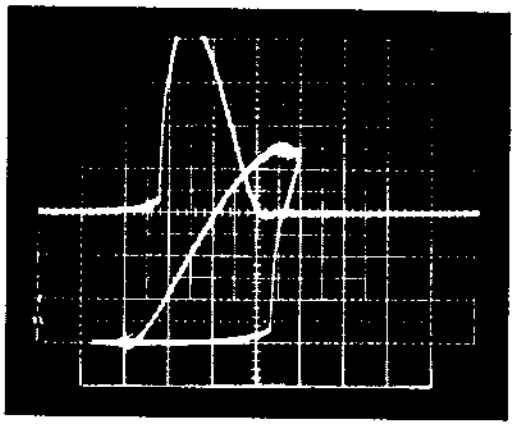
The monopolar ac hand test results were very similar to the dc results: the change in impedance with voltage was very slight. However, the subjects reported very significant sensations - usually a vibration-like feeling in the fingers as if the subject was beginning to lose muscular control. Resistances ranged from 15 kilohms to 2 kilohms, slightly lower than the dc values.

RESULTS, MONOPOLAR ac ARM TESTS

The monopolar ac arm tests results were very similar to the dc results: there usually

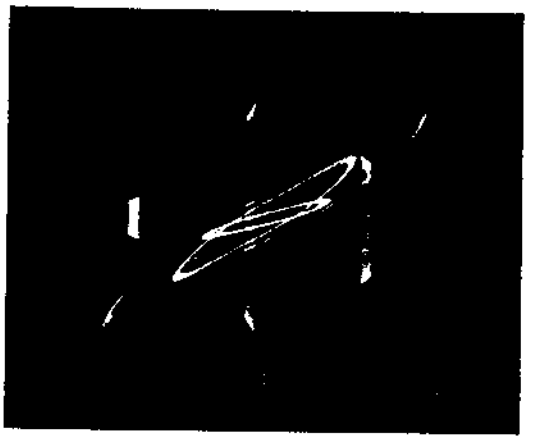
TABLE 2 Measurements

Test	Initial Resistance	Final Resistance	Initial Capacitance	Final Capacitance
Hand, dc voltage	7.4 k	8.6 k		
	10.8	10.8		
	10	14		
	8.3	8.3		
	8.8	8.8		
	6.5	8.3		
	10	10		
	3.3	3.3		
Forearm, dc voltage	100 k	6 k		
	82.5	2.8		
	100	7.9		
	2.5	2.9		
	100	3.7		
	100	5.5		
	125	57		
	150	5		
	100	5		
Hand, ac monopolar	3.7 k	3.8 k		0.25 uF
	12	11.8		0.13
	4.6	5.2		0.17
	7.1	6.1		0.14
	6.0	7.1		0.19
	2.6	2.1	0.24 uF	0.16
	7.5	7.6		0.18
Forearm, ac monopolar	8.1 k	6.4 k	0.18 uF	0.17 uF
	70	23.7	0.057	0.045
	29.8	8.2	0.029	0.059
	98.5	80	-	0.052
	20	9.2	0.059	0.096
	-	61.6	-	0.049
	31.3	16	0.085	0.096
	-	31.3	-	0.035
Hand, ac	5.0 k	5.2 k	0.33 uF	0.26 uF
	11.7	9.3	0.15	0.14
	3.9	8.3	0.32	0.13
	9.0	5.9	0.14	0.13
	8.2	7.0	0.16	0.16
	8.7	-	0.20	-
	6.7	4.5	0.20	0.19
Forearm, ac	31.6 k	14.8 k	0.014 uF	0.041 uF
	46.7	3.0	0.064	0.245
	264	168	0.010	0.010
	111	40	0.040	0.043
	308	96	0.021	0.021
	310	94	0.004	0.006
	66	33	0.022	0.015



Vert (both traces)	1 mA/div
Horiz (upper)	1 sec/div
Horiz (lower)	5 V/div
Initial resistance	82.5 k
Final resistance	2.8 k

Fig. 3. Typical forearm change of resistance.



Vert (both traces)	1 mA/div
Horiz (center)	5 sec/div
Horiz (oval)	10 V/div
Initial resistance	31.6 k
Final resistance	14.8 k
Initial capacitance	0.014 uF
Final capacitance	0.041 uF

Fig. 4. Typical forearm change of impedance.

was a dramatic change in impedance coincident with a painful sensation. Unlike the dc test, there was no particular point of onset of sensation but, rather, a gradual increase in sensation.

Some subject impedances had a character similar to the dc impedance character. Others, however, had a continuous non-linear decrease in impedance with increasing voltage. Resistances at 5 volts were about 100 kilohoms, decreasing to about 10 kilohms at 25 volts.

RESULTS, ac HAND TESTS

The ac hand test results were essentialy the same as the monopolar ac hand tests. The subjects reported the same kinds of sensations where the intensity was directly proportional to voltage. Resistances ranged from about 12 kilohms to about 4 kilohms. Capacitances ranged from about 0.33 to about 0.13 uF. Both the resistance and the capacitance decreased slightly with voltage. The resistance decreased about 2-4 kilohms, and the capacitance about 0 - 0.2 uF. Interestingly, the larger capacitance changes occurred in subjects where the sensation came on suddenly.

RESULTS, ac ARM TESTS

The ac arm test results were similar to the monopolar ac arm tests.

However, none had the continuous non-linear decrease in impedance with increasing voltage.

A new aspect in some subjects characterizing the bipolar ac test is the lack of "ovalness" in the X-Y display. This indicates a continuously changing impedance with voltage at a rate of 60 Hertz. This non-linearity was evident at potentials above 25 volts. Below 20 volts, the display was the traditional oval associated with a pure parallel R-C circuit.

Figure 4, a multiple exposure, shows a typical forearm response. The oval shows the impedance. The vertical lines represent the current at the time of exposure.

DISCUSSION

For all three waveforms, the palm exhibited very little change in impedance compared to the forearm. The highest palm resistance was 12 kilohms. Despite its low resistance, the palm provides better protection against dc than does the forearm.

The subjects were willing to accept a higher transverse palm current than longitudinal forearm current. This is particularly interesting in that the current density in the hand is much greater than that in the forearm.

It would be interesting to subject the hand to even greater voltages - to see if the hand exhibits the same phenomena as the forearm but at a higher voltage. In two subjects there is a hint that there is a change in resistance, but not to the same extent as the forearm.

The sensation of electric shock in the forearm is accompanied by a dramatic reduction in resistance. This resistance does not return to its former value after the voltage is removed. It appears as though the body retains a residual physiological change for some time after the shock.

CONCLUSION

The body impedance does change with voltage and with time of applied voltage. Both the resistive and the capacitive components change. Once these values change, they take time to recover their initial value.

The body is tolerant to low voltages because its impedance is sufficiently high so as to limit the current.

From the monopolar tests, it appears that the body is sensitive to rates of change of voltage or current rather than to change of polarity.

There appears to be a physiological change in the body as a result of applied voltage. The author hopes that further investigation into this physiological phenomenon can yield better methods of protection against and treatment of electric shock.

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APPENDIX 1

DETERMINATION OF PARALLEL RESISTANCE AND CAPACITANCE VALUES FROM AN X-Y DISPLAY

If the voltage across a parallel resistor-capacitor network is applied to either the vertical or horizontal deflection peaks of an oscilloscope, and the current through the network is applied to the other deflection plates, the values of resistance and capacitance can be calculated from parameters of the display. Figure 1 shows the pertinent display parameters.

The parallel resistance is, simply, the slope of the major axis of the ellipse.

$$R = \frac{E_{pp}}{I_{pp}}$$

Where E_{pp} is the peak-to-peak display voltage;
I_{pp} is the peak-to-peek display current.

The size of the phase angle between the voltage and current is proportional to the opening of the elipse.

$$\text{Sin } \theta = \frac{I_{E=0}}{I_{pp}}$$

or

$$\theta = \text{Sin}^{-1} \frac{I_{E=0}}{I_{pp}}$$

Where $I_{E=0}$ is the current when the voltage is zero.

The angle θ is also the angle between the impedance vector of the parallel R-C phaser diagram. See Figure 2.

The impedance, reactance, and capacitance are readily calculated from the values for resistance and phase angle.

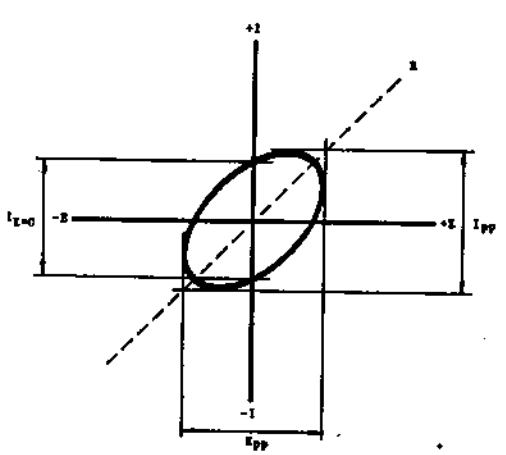

Fig. 1. Parameters of the X-Y display.

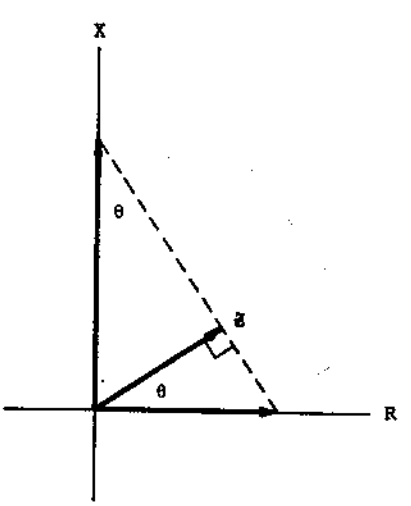

Fig. 2. Phaser diagram, parallel R - C.

DISCUSSIONS

REILLY: The author notes that subjects report perceptible sensations at a voltage level where the current rises rapidly, ie, where impedance suddenly drops. This observation might possibly be explained by a preferred current channel mechanism. In dry skin, current does not enter the skin in a uniform fashion, but rather establishes discrete, preferred channels. The establishment of these channels appears to be a non-linear process. Possibly, the perception threshold voltage corresponds to the establishment of one or more discrete channels in which current is focussed, resulting in enhanced current density at a discrete location.

NUTE: Current entering the body through discrete channels was observed in a few volunteers. These channels are formed in areas where skin breaks are present, such as insect bites (several days old) or skin injury not fully healed. We observed very rapid localized reddening and heightened sensation at these points. However, in other volunteers, there was generalized reddening of that entire portion of the forearm in contact with the electrode. In the remaining volunteers, there were no visible effects.

GAMS: Have there been any tissue culture studies of skin's reaction to application of "low" voltage? Any corresponding biochemical, biophysical, cytological, histological, morphological studies in this regard? (Not including thermal effects.) I suggest undertaking such research.

NUTE: The purpose of my work was to ascertain whether a large accessible surface energized from a low-impedance source at a potential of up to 40 V peak created unacceptable sensations or reactions. It was during this investigation that I noted the phenomena reported in my paper. I too, am curious as to a satisfying explanation. I could imagine that if we knew more about this and similar electrically-induced phenomena, we could do more to protect against or treat the effects of electric shock.

A Five-Part Resistor-Capacitor Network for Measurement of Voltage and Current Levels Related To Electric Shock and Burns

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ABSTRACT

This paper discusses the development of a five-part equivalent body impedance and reaction network which can be used to more accurately relate leakage current and voltage measurements to electric shock than do conventional methods. Measurements of body impedance were made on people over a frequency range of 30Hz to 1 MHz, using four methods, to define body impedance values for various conditions of contact. The advantage of the network is that the current in the body impedance section is the actual current which would be expected if a person made the contact, regardless of source impedance, wave shape, frequency, or combination of mixed frequency currents.

Calculations of body response to voltage, using the network, show that the frequency of maximum electric shock from voltage contact lies between 500Hz and 3kHz instead of 50 to 60Hz. This effect was verified on several people with an "Involuntary Squeeze Test" which measured the voltage required for muscular contractions of the hand up to 20kHz. The squeeze point is a reference intensity of electric shock near the point of inability to let go.

Application of the network to mixed frequencies is discussed, and measurements on people in which 60Hz currents were mixed with currents at frequencies between 30Hz and 100kHz are presented. This data and a comparison of electric shock effects from sine and square waves indicate that the network peak indicated current is the value which most accurately relates to electric shock.

Information on leakage current burn related limits and their measurement with the five-part network is also included. The network actual current in mA RMS can be related to electric burns.

Key Words

Body impedance; reaction network; actual currents; indicated current; involuntary squeeze test; mixed frequency leakage currents.

An ongoing study of leakage current and electric shock hazards in Test and Measuring equipment, controllers and electronic thermometers has led to a series of measurements of body impedance covering the frequency range of 30Hz to 1MHz. The intent has been to develop a method whereby levels of current can be measured on accessible parts of equipment that would be the same as those encountered when a person contacts the equipment.

A three-part resistance-capacitance (RC) network shown as R1, C1, and R2 in Fig. 1, which closely approximates body impedance was derived from the measurements, and sets of values

were obtained to represent wet skin and dry skin in combination with large and small contact areas. Values of internal body resistance were also obtained from the measurements for hand-to-arm, hand-to-hand, and hand-to-foot current paths. The three-part network has been found useful for measurements of expected body currents from sources with either high or low impedance at frequencies up to 1MHz, the upper limit of testing. Measurements with the network compare reasonably with actual body measurements when voltage levels are below those which cause skin breakdown and for currents below burn levels.

A second RC network, R3 and C2, has been added to the body impedance network to compensate for the decrease in muscular reaction to current as frequency is increased. This compensation has been included in most leakage current measuring networks. The pole frequency at which $R=1/2\pi FC$ is chosen to be 700Hz in some networks and 1000Hz in others. The author uses a 700Hz pole frequency and believes it most accurately represents muscular reaction. This can be seen in Fig. 4 where curves A1 and A2 show actual current in R2 for a constant indicated current, V2/R2, of 0.5mA. Current A1,using the 700Hz pole, more closely follows the minimum perception level than does current A2 from a 1000Hz pole.

The combination of body impedance and reaction networks results in a five-part network which can be used to measure "actual currents" which would be expected if a person made the contact and "indicated currents" which are currents compensated for frequency effects on muscular reaction. Since the network represents body impedance, the current in R2 will be very close to actual body current regardless of the source impedance, wave shape, frequency, or combination of mixed frequency currents.

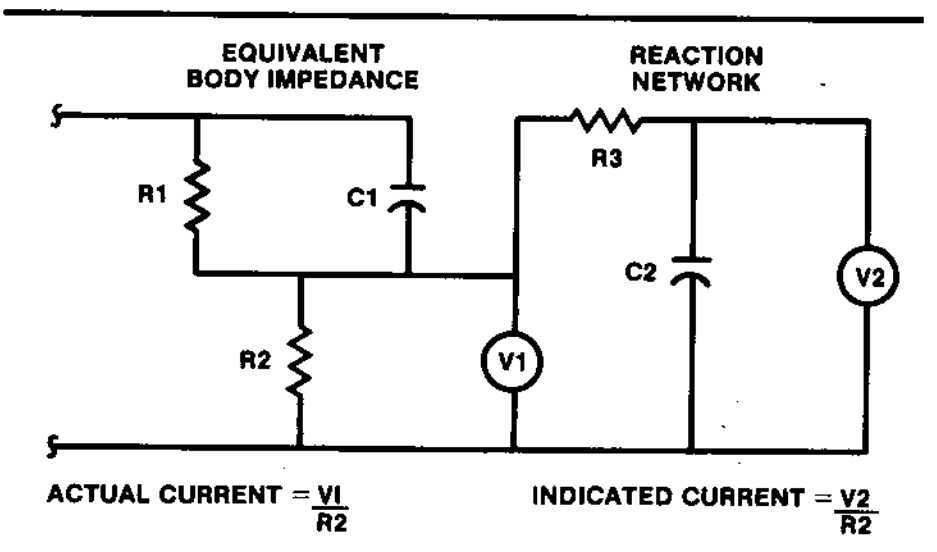

Fig. 1 Five-part network of body impedance with network to compensate for muscular reaction

In the network, R1 and C1 represent skin impedance. Under actual conditions two series skin contacts occur; however, both have been combined into one parallel RC network for the equivalent circuit. Resistor R2 represents internal body resistance. R3 and C2 are the compensating components which reduce V2 in proportion to the decrease in muscular reaction as frequency increases. Current V1/R2 therefore, is the actual current which would be expected if a person made contact with a circuit to which the network is connected. Indicated current V2/R2 is the value ordinarily measured by a leakage current network, such as 1500 ohm shunted by 0.15uF, in which a single indicated current level, for instance 0.5mA through the resistor, would represent the same muscular reaction over the frequency range of approximately 10Hz to 100kHz. Actual current for the case of 0.5mA at 60Hz would rise to 70mA at 100kHz while the indicated current remained at 0.5mA.

The advantage of the five-part network is that the actual current in R2 is the level to be expected if a person makes the contact. This is unlike conventional leakage current measuring networks which measure leakage current accurately only from high impedance sources at frequencies other than the 50 or 60Hz supply mains.

The conventional parallel RC networks have resistance of 1500 or 2000 ohms approximating body and skin resistance for the wet skin large surface area condition at 50 or 60Hz and capacitance to provide a pole for muscular reaction instead of skin capacitance. At high frequencies these networks have impedance lower than internal body resistance. The resistor methods of measuring leakage current, by contrast, have values greater than body resistance at high frequencies but are again correct at 50 or 60 Hz. Modern electronic equipments often have signal currents which add to or mix with supply mains leakage current which can be at any frequency, level, or impedance. Where this occurs whether it be from signal sources or switching power supplies, the five-part network can be used to obtain measurements of leakage currents that relate to body response.

Values for the body impedance network were obtained from measurements on people and have been plotted in Fig. 2 and Fig. 3. The use of impedance paper for the plots allows network values to be derived by inspection. Horizontal portions of curves are resistive while the 45° portions are capacitive. Values for networks approximating the limits of Fig. 2 and Fig. 3 and typical values used by the author for analysis are shown in Table 1.

TABLE 1 Values for the Five Part Body Impedance Network

NETWORK	R1	C1	R2	R3	C2	CONDITION
1	60K	0.007	800	10K	0.022	Finger contact, dry, Fig.2
2	12K	0.02	250	10K	0.022	Finger contact, wet, high pressure, Fig. 2
3	25K	0.05	400	10K	0.022	Gripping contact, dry, hand to hand or foot, Fig. 3
4	1.5K	0.50	200	10K	0.022	Gripping contact, wet hand to arm, Fig. 3
5	15K	0.02	250	10K	0.022	Near worse case small area contact, approx. 1 sq. cm
6	9.5K	0.20	250	10K	0.022	Typical dry gripping contact
7*	1.5K	0.22	250	10K	0.022	Typical wet gripping contact

Resistance shown in ohms

Capacitance shown in μF
R3/C2 muscular reaction pole at 723Hz
R3>>R2

R2 value of 250 represents internal resistance from hand to opposite shoulder

* Network 7 has been proposed for leakage current measurements.

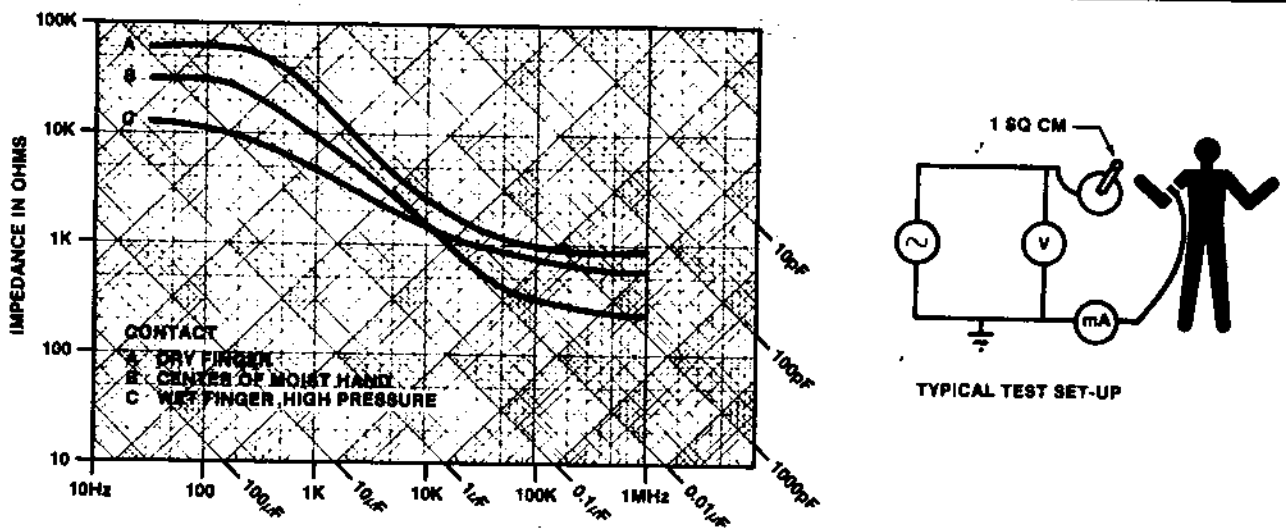

Fig. 2 Body impedance for 1 to 2 sq. cm contact at finger and hand to arm.

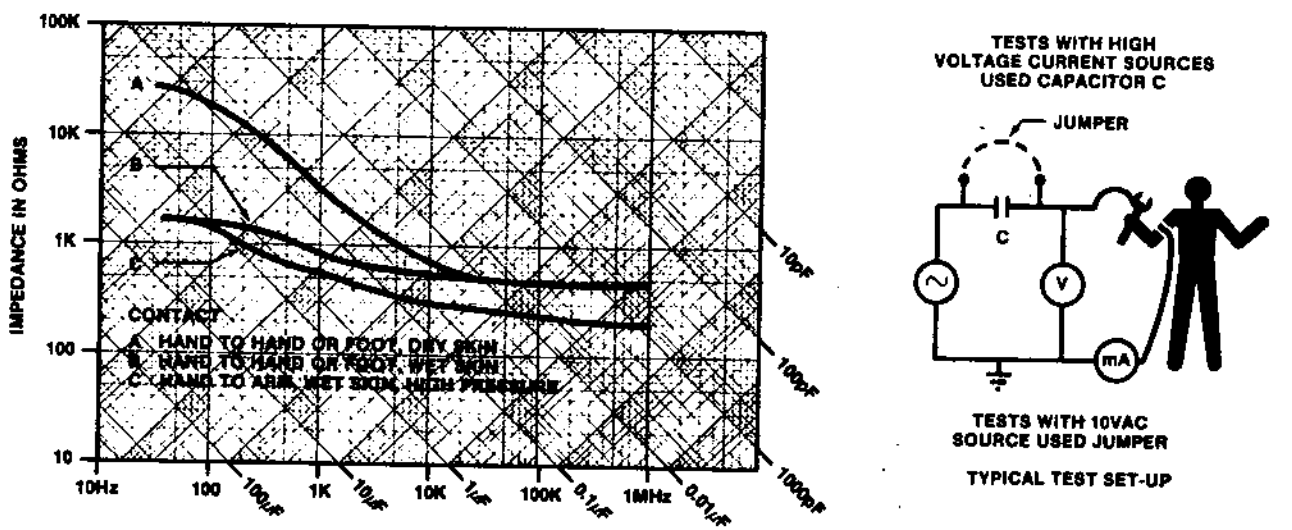

Fig. 3 Body impedance for hand gripping contact to arm, other hand, or foot.

Figures 2 and 3 show the upper and lower limits of impedance measured on five male subjects weighing 61 to 89kg and one female subject of 57kg. Figure 2 gives small area contact impedances for 1 to 2 square centimeter contacts on finger or hand while Fig. 3 shows impedance for the larger area hand gripping condition. Thirtysix sets of measurements were made, from which impedance was calculated using the methods and levels listed below.

1. Constant current — 0.5mA and 1.0mA over the frequency range.
2. Constant voltage — 10VAC between body contacts
3. Perception level currents — 0.5mA and 1mA through the resistor in a 1500Ω/0.15uf parallel leakage current network
4. Current near let-go — Three tests were done at 3.5mA indicated current from the leakage current network up to 100kHz. At 80 and 100kHz, 400mA actual current was held 3 seconds.

Body impedance was not dependent on the test method but was highly dependent on such factors as skin wetness, area of contact, pressure, and frequency of the source. Internal body resistance varied from 140 ohms between hand and forearm to 700 or 800 ohms when contact was moved to the end of the finger. Between hands the internal resistance was 400 to 500 ohms while hand to one foot measured 450 to 500 ohms.

When the body impedance networks were first derived from measurements using high impedance current sources, calculations on the network were made to determine the current from an applied voltage over a broad frequency range. Voltage of interest was 30VAC which in many safety standards is considered safe to touch. Current from the 30VAC source and for a 10VAC source are plotted in Fig. 4, which also shows perception and let-go currents for comparison. Calculated network currents are shown in dashed lines B and D while actual measurements on an individual for wet and dry hands are shown in solid lines C and E. These curves show that the network can be used to reasonably predict body currents from low voltage sources. It was observed on these plots that current from the 10VAC source approaches the let-go level near 1kHz. This indicates that a more severe muscular reaction will occur in the vicinity of 1kHz than will occur at lower frequencies such as 50 or 60Hz when the same voltage is applied. Calculations were then made to determine the voltage versus frequency that would be required to maintain a constant indicated current in the five-part network. A constant indicated current represents a level of constant muscular reaction; therefore, the voltage to achieve it indicates the body response to voltage. Calculations were made for both dry and wet skin using networks 6 and 7 from Table 1 starting with 30VAC. This predicted response of the body to voltage is plotted in Fig. 5 along with measurements made on persons using and Involutary Squeeze Test to verify the response.

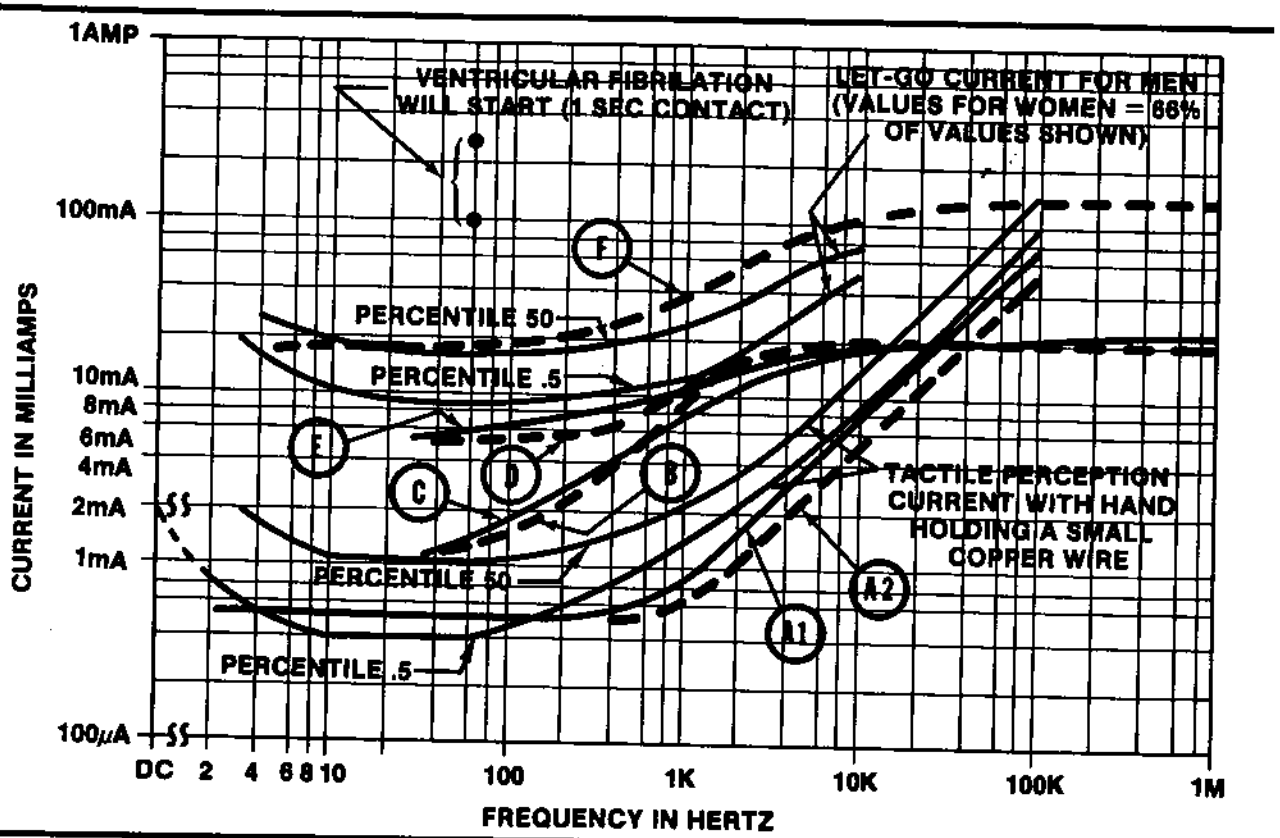

Fig. 4 Body current and pole frequency information plotted with perception and let-go currents for comparison.

A1 Actual current in a five-part network when indicated current is 0.5mA using 700Hz reaction pole frequency.
A2 Same as A1 except pole frequency is 1000Hz.
B Calculated current in a body impedance network representing dry hand-to-hand contact at 10VAC.
C Actual current measured on the subject represented by "B" with 10VAC applied.
D Calculated current in a body impedance network representing wet hand-to-hand contact at 10VAC.
E Actual current measured on the subject represented by "D" with 10VAC applied.
F Current in the wet hand body impedance network (No. 7 of Table 1) with 30VAC applied.

The Involutary Squeeze Test was devised to verify the frequency effect of body response to voltage. In this test the sqeeze point is a reference level of electric shock near the point of inability to let-go. To perform the test as depicted in Fig. 5, voltage was increased by the subject until a conductive, spring-loaded probe, which was held in the hand, was squeezed involuntarily due to muscular contractions from the current. The subject then stopped, data was recorded, and the voltage reduced to zero. This procedure was repeated for a series of measurements between 30Hz and 20kHz. The data clearly shows that voltage at frequencies in the vicinity of 500Hz to about 3kHz are the most severe for the body contact because the lowest voltage which forced the operator to squeeze the probe occured in that range. The involuntary squeeze test was performed on five people, including one female, with similar results.

This frequency effect of voltage differs from the commonly held, but incorrect, belief that voltage at supply mains frequencies of 50 or 60Hz is the most severe for body contact. The effect occurs because skin capacitance reduces impedance before reduced muscular reaction to the frequencies occurs. The belief concering 50 or 60Hz occurs because long-published curves of body reaction to electric current correctly show that the minimum current to cause a phenomenon such as "inability to let go" is near 50 or 60Hz. The response to applied voltage, however, is not the same.

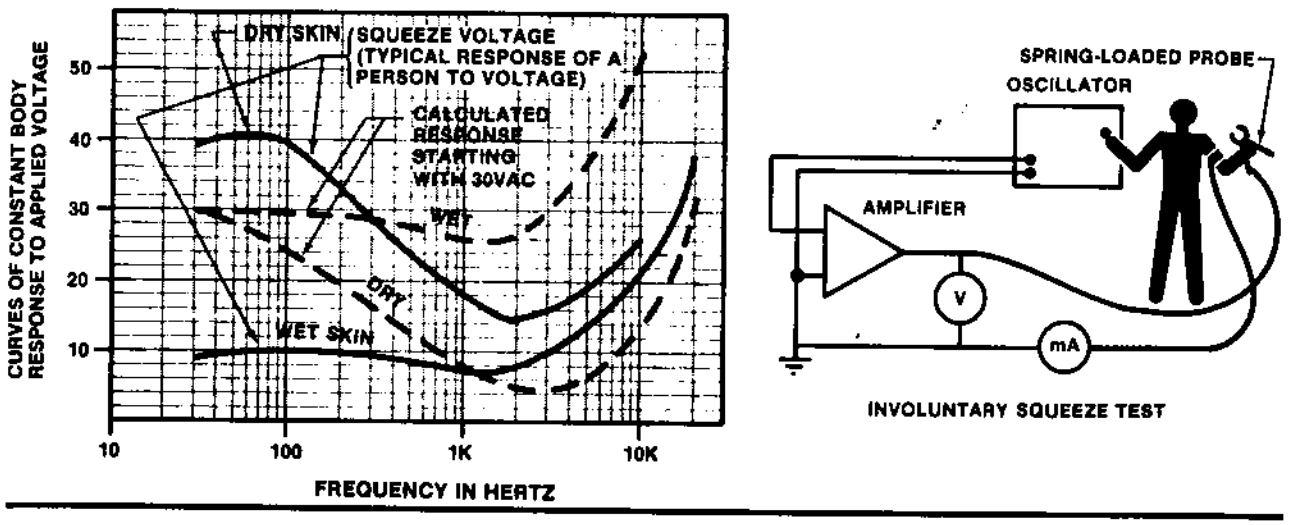

Fig. 5 Response of the body to applied voltage.

Another use for the five-part network is measurement of mixed frequency leakage currents which occur when signal currents in equipment such as AC Voltmeters or electronic thermometers mix with supply mains leakage currents. Switching power supplies also generate mixed frequency leakage currents.

The five-part network is ideal for measuring mixed frequencies because the body impedance network ensures that the actual current will be equal to body current from the two or more sources and the reaction network properly weights the mixed frequency components to yield a measurement that relates to electric shock.

Several tests have been conducted to verify that mixed frequency currents made with a network can be related to electric shock intensity. The necessary network is one compensated for muscular reaction. When the five-part network is used an additional advantage occurs in that the actual network current will equal expected body current regardless of source impedance and frequencies. Figure 6 describes a test in which 1mA of 60Hz was mixed with perception level currents from 30 Hz to 100kHz. This test was conducted on several people with very similar results. Data from a typical test is plotted in Fig. 6. Ideally, the 60Hz equivalent readings of Step 4 in the figure should exactly match either the RMS or peak level of Step 2. Actually, the 60Hz equivalent levels of peak current were always within 25% of Step 2 except for the 100kHz point and the RMS equivalent levels were within 36% of Step 2. All considered, these deviations are reasonable for shock prediction.

An analysis of the peak versus RMS readings in the test indicates that peak indicated current readings from the network would be preferred for this situation. The network measurement of 2.9mA peak is always somewhat higher or equal to the equivalent 60Hz shock level of Step 4. This is on the side of safety and the deviation of the peak 60Hz equivalent levels from the ideal is smaller than with RMS measurements. By contrast, the RMS network measurements produced values below the 60Hz equivalent shock levels, the wrong side from a safety standpoint. These characteristics were evident with each person tested for mixed frequency current response. An involuntary squeeze test which compared shock effects of sine and square waves has also shown that the peak indicated current most accurately relates to electric shock. Network indicated current from the sine and square waves had the same peak value at the squeeze point even though the rms levels differed up to 60% at frequencies below 100Hz for the dry skin case.

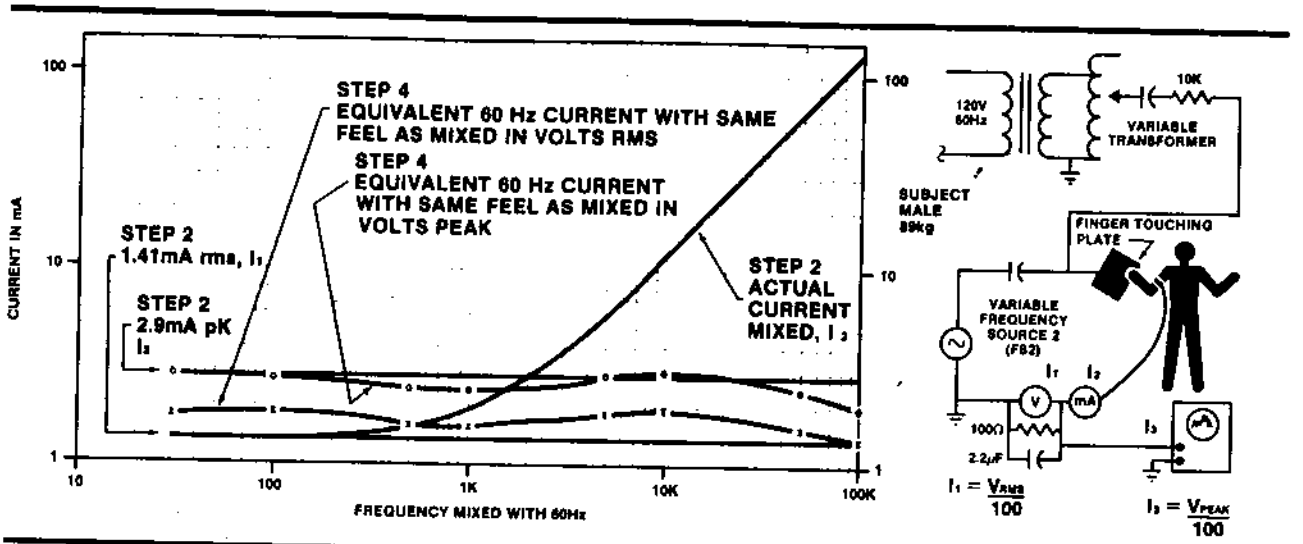

Fig. 6 Typical mixed frequency leakage current test.

Procedure

Step

1. **Adjust 60Hz to 1mA on I_1 and I_2.**
2. **Add current from FS2 until I_1 reads 1.41mA rms. Record I_1, I_2 and I_3.**
3. **Reduce FS2 to zero.**
4. **Increase the 60Hz current until the same feeling of shock intensity as with mixed currents. Record I_1, I_2 and I_3.**

The measurement of actual current V1/R2 in a five-part body impedance network can be compared directly with leakage current burn related limits. Generally burns occur when current densities exceed 300 to 400mA RMS per sq. cm. Small area touch burns of 0.2 sq. cm, therefore, can be expected at 60 to 80mA RMS. This corresponds closely to limits of 70mA RMS allowed at 100kHz in Safety Standards such as ANSI C39.5 and UL1244, and is somewhat higher that the 70mA peak level allowed in IEC Publication 348.

Burns are believed to occur at these current densities at any frequency, however, they are of secondary importance at low frequencies where the current levels risk fibrillation. Burns become of primary importance above 10kHz where the risk of fibrillation is reduced. Above 50kHz, or thereabouts, the tingling sensation of electric shock goes away and heating is the major effect of current through the body.

At frequencies where burns are of concern, body impedance is reduced by skin capacitance to levels near the internal body resistance. The body impedance network does the same. Greatest accuracy for small contact burns can be achieved with a network where R1 > 30k and C1 is about 0.004uf when the network impedance determines the current. However, since most burn current sources have additional impedance limiting through resistance or stray capacitance, a network with values for wet skin, large contact area such as network 7 of Table 1 gives satisfactory results. Network 7 reduces to the internal body impedance level at 3kHz compared to 100kHz for the very small area network. Burn current errors due to network 7 between 3kHz and 100kHz would be in the direction of safety.

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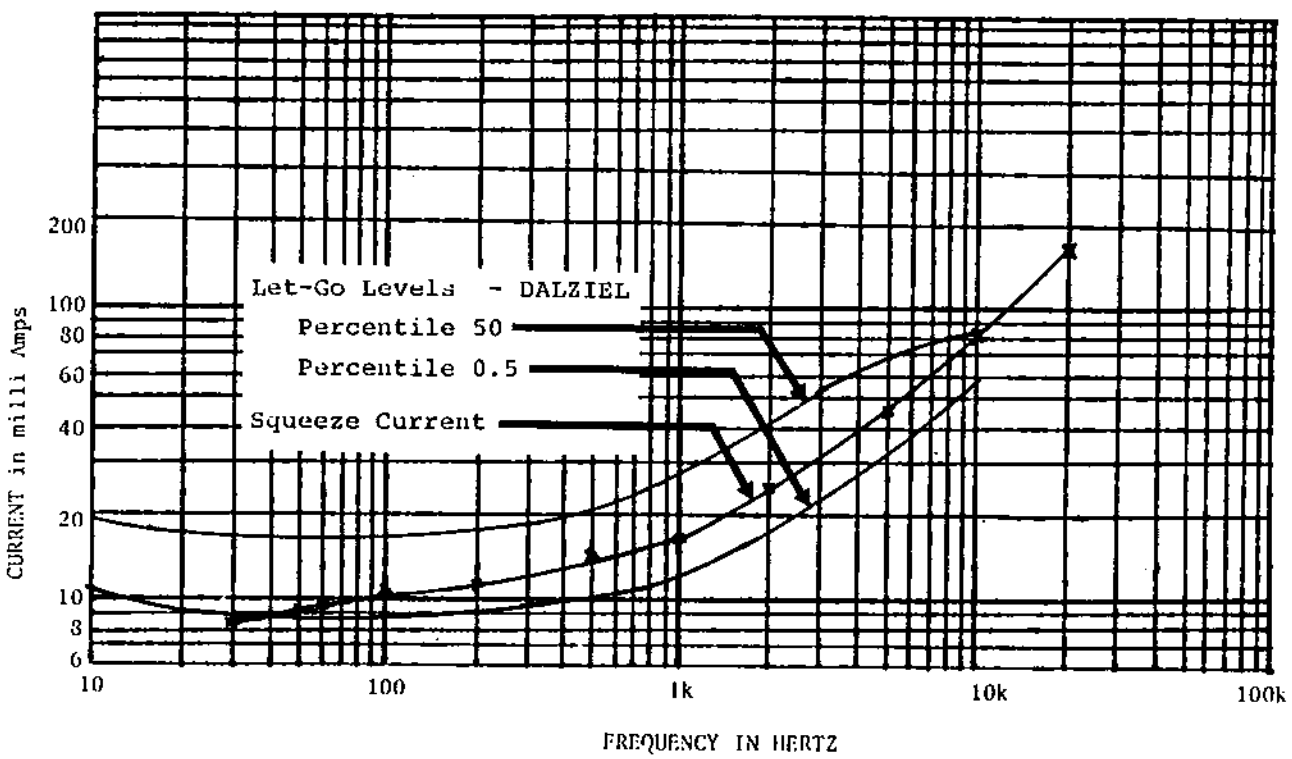
2. Underwriters Laboratories Inc. Development of test equipment and methods for measuring potentially lethal and otherwise damaging current levels. **Prepared for US Consumer Product Safety Commission, UL Project USNC-94, 79ME10520, May 1981.**

DISCUSSIONS

BRIDGES: (1) Would you compare your squeeze test results with Dalziel's let-go data? (2) How many subjects were involved in each series of tests?

HART:

(1) The Involuntary Squeeze test was devised as a reference level of electric shock intensity near the level of inability to let go. The method used to verify that the shock intensity remained the same, was to measure the current levels and compare them with the let-go levels of Dalziel (see Figure 7).



This current curve was measured on subject "D" and is typical of other subjects

Fig. 7 - Comparison of squeeze current with let-go levels of Dalziel.

A plot of the current in every case, for sine wave tests, falls in the vicinity of the 0.5 to 50 percentile let-go curves of Dalziel and has the same shape as the let-go curves. This verifies that shock intensity is the same at each frequency. Therefore, the plot of squeeze voltage (see Figure 8) represents the body response to voltage for the condition tested.

(2) Male 70 kg, dry hand; sine, square, and triangular waves.
Male 61 kg wet skin sine, square and triangle waves.
Male (wt not available) dry hand sine wave; wet skin sine wave.
Female 57 kg dry hand sine, square, triangular waves.
Male 89 kg wet skin sine, square, triangle waves.

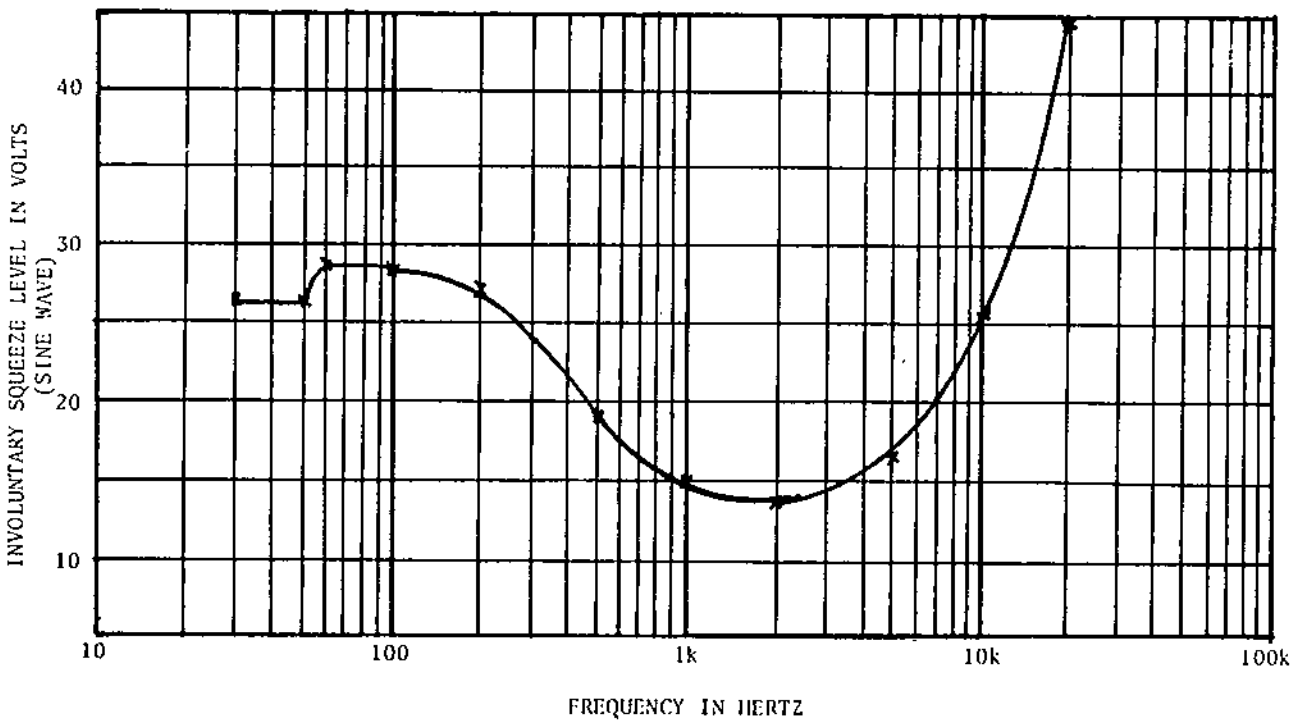
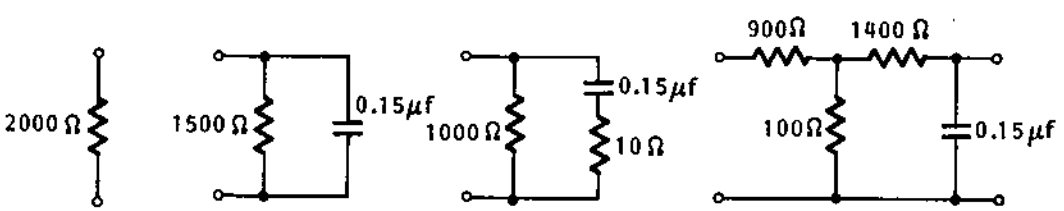


Fig. 8 - Squeeze voltage for subject "D".

OSMAN: Did you consider standard test loads of NEPA, AAMI, etc? If so, what are the advantages of yours over theirs?

HART: Four other leakage current measuring networks were considered before the proposal to use the five part network was investigated. These are:



The advantage of the five part network lies in the fact that the body impedance section will produce a current equal to that expected if a person touches the circuit regardless of source impedance, frequency (tested to 1 MHz), wave shape, or combination of mixed frequency sources. This actual current (v_1/R_2) can be compared directly with levels that cause electric burns. The reaction network will then weigh the various frequency components to produce an indicated current (v_2/R_2) that relates to electric shock intensity.

RESISTIVITY CHANGES OF TISSUE DURING THE APPLICATION OF INJURIOUS 60 HZ CURRENTS

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ABSTRACT

Changes in resistivity have been demonstrated with temperature alteration and tissue degradation. Previous studies indicate a -5 ohm/^{o}C. It is well known that elevated temperature over various periods of time produce tissue necrosis. A change in resistivity occurs during application of 60 Hz currents with a concomittant temperature rise. This study was designed to evaluate the time alteration of resistivity during application of 60 Hz currents to the living animal. Results in the living anesthetized dog demonstrate non-linear alterations in resistivity with tissue temperature elevation. The tissue resistivity is reduced with increasing temperature. It is also reduced by a constant elevated temperature with tissue damage. This study compares resistivity alterations with both tissue vitality and tissue temperature elevation. The tissue integrity was evaluated using high resolution nuclear magnetic resonance (NMR) spectroscopy.

KEYWORDS

Electrical injuries; current distribution; muscle resistivity; electric burning; temperature changes; nuclear magnetic resonance (NMR) spectroscopy; four-in-line electrode array; 60 Hz notch filter.

INTRODUCTION

The injuries caused by electricity have been increasing since the advent of commercial electric power. Results of a recent survey from the Consumer Product Safety Commission indicate more than 2400 patients suffering from electrical injuries were admitted to emergency care facilities in the United States during 1977. Studies of current distribution in the body have delineated the current pathways and the effects of the current on the tissue. (Sances, 1981a, 1981b, 1981c, 1983). Changes in tissue resistivity have been noted with changes in tissue vitality (Sances, 1981b; Chilbert, In Press-a, In Press-b).

The muscle resistivity following electric burning decreases as much as 70% (Chilbert, In Press-a). The changes induced by the passage of 60 Hz current can be monitored by the use of a 60 Hz notch filter and a four-in-line

electrode array during the application of injurious current levels to the experimental animal. Both the temperature and the integrity of tissue are important factors for determination of tissue resistivity; changes in either can alter the resistivity. In this study resistivity and temperature changes were monitored during the application of one ampere, 60 Hz current across the hindquarters of the dog. Nuclear magnetic resonance (NMR) spectroscopy of burned muscle was performed to delineate tissue vitality and compared to the final post burn resistivity measurements.

METHODS

Studies were conducted in 7 mongrel dogs, 20 to 30 kg, anesthetized with 11mg/kg sodium pentobarbital administered intravenously. All the dogs were intubated and maintained on a respirator. Arterial blood pressure and heart rate were monitored via femoral artery lines using an Abbott monitoring system (model FA-11).

Prior to insertion of the arterial line, a control tissue sample was excised from the gracilis muscle of the right hindlimb for NMR spectroscopy. The arterial line was then inserted in the femoral artery of the same limb. The left gracilis muscle was then exposed for control resistivity measurements. Seven regions along the length of the muscle were used for transverse (perpendicular to the muscle fibers) and longitudinal (parallel to the muscle fibers) resistivity measurements. Region I was the most distal and region VII was the most proximal.

Resistivity measurements were performed with a four-in-line electrode array having a 0.25 cm space between electrodes. The array is placed on the muscle surface and 100 microamperes of 70 Hz current are passed between the outer two electrodes and voltage is measured between the inner two electrodes. This method has been described in greater detail elsewhere (Sances, 1983). The current was delivered by a Hewlett-Packard model 204B oscillator. Current and voltage levels were measured using Simpson model 464D digital meters.

Following the control measurements, five Yellow-Springs Instruments thermistors, with a 0.1 sec time constant, were placed in regions I-V and VII. Copper bands, 1 cm wide, were placed proximal to the ankle on both hindlimbs, using a conducting jelly-electrode interface. One ampere of 60 Hz current was passed through the copper bands until a 60° C temperature was reached in the most distal muscle region (I), approximately 10 cm from the copper band. During passage of the current, the resistivity was monitored in the transverse direction of region I using the four-in-line array with a 60 Hz notch filter. Temperature and resistivity were recorded every 30 seconds during the current application.

After cessation of the one ampere current, resistivity was monitored in region I until the temperature reached control values. Another set of transverse and longitudinal measurements were then made in all the regions. Finally, sections of muscle were removed for NMR spectroscopy from regions I, IV, and VII; after which the dogs were euthanized with an overdose of barbiturates.

Calculation of the resistivity transverse to the muscle fibers was made using the formula presented by Rush (Rush, 1962):

$$\rho_T = 2\pi a V_L / I \quad \text{ohm-cm} \qquad (1)$$

Resistivity in the longitudinal muscle direction was determined by:

$$\rho_L = (V_T/V_L)^2 \rho_T \quad \text{ohm-cm} \qquad (2)$$

I is the applied current (mA), V_L is the measured voltage in the longitudinal muscle direction (mV), V_T is the voltage in the transverse muscle direction (mV), and a is the electrode spacing (cm). Approximation of the longitudinal resistivity change from the voltage measured in the transverse direction during the application of the one amp current is obtained from the following proportional relationship:

$$\Delta\rho_L \propto \Delta V_T$$

The derivation is given in Appendix 1.

RESULTS

The temperature measured in regions I, II, III, IV, V, and VII show a typical S-curve rise with an exponential decline. Fig. 1a shows the curves for regions I, II,III, IV, V, VI, and VII; note that each shows the same rise and decline characteristics. The maximum temperature of 60° was measured in the distal region (I), and the maximum temperatures in the other regions decreased as the distance from the current electrode increased. Typically, region IV reached 44° C and region VII reached 40° C (Table 1).

The resistivity initially increased with the application of one ampere of current. The lower limbs contracted tetanically as did the abdominal muscles. The resistivity declined from the initial measured value through both the temperature increase and decrease in region I. At 60° C the resistivity was at 50% of control values. After current cessation and cooling, the resistivity decreased to 30% of control in the longitudinal direction (Fig. 1b). The resistivity decreased less as the distance from the current electrode increased. The decrease in resistivity varied with the maximum temperature in the region. Table 1 compares resistivity changes with peak temperatures.

Tissue samples removed for NMR spectroscopy show changes in the quantities of phosphocreatine, adenosine triphosphate (ATP), adenosine diphosphate (ADP), nicotinamide-adenine dinucleotide (NAD), inorganic phosphate and monophosphate esters (Fig. 2). Phosphocreatinine, ATP, ADP and NAD are completely absent from the postburn tissues that had reached 60°C, whereas regions of cooler temperature demonstrate graded decreases of these metabolites as a function of the temperature attained. In each case, there is an increase in the concentrations of inorganic phosphate and monophosphate esters that is commensurate with the loss of phosphocreatine, ATP, ADP and NAD.

CONCLUSIONS

The changes in temperature with time are typical of heating and cooling curves seen in other studies (Henriques, 1947a, 1947b). Tissue damage seen at the higher temperature levels is similar to the dermal studies of Moritz and Henriques (Moritz, 1947a, 1947b). The NMR data indicate that electrical burns result in hydrolysis of phosphocreatine, ATP, ADP and NAD with formation of inorganic phosphate, some monophosphate esters and the non-phosphorylated counterparts. From knowledge of the relative concentrations of these metabolites one can ascertain the viability of the tissue (Norwood et al,

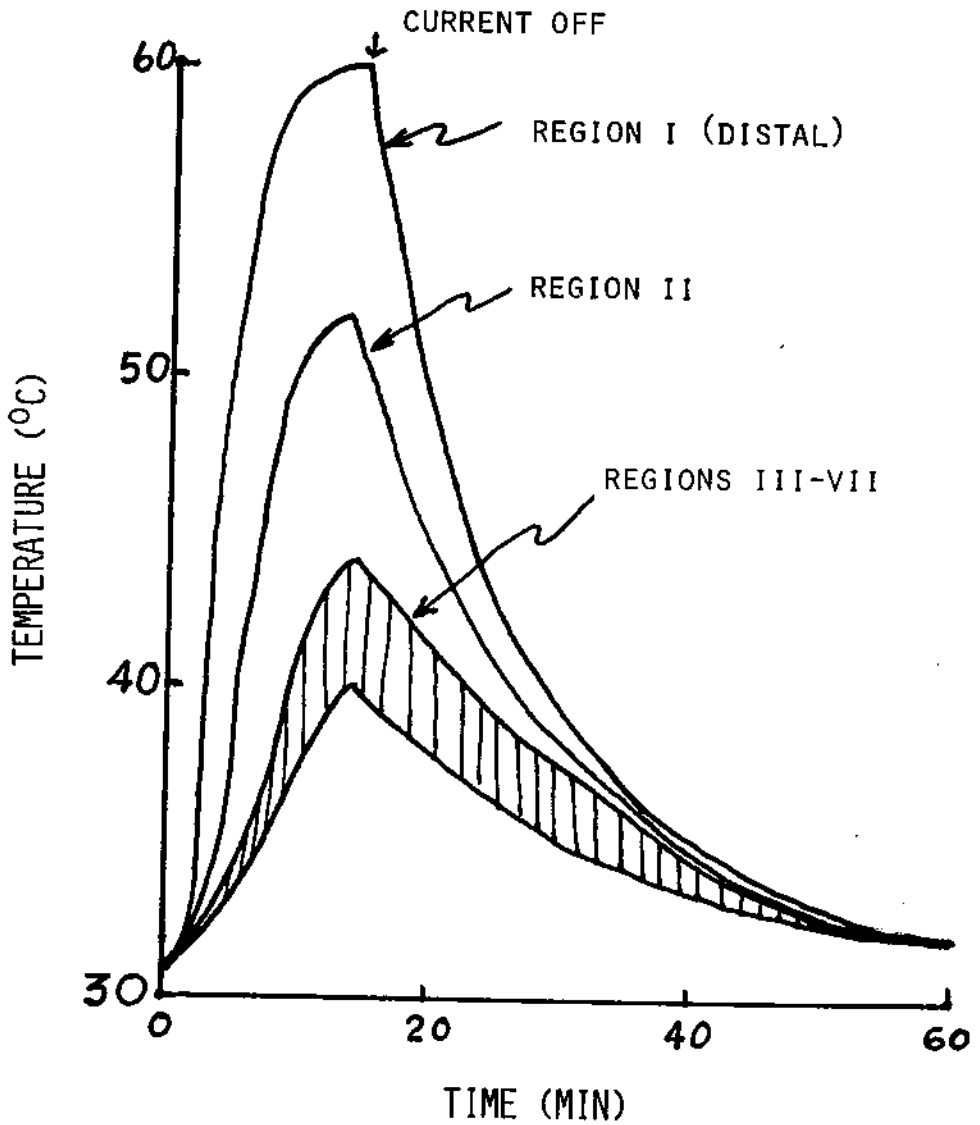

Fig. 1a: Temperature change of gracilis muscle during the application of one ampere, 60 Hz current applied between the hind limbs of the dog. Region I is muscle nearest the current electrode and region VII has the greatest distance. The temperatures in regions III-VII were randomly distributed within the bounds.

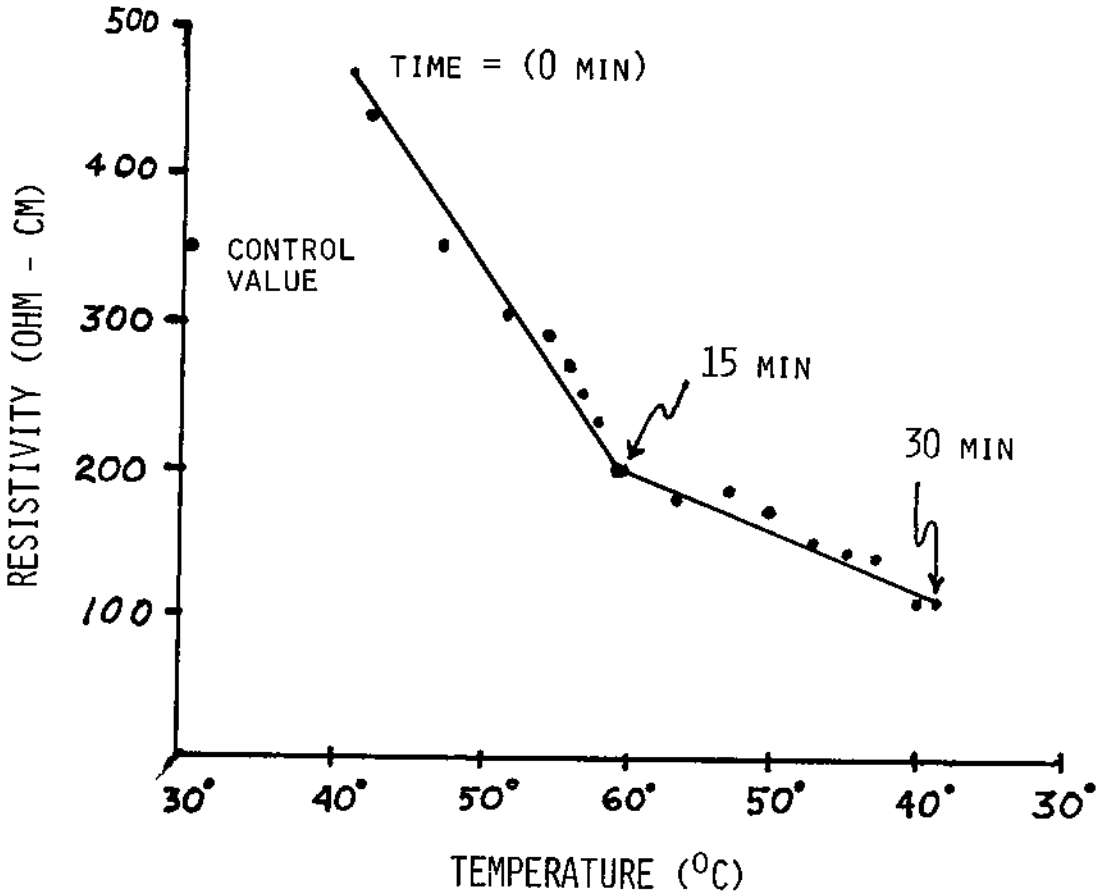

Fig. 1b: The longitudinal resistivity estimated from measurements of the transverse voltage compared with the rise and decline of the temperature in region I. Note that the resistivity continues to decrease while cooling occurs in the muscle.

1979). Tissues that completely lack phosphocreatine and ATP are not likely to resuscitate, whereas tissues that still contain these metabolites though at reduced levels are likely to retain viability. Comparing the time-temperature curves to the NMR results, one notes that some alterations occur in all the postburn regions tested but also that the extent of damage depends on the temperature attained in the various tissue regions. Regions of lower peak temperature still contain phosphocreatine and ATP, and thus should retain viability.

TABLE 1 Changes in Resistivity are Shown with the Peak Temperature of the Seven Measurement Regions in the Gracilis Muscle. Total Reduction of ATP, ADP, NAD, and Phosphocreatne Occurred in Regions I and II While Only Reduced in Regions III-IV, with Region III Being More Reduced Than Region VII.

	Gracilis Muscle	Control Resistivity (Ohm-Cm)		Post Burn Resistivity (Ohm-Cm)		Peak Temperature ^{o} C
		Long.	Trans.	Long.	Trans.	
Distal	I	347	912	115	151	60
	II	332	910	163	254	52
	III	325	924	145	312	46
Middle	IV	360	885	140	402	44
	V	296	951	170	538	43
	VI	339	943	257	597	42
Proximal	VII	388	894	330	750	40

Resistivity in region I is reduced to 17% in the transverse direction and to 32% in the longitudinal direction from the control values. In contrast, region VII shows only a 16% drop from control. Parallelling the results of the NMR to the resistivity changes suggests that the regions with peak temperatures less than 45^{o} C should retain viability.

Resistivity monitored during the application of 1 ampere of 60 Hz current delineates the pathologic and thermal effects. Although both parameters are inseparable, the pathologic changes during cooling have the greatest bearing on the final resistivity value. During the rise in temperature, the resistivity decreases because of both temperature and pathologic changes. Many have shown that resistivity decreases with increasing temperature (Geddes, 1967; Chilbert, In Press-b; Crile, 1922; Galeotti, 1902; Schwan, 1955; Swatland, 1980). Gross histologic abnormalities seen in electrically injured tissue have been correlated with large reductions in resistivity (Chilbert, In Press-a). During the decline of the tissue temperature, the resistivity should increase, however continuing pathologic changes cause a further drop in resistivity.

Measurements of resistivity during the application of injurious current levels demonstrates the change and indicates an overall decrease in the total body impedance. Simultaneous measurement of the electric field and resistivity could show any alteration in the current distribution. This study has shown the resistivity trend with temperature.

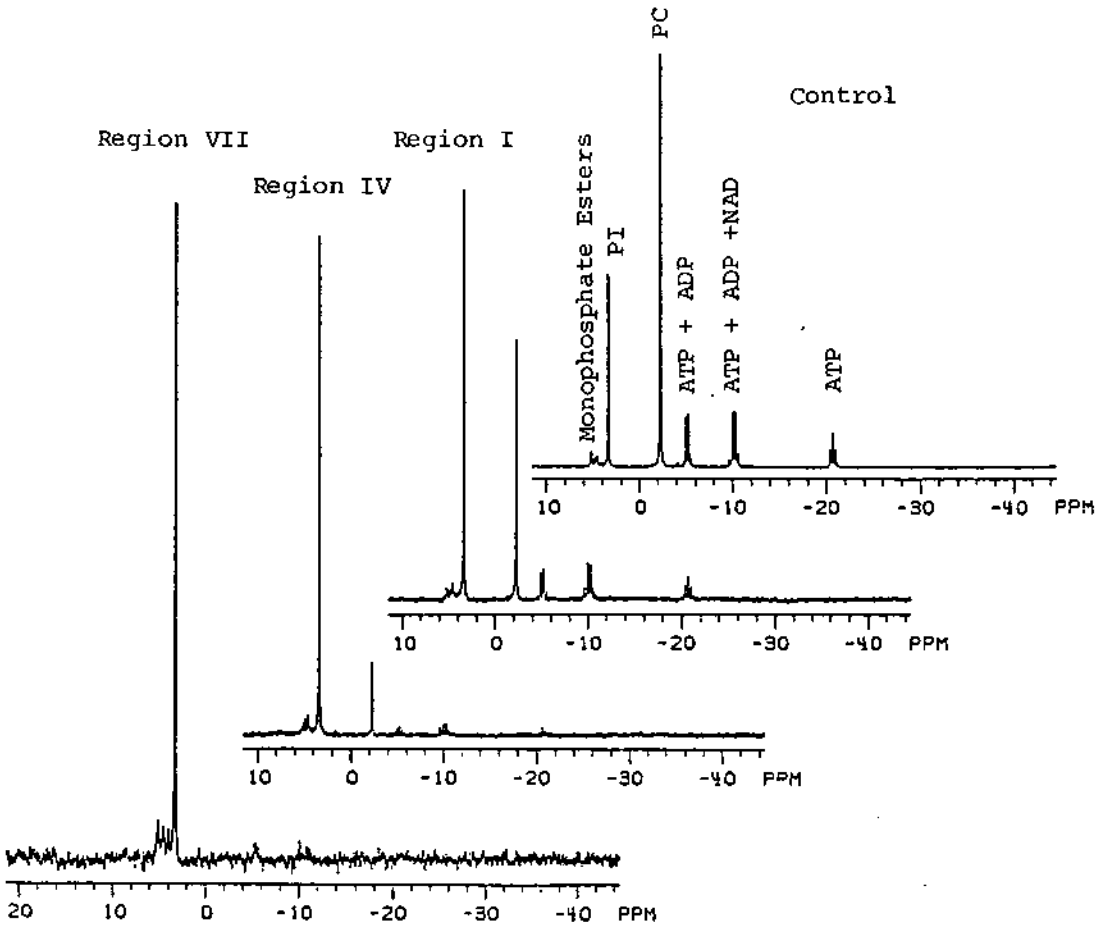

Fig. 2: ^{31}P NMR spectra of perchloric acid extracts of muscle: a-postburn sample of Region I; b-postburn sample of Region IV; c-postburn sample of Region VII; d-preburn control. Region I is associated with a 60°C temperature and a 68% decrease in longitudinal muscle resistivity, Region IV is associated with a 44°C temperature and a 60% decrease in resisitivity and Region VII is associated with a 40°C temperature and a 16% drop in resistivity. ATP-adenosine triphosphate; ADP-adenosine diphosphate; PC-phosphocreatine; PI-inorganic phosphate; NAD-nicotinamide-adenine dinucleotide. MONOPHOSPHATE ESTERES include adenosine monophosphate, surgar phosphates and other nucleoside monophosphates. Spectral assignments are those of Barany and Glonek (1982). When compared with the preburn control (d), the burned tissue exhibits reduced concentrations of PC, ATP, ADP and NAD with concommitant increased concentrations of PI and monophosphate esters.

Acknowledgment
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Appendix 1

From the equations 1 and 2, one gets the following by substituting 1 into 2:

$$\rho_L = \frac{(V_T^2)}{V_L^2} \frac{2\pi a}{I} V_L \quad \text{or} \quad \rho_L = (V_T/V_L) \frac{2\pi a}{I} V_T$$

Experimentally one finds that the percent change in the measured voltages are approximately the same:

$$\Delta\,\%\ V_T = \Delta\,\%\ V_L$$

therefore V_T/V_L can be considered constant with $2\pi a/I$, hence:

$$\rho_L \propto V_T \quad \text{or} \quad \Delta\rho_L \propto \Delta V_T$$

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AN "EQUIVALENT VOLTAGE" FOR SINUSOIDAL AND NON-SINUSOIDAL VOLTAGE WAVEFORM

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ABSTRACT

It is well known that the frequency and waveshape of an applied voltage are important in determining the current waveform which passes through a human body, and it is the current that determines whether an individual can let-go of the energized conductor. The frequency dependence of both the body impedance and the human sensitivity to current complicate the task of determining safe voltage levels for arbitrary ac voltage waveforms. The "equivalent voltage" approach described here translates an arbitrary ac voltage waveform into an "equivalent" (from the standpoint of causing let-go) 60 Hz wave. Two different voltage waveforms with the same equivalent voltage are equally likely to produce a "can't-let-go" condition. The equivalent voltage concept proposed here permits retention of familiar 60 Hz safe voltage limits provided these limits are applied to the equivalent voltage.

The equivalent voltage is the product of the peak voltage of the waveform and a weighting function. The weighting function for sinusoids is composed of two factors: the frequency-dependent impedance of the human body, and a measure of the relative sensitivity of the human let-go response to sinusoidal currents of different frequencies. Non-sinusoidal voltage waveforms are treated by appropriately summing the equivalent voltages of their sinusoidal components. Dalziel and others have demonstrated that in some cases of superimposed ac signals, the peak current is the relevant measure of the current. A generalized measure of the current waveform is introduced which is consistent with both the peak current concept and the varying sensitivity to different frequencies. The application of this concept to complex voltage waveforms is illustrated for the case of a square wave.

KEYWORDS

Human body impedance; frequency dependence; let-go current thresholds; safe voltage levels; digital voltage waveforms.

INTRODUCTION

Historically, telephone systems have been repaired, reconfigured and maintained while the telephone conductors were continuously electrically energized. Since these systems are powered by low-level dc voltages, the hazard associated with such exposure has been limited. In the future, however, the transmission of frequency-multiplexed and digital-type signals over the telephone networks could result in increased exposure to higher-frequency voltage waveforms. Owing to the frequency-dependence of both the human body impedance and human current sensitivities, safe voltage limits based upon 60 Hz sinusoidal excitation are inappropriate for the higher-frequency, non-sinusoidal waveforms. This paper describes an approach to extrapolating safe voltage limits for 60 Hz sinusoids to higher frequency or non-sinusoidal waveforms. (For the purposes of this paper, the criterion for a "safe voltage level" is taken as avoiding currents above the let-go level.) This approach defines an equivalent voltage which is the product of the peak voltage V_p of the waveform in question and a weighting factor W. The weighting factor depends upon the waveform, the frequency dependence of the human body impedance and the sensitivity to currents of different frequencies. Assuming a determination has been made as to the level of 60 Hz voltage which is acceptable, that same level can be applied to the equivalent voltage.

At those frequencies at which the body impedance is low or the current sensitivity is high relative to 60 Hz, the weighting factor is greater than one. Accordingly, the allowed peak voltage must be diminished relative to that permitted at 60 Hz. The primary advantage of this approach, aside from retaining familiar 60 Hz safe voltage limits, is that for signals composed of more than one frequency, appropriately summing the equivalent voltages of each component yields an equivalent voltage for the composite signal.

The definition of the weighting factor W for sinusoidal waveforms is straightforward and is described first. The extension of these results to non-sinusoidal waveforms is less direct and is addressed in the last section.

SINUSOIDAL VOLTAGE WEIGHTING FACTOR

Two factors comprise the weighting factor W: the first factor, z(f), describes the relative decrease of total body impedance and the second factor m(f) describes the rise of the current threshold of the let-go response. We turn first to z(f).

Numerous investigators from Freiberger in 1934 to the present have addressed the frequency-dependence of the total body impedance. Figures 1 and 2 present the results of our measurements of the complex impedance Z(f) versus frequency f for the hand-to-hand current path with dry, full-hand contacts (approximate contact area of 80 cm^2 on each palm). For trained personnel, this path and contact represent a

reasonable worst case. The equivalent voltage proposed here is premised on this case and is not appropriate for more extreme contacts (full immersion, chest area contact, etc.) Ten subjects were tested. In Figure 1, the magnitude of the impedance at frequency f is shown normalized relative to the magnitude at the lowest frequency (here 5 Hz) and is referred to as the normalized impedance $z(f) = |Z(f)/Z(5\ Hz)|$. The data points represent the mean plus and minus one standard deviation of resulting measurements. The normalized impedance provides a measure of the average reduction in the total body impedance versus frequency. Figure 2 illustrates the corresponding phase shift versus frequency.

An analytic description of the frequency dependence of the total body impedance was obtained by fitting the frequency dependence of the Freiberger equivalent circuit FEC shown in Figure 3 to the average normalized impedance. The resulting expression for the normalized impedance is given by

$$z(f) = \frac{|Z(f)|}{|Z(5)|} = \left| \frac{1 + (f/f_1)^2}{1 + (f/f_2)^2} \right|^{1/2} \qquad (1)$$

where $f_1 = 930$ Hz and $f_2 = 65$ Hz. The frequency-dependence of Equation (1) is illustrated in Figure 1. This basic model can be extended to other contact areas by adjusting the values of f_1 and f_2. In addition to the replicating the body impedance in the frequency domain, the equivalent circuit shown in Figure 3 has been demonstrated to approximate the temporal response of the human body to more complex waveforms (triangular, square wave) in the range of a few tens of volts from both voltage sources and current sources. Figure 4 shows a comparison of the current waveforms resulting from a voltage square wave applied to an FEC and a human subject. The subject here made small area contacts (fingertip) with the voltage source and the FEC was adjusted as indicated above to reflect the reduced contact area. Although the total body impedance is known to exhibit significant non-linearity at large voltage and current levels, the non-linearity is sufficiently small at the levels in Figure 4 that the linear FEC reproduces the current waveform with reasonable fidelity.

The second factor which contributes to the overall weighting factor describes the variation of the let-go current threshold with frequency. The let-go current threshold has been found (Dalziel, Ogden, Abbott, 1943) to increase with the frequency, that is, high frequency currents must be larger to produce the same effect. Neglecting the very-low frequency ($f < 10$ Hz) rise in the threshold, the let-go current threshold at frequency f, I(f), may be approximated by the following expression

$$I(f) = I_0 m(f) = I_0(1+f/2200\ Hz) \qquad 10\ Hz < f < 10\ kHz\ . \qquad (2)$$

This approximation is illustrated in Figure 5 by a comparison of (2) and the threshold of current at which 99.5% of the population can let-go as reported in Dalziel, Ogden, and Abbott (1943).

If (2) were the only frequency effect, the voltage limit could be allowed to rise with frequency proportional to m(f). However, since the body impedance diminishes as the frequency increases, the voltage limit must take both of these frequency effects into account. In general we may write (for frequency f)

$$V(f) = |Z(f)|I(f) \ . \tag{3}$$

where V(f) and I(f) represent the magnitude of the voltage and current, respectively. Given a safe voltage limit at one frequency, say 60 Hz, knowledge of (2) and the frequency dependence of the electrical impedance of the body permits the determination of the correspondingly safe voltage at any other frequency. The power-frequency voltage limits satisfy

$$V_{LIMIT} = V(60) = |Z(60)|I(60) \ . \tag{4}$$

Dividing (4) by (3) and rearranging, we find

$$V_{LIMIT} = V(f)\left|\frac{Z(60)}{Z(f)}\right| \frac{I(60)}{I(f)} \tag{5}$$

or, from (1) and (2)

$$V_{LIMIT} = V(f)\left|\frac{z(60)}{z(f)}\right| \frac{m(60)}{m(f)} \ . \tag{6}$$

the quantity on the right hand side of (6) is in a sense equivalent to V_{LIMIT}. That is, the current produced will result in an equal likelihood of inability to release. The right hand side of (6) is the equivalent voltage and permits the retention of the frequency-independent voltage limit V_{LIMIT} provided the limit now applies to the equivalent voltage V_e defined below. In (6), the constant factors z(60), from (1), and m(60), from (2), may be combined into a single constant. The equivalent voltage V_e of a sinusoidal signal of V (peak volts) at frequency f is

$$V_e = V\left|0.75\left|\frac{1+(f/f_2)^2}{1+(f/f_1)^2}\right|^{1/2} (1+f/2200)^{-1}\right| \tag{7}$$

$$= VW(f)$$

where

$$f_1 = 930 \text{ Hz} \quad \text{and} \quad f_2 = 65 \text{ Hz} \quad . \tag{8}$$

The values of f_1 and f_2 in (7) are the values for large area contacts (930 Hz and 65 Hz, respectively). The values for large area contacts were chosen to be consistent with the fact that most voltage limits conservatively assume a large area contact. A plot of the weighting function W(f) (term in brackets in (7)) versus frequency is given in Figure 6. Where W(f) is greater than 1, the actual voltage must be reduced in order for the equivalent voltage to satisfy (6). Observe that for power frequency, the equivalent voltage and the actual peak voltage are identical.

NON-SINUSOIDAL VOLTAGE WEIGHTING FACTOR

As written above, W(f) is satisfactory for single frequency signals. However, for more complex voltage waveforms, the equivalent circuit shown in Figure 3 and described by z(f) in (1) results in a non-sinusoidal current waveform. Assessing the let-go hazard posed by non-sinusoidal currents is not straightforward. There is, however, some guidance available. For low frequency signals ($m(f) \simeq 1$), Dalziel and others (1941,1943) have shown that the peak current is the relevant measure of superimposed current waveforms. But a constant peak current is not consistent with (2), or with the measurement of human sensitivities to periodic pulse currents by Osypka (1968). Osypka demonstrated that as the width of a dc current pulse is decreased (at a constant repetition rate of 1 Hz), the peak current necessary to evoke a variety of responses increased. How then may one treat complex voltage waveforms? Fourier decomposition of a voltage of a given time-varying voltage V(t), yields a spectrum of voltage sinusoids $\tilde{V}(f)$ where

$$\tilde{V}(f) = \int_{-\infty}^{\infty} V(t) \exp(-j2\pi ft)\, dt \quad . \tag{9}$$

For each frequency component, an equivalent voltage may be defined (7) which is proportional to the hazard posed by the current produced by that component. Simply summing the magnitudes of the equivalent voltages provides an acceptable measure of multi-frequency voltages when no specific phase relationship exists between frequency components. However, a simple summation of magnitudes may be a conservative measure of a coherent signal. Therefore, a more appropriate measure of multi-frequency signals which takes into account the relative phases of the frequency components and the phase shifts introduced by the body impedance may be defined as below

$$V_e = \text{peak}\left|\int_{-\infty}^{\infty} \tilde{V}(f)\tilde{W}(f) \exp(j2\pi ft)\, df\right| \tag{10}$$

where $\tilde{W}(f) = 0.75 \frac{1+j(f/65)}{1+j(f/930)} (1+|f|/200)^{-1}$ and $\tilde{V}(f)$ is defined in (9). This measure of the equivalent voltage is consistent with both the peak current measure of let-go current and the single-frequency variation of the current threshold (2). For signals containing appreciable low frequency components ($f < 6$ Hz), (2) and hence (7) and (10) could be

modified to reflect the low frequency rise in the let-go current threshold. Similarly, to accommodate signals with appreciable spectral content above 10 kHz (where information on let-go thresholds is unavailable), a conservative approach should dictate freezing W(f) above 10 kHz to its value at 10 kHz.

As an illustration of the application of (10) to a non-sinusoidal voltage, we consider the case of a square wave of voltage of period T and fundamental frequency $f_s = 1/T$:

$$V(t) = \begin{cases} +1 & nT < t \leq (n + 1/2)T \\ -1 & (n + 1/2)T < t \leq nT \end{cases} \quad (11)$$

The evaluation of (10) for square waves of various fundamental frequencies (11) can be translated directly into a weighting function for square waves. This weighting function for square waves is plotted versus frequency in Figure 6. The square voltage wave produces spikes of current through the body which result in a substantially larger weighting function for a square wave as compared to a sinusoid of the same period.

The approach in (10) is generally applicable to arbitrary voltage waveforms, although above 10 kHz, information on let-go currents is unavailable. The theoretical extension of the known current thresholds to the arbitrary current waveform remains an area of uncertainty. Further empirical investigation of the human let-go sensitivities to non-sinusoidal current waveforms is desirable in order to judge the appropriateness of the equivalent voltage approach.

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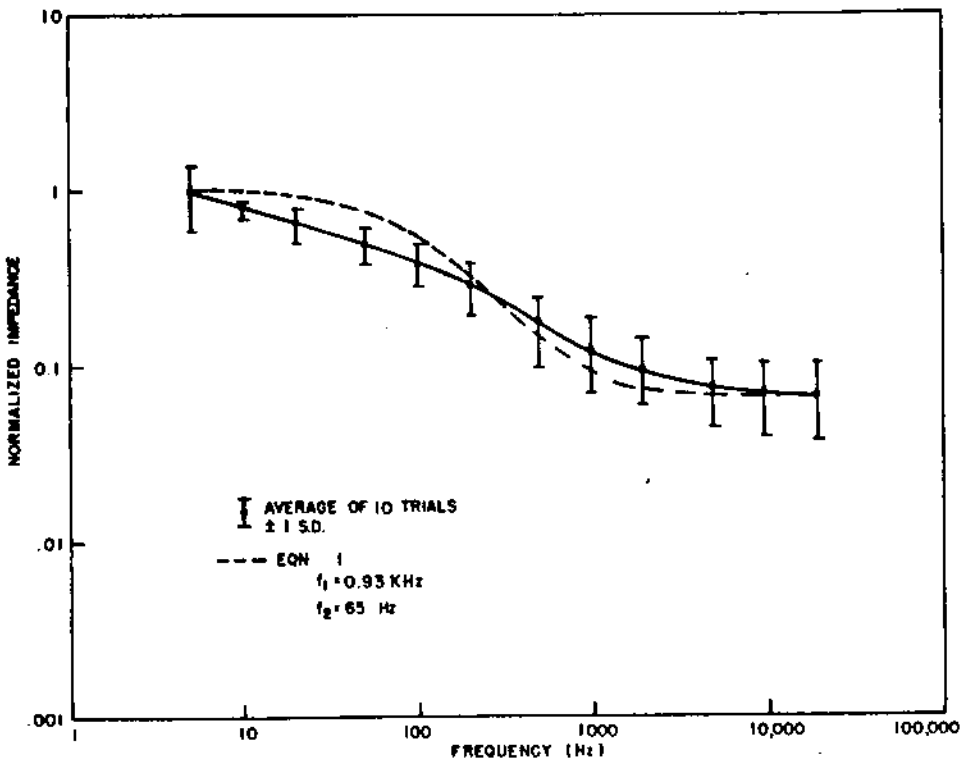


FIG. 1 NORMALIZED BODY IMPEDANCE (LARGE AREA CONTACTS) AS A FUNCTION OF FREQUENCY, DATA AND APPROXIMATION

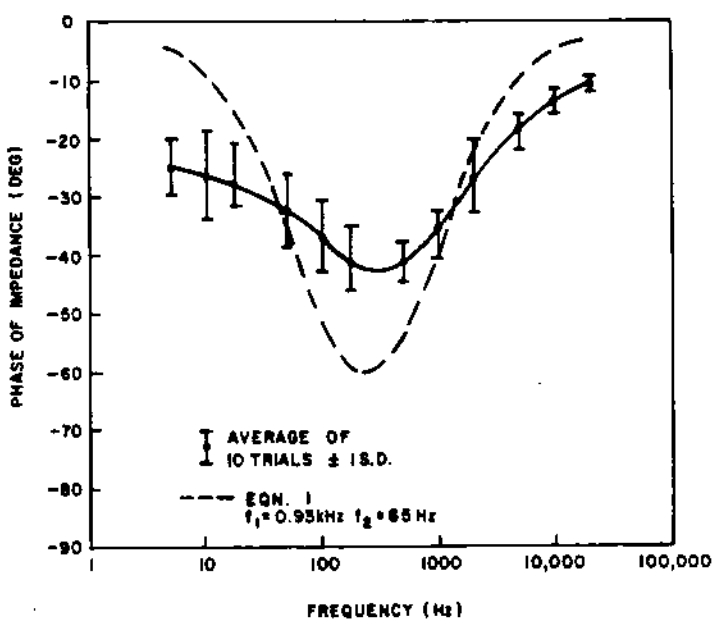


FIG. 2 PHASE ANGLE OF BODY IMPEDANCE (LARGE AREA CONTACTS) AS A FUNCTION OF FREQUENCY, DATA AND APPROXIMATION.

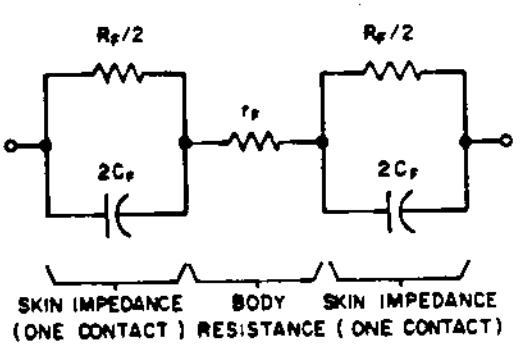
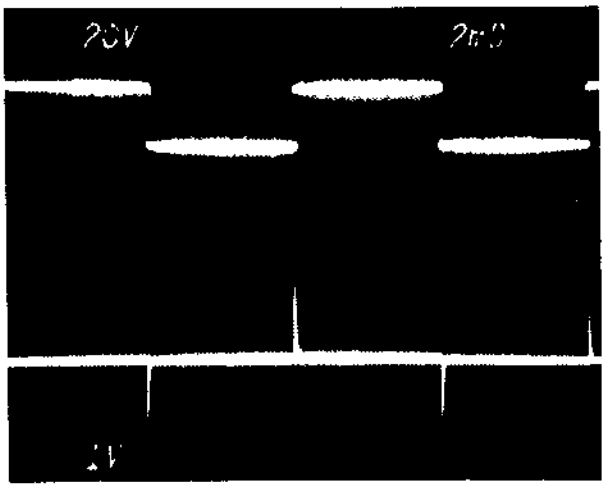


FIG 3 DISCRETE COMPONENT MODEL OF THE TOTAL BODY IMPEDANCE

(a) FEC



(b) SUBJECT

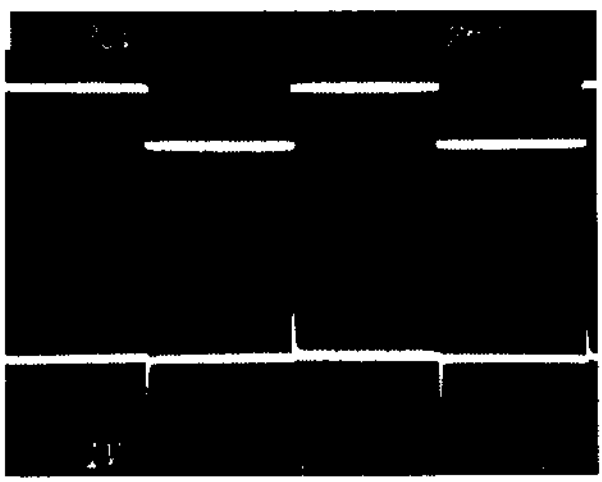


FIG. 4 A SQUARE WAVE FROM A VOLTAGE SOURCE (UPPER TRACES) PRODUCES NEARLY IDENTICAL CURRENT WAVEFORMS (LOWER TRACES) THROUGH (a) THE FEC AND (b) THE SUBJECT.

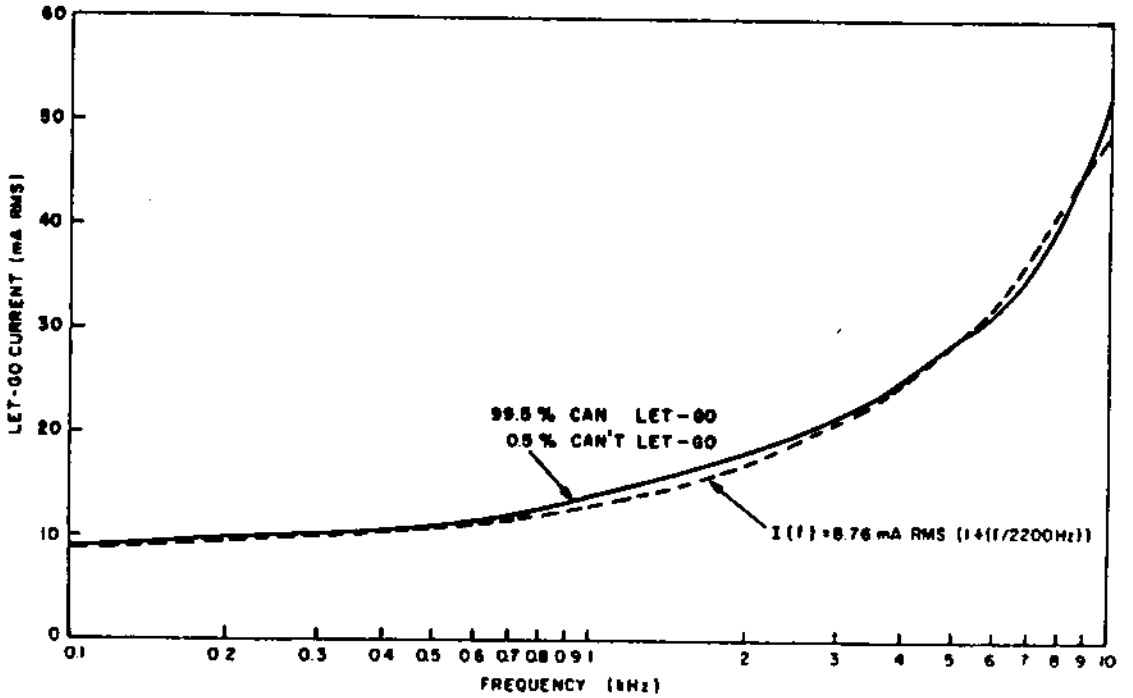


FIG. 5 EFFECT OF FREQUENCY ON LET-GO CURRENT THRESHOLD FOR MEN, DATA AND APPROXIMATION

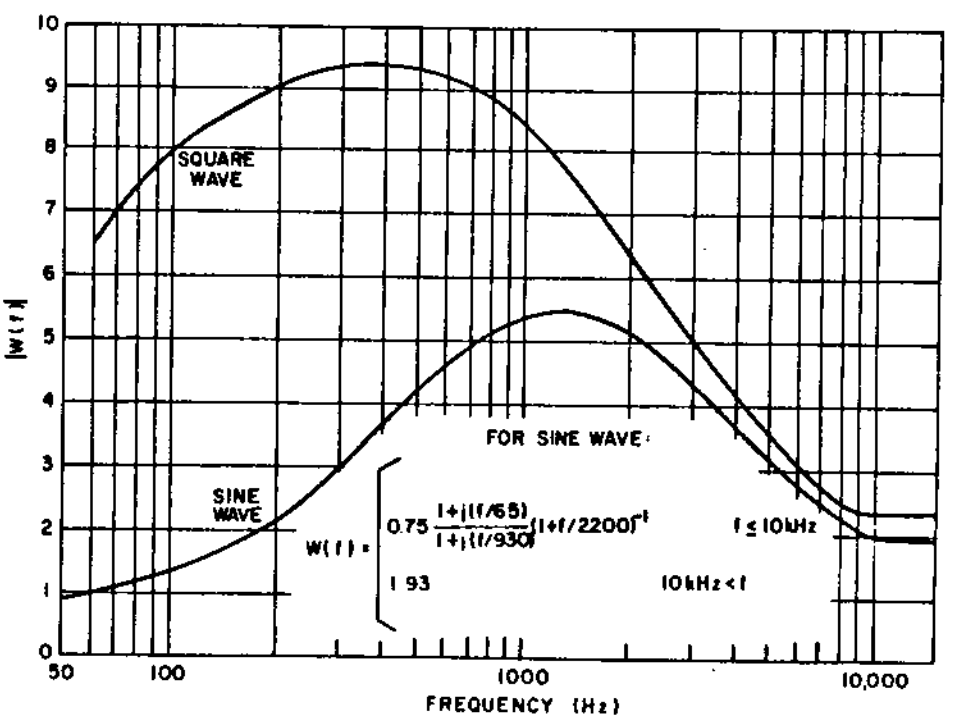


FIG. 6 SINUSOIDAL AND SQUARE VOLTAGE WAVE WEIGHTING FUNCTIONS

DISCUSSIONS

REILLY: The author applies linear network analysis to the evaluation of waveshape sensitivity for electrical stimuli. Mechanisms responsible for perception and muscle contraction alike involve activation of excitable membranes, which are highly nonlinear. This calls into question whether the linear analysis approach can be properly applied to such systems. The studies of Roy et al. (paper 2.3 in this session) vividly illustrate that major threshold changes in cardiac stimulation are produced by simply altering the dc offset of the same waveshape. Our own perception studies with oscillating transients (paper 7.1) indicate that nonlinear models can be used to describe sensitivity to these stimuli. Would the author please comment on these observations?

MENENDEZ: Mr. Reilly is correct in his statement that non-linear effects can invalidate attempts to use linear models. There are at least two sources of non-linearity in the response of the body to imposed voltage: the body impedance and the current susceptibility. In these experiments, the linear body impedance model, which was obtained at low-level voltages, was demonstrated to replicate the body impedance for non-sinusoidal voltages of a few tens of volts. The current susceptibility is a thornier issue. The macroscopic let-go response to multi-frequency currents has not been thoroughly documented, although Dalziel indicated the peak current controlled let-go for the superposition of two sinusoidal currents (60 Hz and 180 Hz) of variable phasing. This work suggests the peak of the linear superposition of more than two sinusoidal currents might be an appropriate measure of let-go hazard. This paper presents the results of carrying out such an analysis for a square wave.

The recent work in the microscopic response of individual nerves offers the exciting prospect of unifying and illuminating the available macroscopic response information. The analogy between sub-threshold nerve response and an RC circuit presented by Geddes (paper 1.4) suggests a single-pole linear network model for unidirectional stimulation. The duration-intensity relation (current) is very similar to that observed by Dayka. (Note, the response of such an RC circuit to single-frequency stimulation would closely follow the observed rise in the let-go current threshold with increasing frequency. A similar observation was indicated by Hart in paper 5.1.) For general bi-directional current stimulation, the non-linear nature of the membrane is most important. A negative pulse rapidly following a positive pulse can negate the effect of the latter. By ignoring the ability of subsequent pulses to extinguish the excitation produced by an above-threshold pulse, the linear-systems model fails to describe the non-linear response of the nerve, but the model would appear to be a conservative measure of the hazard.

As regards the dc offset question, this paper was not intended to include the effects of very low frequency ($f < 10$ Hz) stimulation. The waveforms considered here therefore contain no dc component.

INTRA-BODY CURRENT PROBES

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ABSTRACT

Physiological experiments on electrocution and shock necessitate sensors capable of measuring electric currents in live animals. A device similar to a thin (1 mm) flexible current transformer is wrapped around anatomical elements such as bone and muscle to read current values through magnetic coupling. The sensor is made by winding small caliber copper wire around a high-mu magnetic core. Sensitivities in the order of millivolts per ampere can be achieved. The useful range of the probes extends from milliamperes to hundreds of amperes. A miniature, slotted ferrite ring has also been used to read current through blood vessels. Due to the small size of the probes, surgical implantation presents few problems.

KEYWORDS

Current probe; electrocution; electric shock; current distribution.

INTRODUCTION

Since 1982 the Canadian Electrical Association has supported a research project at the Royal Victoria Hospital in Montréal with the aim of improving the treatment of electrical burns. The treatment of electrical burns is surgically and clinically difficult in part because of a not-well-known phenomenon labeled "progressive necrosis" that often leads, in the case of electrical burns, to successive amputations. IREQ offered technical and scientific assistance to Royal Victoria in view of the significant electrotechnical content of the project. Discussions held between Rollin Daniel and Paul Ballard of Royal Victoria's Microsurgical Laboratories and myself led us to believe that in order to evaluate the relationship between electrocution current and tissue damage, a sensor was needed with the capacity to evaluate tissue current density, especially in muscular tissue, but in other structures as well. The surgeons would implant the sensor in test animals (pigs, in this case), and a computer would be available for the recording of the relevant signals. From the surgeons' point of view, the probe had to be unobtrusive in order to facilitate implantation and minimally disturb the test animal. With these requirements in mind, I set out to design a probe with the prime requirement of minimal size. The requirement that the probe be adaptable to different anatomical structures also suggested that it should be mechanically flexible.

CONSTRUCTION

The classical solution to the above requirements would involve the design of a current transformer with the proper physical characteristics. However, current transformers are made with rigid magnetic cores and the cross section requirements on the core would severely limit the magnetic flux available. As it turns out, a small device can be made using the general concept of a current transformer that can be used in magnetic saturation to provide a useful signal over the range of currents applicable to studies on electric shock and electrocution.

EARLY MODEL

The first units were made using as a magnetic core a relatively long (10 cm) strip of mu-metal (designated NETIC) of modest section (0.2 x 6 mm) as shown in Figure 1.

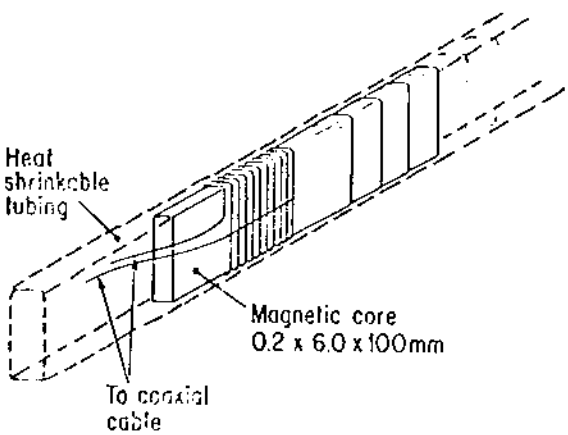

Fig. 1. Construction of early model of current probe.

The core is electrically insulated with tape and tightly wound with small wire (0.1 mm in diameter) from one end to the other. Another layer of insulation covers this winding and the wire is returned to its starting point as a second winding (wound in the same angular direction) or through a straight path (shown). Connections are made to a coaxial cable and the assembly sealed in heat-shrinkable tubing.

The probe is entirely insulated electrically, and contrary to regular transformers, the magnetic circuit does not form a closed loop. The installation consists in bringing together the two extremities of the probe so as to form a closed path within which the tissue bearing the current is contained.

Surgical implantation of the device in the hindlimb of a pig was performed by Paul Ballard and electrocution tests were run demonstrating the usefulness of the device. The transfer constant of the probe ranged between 10 and 30 mV/A according to the current range.

REFINED MODEL

In order to obtain a reasonable signal level with a device of smaller size as well as to get good small current sensitivity, a magnetic alloy with very high initial mu and low coercitivity, supermalloy, was obtained (Carpenter Technology, Reading, Penn.). A plate of supermalloy was mechanically worked to the shape of a small cylinder 0.25 mm in diameter and thereafter annealed in hydrogen according to a procedure known to maximize magnetic permeability (1175°C for 3 hours, cool at 200°C per hour to 480°C and any rate thereafter). This procedure was designed by Raynald Simoneau, Direction Matériaux, IREQ.

The core was then covered with a thin plastic insulation and held under tension by two mandrels on a glass blower's lathe. A glass blower's lathe has two colinear shafts rotating at identical angular speed. This setup allowed the tensioning of the filiform magnetic core for the winding of a 50 micrometer varnished copper wire. In this case, only one layer of winding was applied, the electrical return being made through the magnetic core. The winding was connected to a coaxial wire, 0,8 mm in diameter. The assembly was covered with heat shrinkable Mylar (Stone Industrial, College Park, Md). The resulting probe is about 1 mm in diameter. The construction of such small probes is heavily dependent on the ability to apply thin insulation layers. In the construction described above, half of the section of the probe is plastic insulation.

Other core materials were tried: ferrite powders, metglass (a new amorphous magnetic material) and air or copper as reference. It was found that low-mu materials are generally unsatisfactory because of the low signal levels generated. For example, we found that a refined probe (1 mm in diameter) without magnetic amplification would yield a signal level of only 3 microvolts per ampere as compared to approximately 500 microvolts per ampere with a supermalloy core. In an electrically perturbed environment the difference is highly significant.

PERFORMANCE

This section discusses the characteristics of the 1-mm probe.

Shifts in Magnetic Core Performance

The magnetic permeability of the core material within the probes can be affected by specific factors. This is turn affects the probe's gain. When appreciable mechanical stress is imposed on magnetic alloys permanent reductions in the permeability of the core are produced. Appreciable changes can be intuitively associated with handling rougher than light inelastic deformation of the core.

Careful manipulation of the units during surgical implantation is successful in eliminating these variations. Also, when initially produced, the probes are appropriately shaped before calibration. Another type of drift in permeability may occur over time without electrical or mechanical handling of the probes. We have observed that probes spontaneously increase in permeability for some time after fabrication. A further special effect is related to powerful magnetic solicitation of the probes (being under the influence of a strong current). Such a treatment will improve the smoothness of the waveshape obtained from the probe when solicited by small currents (below 1 ampere).

In practice, very accurate measurements of intra-body currents with the probes should be preceded by a short calibration procedure. Such a procedure can be carried out with the probe already in place.

Probe Signal Versus Current Amplitude

Calibration of the 1-mm probe over a range of 15 mA to 75 A shows two distinct regions delimited by a current of approximately 20 A. Below 20 A, the signal from the probe is an accurate representation of a 60-Hz sinewave. Above this value, severe distortion of the waveshape occurs, similar to magnetic saturation waveforms, as shown in Figure 2. In spite of the waveshape distortion, calibration can be

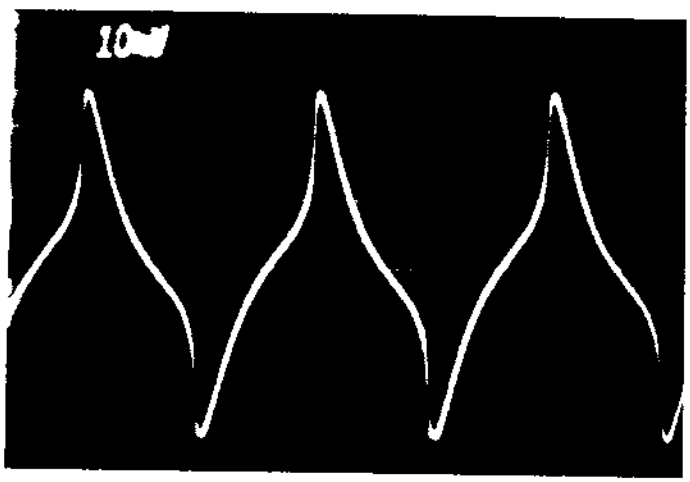

Fig. 2. Waveshape generated by a 1-mm probe solicited by a sinusoidal current of 40 A. Horizontal scale is 5 ms/div.

obtained by plotting the crest-to-crest value of the probe's output voltage against rms current, as shown in Figure 3.

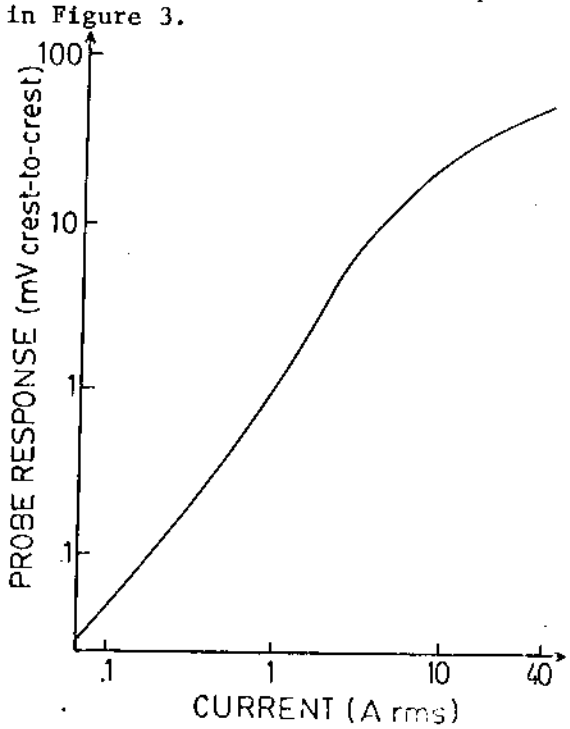

Fig. 3 Amplitude calibration of crest-to-crest probe output voltage vs tissue current (A rms). 1 mm probe.

Phase Shift

The probe output is approximately 60° ahead of the current signal, with little variation over the amplitude range.

Frequency Response

The bandwidth of the probe is essentially dependent on the magnetic material used. The half-amplitude bandwidth of the 1-mm probe with supermalloy core is 50 Hz to 7 kHz.

Electrical Parameters

The winding resistance of the 1-mm probe is 30 Ω, inductance is 2.9 mH. Since the unit does not perform as a classical current transformer, there is little reason to load it with a burden of low impedance. Loading the probe simply results in the expected signal attenuation.

Selectivity

An important characteristic of such a probe is its selectivity, or ability to reject the signals contributed by neighboring currents outside its loop. In order to check this rejection figure, the probe was shaped into a circle approximately 3,5 cm in diameter. First, the uniformity of the response to a current of various positions inside the loop was investigated. It was found that this figure varied very little unless the current-carrying wire was placed in contact with the loop itself. In this case, sensitivity relative to the center of the loop decreased to 91%.

When the wire was placed outside the loop and in contact with it, the signal was 10% of actual value. This decreased to 3% when the wire was placed 3 cm away. When all outside contributions are compared to the inside contributions, one finds that outside contributions would amount to 20% if they all fell in phase. Actually, the outside contributions shift in phase according to position along the probe's length and the external noise rejection figure is expected to be much lower (in fact, in a completely symmetrical current distribution, they would be expected to even out).

Toroidal Probe

In 1939, Weeks and Alexander devised a toroidal clamp functioning as a current transformer that could be closed around the blood vessels of experimental animals, allowing intravascular current evaluations. We designed a simplified model of this probe in the form of a miniature ferrite torus, slotted to allow the insertion of the blood vessel and evenly covered with winding wire.

GENERAL COMMENTS

Implantation

Surgical implantation of the probe must be done properly in order to insure that accurate signals will be obtained. First, the ends of the probe must be in close contact with each other. If the probe length exceeds the circumference of the anatomical part, two turns can be made and the gain will be increased by a factor of approximately 1.5. However, the two ends must still be in close contact in order to insure proper rejection of external signals.

Secondly, unwanted current contributions from physiological fluid can be avoided in some cases by packing the interstice between probe and anatomical part with closed cell polyurethane foam. This setup may also be useful in accommodating muscular contractions and probe overhang. The approach of magnetically shielding the probe overhang with thin magnetic foil in order to desensitize it has not proven very effective in our experience.

Ultimate Size and Sensitivity

The 1-mm probe presently in use has a detection threshold of approximately 1 mA, corresponding to a 1 microvolt signal. Sensitivity increases with winding turns, core permeability and section. Some gains could be achieved by using extremely thin wire and insulation layers in probe construction. Sensitivity (and detection threshold) and size work against each other. However, for the large currents observed in muscles during electrocution it is probable that a probe as small as a few tenths of a millimeter would be effective.

Actual Measurements

In the studies of electrocution carried out at Royal Victoria, Paul Ballard has repeatedly implanted the current probes, most commonly around the semimembranosus muscle in the pig hindleg. The currents measured vary widely (amperes to tens of amperes) according to the parameters of the test performed: electrode placement and contact, injected energy, etc. Future publications by the Royal Victoria team will present and interpret the data.

ACKNOWLEDGMENTS

Thanks to Leonard Bolduc and Louis Masson for many discussions and to Jean-Paul Thivierge for technical assistance. All are from Appareillage de réseau, IREQ.

REFERENCE

Weeks, A.W., Alexander, L. (1939). The distribution of electric current in the animal body: an experimental investigation of 60 cycle alternating current. Journal of Industrial Hygiene and Toxicology, 21, 10.

DISCUSSIONS

SANCES: Paul I'd like to complement you and Paul Ballard on the excellent job that you've done. We tried to do this ourselves but unsuccessfully. I am so pleased to see that your lab has designed these probes. You've done a magnificent job and I think that this is going to help us to be able to put probes around bones and vessels and so forth.

J. BEATTIE: I believe your current probes would be better designed with twisted pair leads rather than the indicated coaxial cable. Your main source of interference is magnetic rather than electric. Better yet, protect against both with a twisted pair within a shield.

P. HEROUX: The coaxial connection was originally intended to guard against arcing interference rather than 60 Hz. With present probe dimensions and signal levels, neither electric nor magnetic interference seem to present problems. The second suggestion is sound and seems clearly preferable if very small probes must be constructed.

Chapter 4

Panel Meeting on Body Impedance

PANEL MEETING ON BODY IMPEDANCE

Chairman: Prof. G. Biegelmeier, WG04, IEC/TC64, Austria

Vice-Chairman: J.P. Reilly

Panel: Prof. R. Hauf, Dr. P. Heroux, Prof. W.R. Lee, R.C. Menendez, Dr. A. Sances, Jr., A. Smoot, O.Z. Roy

BIEGELMEIER: The first topic is the applicability of measurements of body impedances of corpses and of animals to living persons. And I would like to say a few words on that. I mentioned today that there is a considerable difference at low voltages between body impedances measured on corpses and on living persons and it seems that the main reason for these differences is that the skin impedance of a corpse is very high compared to that of a living person. Just to give you an example, if you apply 25 V to a living person, you measure about 3000 to 4000 Ω for hand-hand impedance, while on corpses you would measure impedance in the order of 10,000 ohms. This is one difference and the second one is, of course, the temperature of the tissue - a corpse would have lower temperature, therefore a higher resistivity, and this in my opinion, is the major factor to be considered. Therefore, I would ask the members of the panel whether they want to make some remarks regarding this topic.

SANCES: Mr. Prieto and Mr. Chilbert of our laboratory had occasion to do studies on cadavers. Cadavers are usually kept in the cooler at about 3°C until we use them, and, as I recall, the cadavers were just about brought to room temperature before the studies were done. Large electrodes were used to measure resistance from hand to hand and from hand to foot. We did studies at 2000 V, and as I recall, the resistance that we measured was somewhere between 400 or 500 Ω, so it is consistent with the work that you cited in your papers.

BIEGELMEIER: Furthermore, the difference of skin impedance of a corpse and a living person must have some connection with the blood circulation.

Freiberger also measured resistance of corpses a few hours after their death. He always used a correction factor for the resistivity depending on the temperature[1], so there is a possibility to make corrections when you adapt the values from a corpse to a living person. I was asked to make some references regarding measurements on animals and the comparison, as far as the body impedance is concerned, to human beings. This is of course a difficult question so I would like to know what the panel thinks about it.

REILLY: When we're talking about an experiment in which skin impedance is of importance, we have to examine which properties are comparable in the living human with those in the corpse or in the animal. I presume that corpses are used because conditions are tested that are not appropriate for tests in a living person. The properties that are important in relationship to skin impedance concern mostly those of the corneum, namely, its thickness and the concentration and arrangement of sweat glands. Others have mentioned the presence or absence of hair and most importantly hydration of the corneum and of course the possibility of skin damage. We know that corneum is an excellent insulator if it is dry, although it is only some 50 micrometers thick on the forearm and slightly thicker on the palm. So it's a very thin layer. I think we have to examine role of the sweat glands in hydration and ask whether they are similar in a corpse or an animal with those of a living human.

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[1] Freiberger, H. (1934). Der elektrische Widerstand des menschlichen Körpers gegen technischen Gleich- und Wechselstrom. Berline: Verlag Julius Springer Berlin, 1934. Translated from German by Allen Translation Service Maplewood, N.Y., Item No. 9005.

BIEGELMEIER: Thank you. I might also present another question. I said this morning that the capacitances of the skin in humans are very large. I thought this to be due to the presence of sudoriferous ducts in the skin. But, recently Mr. Bridges has observed similar effects in experiments on monkeys which do not have sudoriferous ducts. Therefore, my theory is not very convincing. What do you think about that? What might really be the origin of these large capacitances in the skin?

SANCES: Do you think it could be the capacitance between, the electrode's interface and the tissue

BIEGELMEIER: You see, you certainly cannot calculate the capacitance by taking the thickness of the epidermis; you just do not get the correct values. When you model the skin structure as little cylindrical capacitors with 300 to 400 saline filled cylinders per square centimeter of skin, and so that every one of these sudoriferous ducts form a little cylinder condenser, then the calculate results fit very well with the capacitance measurements, but because the monkeys don't have these ducts I'm at a loss how to explain the large capacitances of the skin.

REILLY: There's an alternate view that has been proposed for the existence of this high capacitance. Even though I have some trouble with this view I'll bring it to your attention. The problem with explaining the capacitance of the human skin is that if you assume the dielectric layer to have the thickness of the corneum it is difficult to explain the very large capacitance values that one finds experimentally. Prof. Biegelmeier has done calculations showing that just the shape of the sweat gland ducts alone may provide the capacity that is consistent with experimental results. Other possibilities have been mentioned by Lykken[2] in which he treated the layers of the corneum as being depositions of individual cells, each one having an extremely thin membrane comparable to individual cells, and then filled with a conductive fluid. Then one has a situation in which, although the corneum is relatively thick, it is composed of layers of thin membranes which are filled with conducting fluid. With that kind of a model some one hundred cell layers could explain the high value of capacitance. The problem I have with that view is that it is questionable if it is consistent with what exists in dead skin tissue.

BIEGELMEIER: Thank you Mr. Reilly. Does anybody in the audience want to put a question concerning the analogy between animals and human beings and the applicability of various models.

HOYLE: It should be possible to resolve this question of sweat glands and their effect very easily because there are horses which sweat and there are dogs which don't sweat. I think elephants don't sweat, and so on. There are all the great apes to be looked at, perhaps there is some factor which could be revealed if you made a comparison between these two sets of animals. I don't know if there are any other hairless animals like ourselves, but that also might be a thing we could look at.

SANCES: I believe the reason many of the studies have been done in the pig is because the skin appears to be similar to that of the human. Also, if you use a hog which is roughly 200 lbs weight and thus you get the mass similarity. Obviously we have differences in the geometry and the configuration of the internal organs, but the spinal column is quite similar to that of the human as well as the lungs, and other internal organs except that the extremities are different. So it is not a bad model as far as we can tell. On the other hand, we have difficulty getting approval to use other animals. We have suggested that we needed a large number of monkeys for burn studies, but we were advised by NIH not to proceed; so we had to choose an animal species which were commonly used in the laboratory.

[2] Lykken, D.T. (1971) "Square-Wave Analysis of Skin Impedance." Psychophysiology, 7 (2), pp 262-275.

Perhaps the chimpanzee would be one of the better animals because extremities are similar to those of man.

BIEGELMEIER: Thank you, and as an electrical engineer I'd like to put another question. It seems to me, as far as ventricular fibrillation is concerned, that there are two groups of investigator, one group experiments with dogs and the other group experiments with pigs. I wonder what do the experts think - which animal species might be better suited for these experiments on fibrillation threshold. Who can answer that question?

ROY: We've done experiments with dogs and we've used the dog model extensively and some of our work has been with pigs. We haven't noticed any significant difference between the two species.

BIEGELMEIER: So you think it is just the same whether you use dogs or pigs?

ROY: I would say yes as long as you're working directly on the heart.

BIEGELMEIER: Yes, but of course one of the most decisive experiments are the experiments where voltage is applied from fore leg to hind leg, and then we may find a big difference between a pig and a dog.

ROY: That is absolutely correct. We haven't done any experiments in our laboratory with fore-leg to hind-leg or right to left arm current path and this brings me to the question of cadavers and the living cell. The work that has been described in some of the papers deals with the effect of skin and the differences between the living person and a cadaver. When you work with a cadaver you are not working with a dynamic system in terms of the internal structure and I really don't know what that means in terms of current distribution or resistivity. I must qualify that by saying that we're working directly on the heart and introducing the current there so we don't have the complexity of the path and direction of current flow.

BIEGELMEIER: I think of course that here we might find a lot of information in the book of Freiberger which is as far as I know has been translated into English also.
Also, when you look at the weight of the heart of a dog, it is a very big heart so in experiments concerning fibrillation threshold with dogs we are certainly on the conservative side, in my opinion. I'm not speaking about applying voltage to the heart itself but from fore-leg to hind-leg.

SHERMAN: It is well known that every cell has a capacitance associated with a membrane, and particularly so for excitable membranes, such as nerve cells and muscle cells, and muscle comprise the bulk of the tissue. This capacitance usually disappears with the death of cells because the integrity of the membrane is lost and the ions can move across the membrane relatively freely, unlike the situation in a living cell. I wonder, whether death shouldn't actually lead to an opposite result, that is to a decrease in capacitance and whether the existence of all those individual cellular capacitors cannot explain the relatively high capacitance value present in the living human even though it is difficult to reconcile with the fact that the capacitance is also very high in a cadaver. Can anyone on the panel comment on this?

BIEGELMEIER: It is certainly only high in the skin of the corpse. The capacitance in the body itself is always very small. When you look at the measurements of Freiberger on many hundred corpses you find that when he peals off the skin, he measures practically no capacitance, he measures nearly a purely ohmic resistance.

SHERMAN: Which probably indicates that the current path is interstitial rather than through the cells, that is it bypasses most of the cells. After death it is likely that the bulk of the cells also becomes significantly more conductive and

that would result in the decrease in the resistance in a cadaver, which agrees with what you said. But in the skin the effect is opposite, and that indeed seems very strange.

BIEGELMEIER: Is there anybody who can answer that question?

CHILBERT: Well, as far as the current itself is concerned, the pathway that we have found in the animals is mainly through the muscle tissue because that is the major tissue in the limb. As far as the interstitial space is concerned, the current probably favours the interstitial space but it also goes through the cells. However, the net capacitance of the whole system is not necessarily evident at lower frequencies; however, going to higher frequencies you do see that the current in fact has a capacitive component to it much greater than one would see at power line frequencies.

HEROUX: When the cells in the epidermis die it is true that the membranes become full of holes and that the conductivity will increase. When cells become desiccated, then the mobility of ions will become much lower. I should also like to point out that the dielectric constant of water when it is in very small quantities is different from what it is in bulk. Unfortunately, I don't remember in which direction it changes but the changes, if I remember correctly, are quite significant.

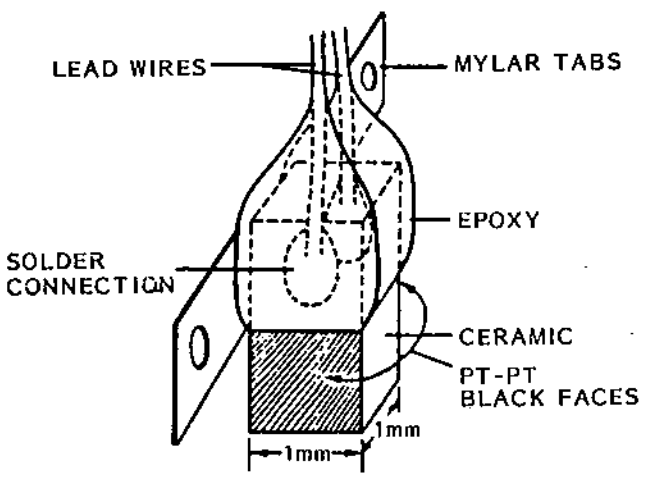
BRIDGES: I would like to provide a comment dealing with my experiences with what I term "heterogeneous dielectrics". These dielectrics can be, for example, coarse sand with some moisture in it. When you have that kind of condition, even though moisture may comprise only 1 or 2% of the bulk, for example in soils, you will measure a relative dielectric constant, not about 81 or 80 which is the dielectric constant of water, but over 800 at 60 cycles, or over 10 000 for other reasonably wet materials. This comes about from the way in which you have ionic conduction paths in the moisture. So based on this experience, I can develop any number of models that would give high dielectric values in a reasonably dry membrane. The problem, as I see it, is the fact that as we increase the field gradient across the skin, that is increase the voltage applied to the subject, this capacitance tends to disappear perhaps because of the increased mobility of the ions or due to some avalanching effect, which masks that capacity. The fact that capacitance changes with voltage or field intensity, to me is perhaps the most interesting issue that needs to be looked at.

BIEGELMEIER: Thank you Mr. Bridges. I think this concludes the discussion of the first topic. Topic number 2 is the distribution of the current in the body.

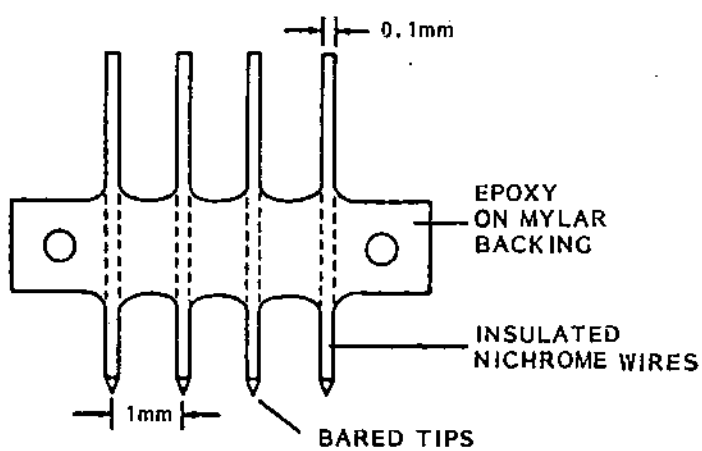
SANCES: We have conducted experiments using voltages from 2.1 kV to 14.4 kV in the hog. The hogs were anesthetized and they were about 200 pounds each. In some experiments a large ground plate was on the hind quarter. We touched the opposite hind limb. Also current paths from the hind limb to the fore limb were studied. With typical copper or aluminium conductor contact the impedances were about 216 Ω. Approximately 10 A was flowing at 2 kV through the animal. While working with Dr. John Szablya from Pullman, Washington, we were measuring not only the impedance but also the angle, which was capacitive and about 40°. The resistance during these experiments was as low as 133 Ω. When we used the larger voltages, substantial arcs were drawn. Under these conditions 50 A was passed through the animal; however, the resistance changed little. Initially, a high impedance was measured, followed by skin damage. Then the currents went freely through the tissues, with an impedance of about 200 Ω.[3]

Subsequently, we conducted studies in the laboratory to obtain an understanding of the currents distribution. In these studies we had 2 rings about the hind limbs of the hog and measured the currents in the region of one of the hind limbs. Over the last 15 years our staff has developed various probes for measuring current

density, but I think the latest one that has been developed by Paul Heroux[3] and Ballard is very exciting. We have been using a loaded probe (Fig. 1). It is about 1 millimeter on a side to half a millimeter on a side and is placed in the tissue. It is ceramic and it has platinum blacked faces. We use platinum black because it has a high capacity for use at relatively low frequencies, such as at 60 Hz. We also used the 4 electrode method. With the 4 electrode method a current is applied to the outer 2 electrodes and the potential is measured on the inner 2 electrodes. With suitable techniques the impedances and the current density can be determined. To measure the current density during the application of 60 Hz currents, a 70 Hz current is applied. A filter is used since we were very close to the 60 Hz value. Therefore the ongoing current density and the impedance in the tissues could be determined concurrently. Figure 2 shows the cross section of the hog's legs. We have a tendon in the hog which is fairly large, skin and some bone, but the majority is essentially muscle where the greatest percentage of the current traverses. We have also studied the fat. What was done was to apply currents and to determine how long it took for the temperature to rise as a function of applied energies to the hog. Thermistors were imbedded in the tissue. It appears that we begin to destroy vessels and nervous tissues at about 55°C.



(a)



(b)

Fig. 1 - The loaded probe (a) and four in-line electrode (b) current density measuring systems.

[3] See paper by P. Heroux in these proceedings. (Editor's comments)

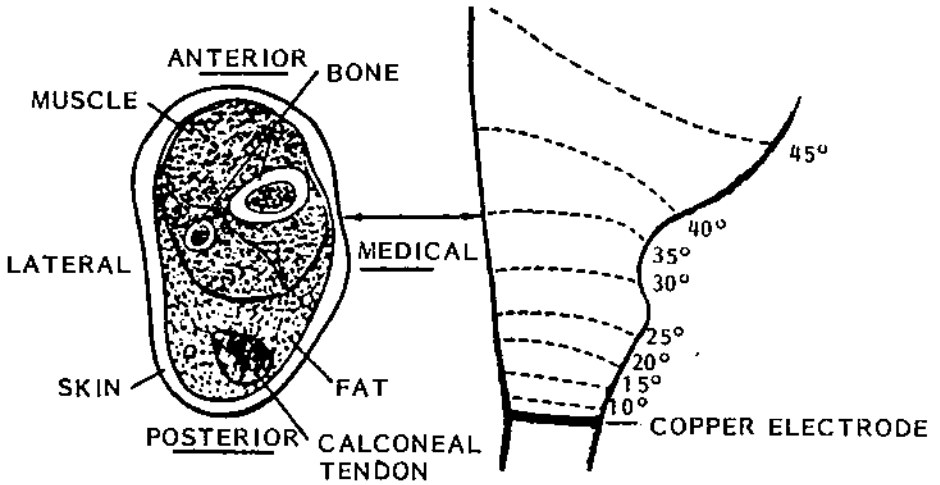


Fig. 2 - Experimental setup for current density measurements with cross-section where resistivities and current densities were evaluated. The lines on the limb (right) indicate percentages of the total applied voltage measured in the dermis from the copper input electrode to proximal regions of the animal.

We used various techniques to measure current density in an artery, in the nerve, in the muscle, in the fat, in the bone marrow, and in the bone cortex. These studies were conducted with 10 milliamps up to 1 A currents applied to the hind limb of the hog. In summary, we found that the greatest amount of current goes through the artery (up to 35 milliamps per square centimeter with 1 A applied), followed by nerve, muscle, fat, bone marrow, and bone cortex (Fig. 3).

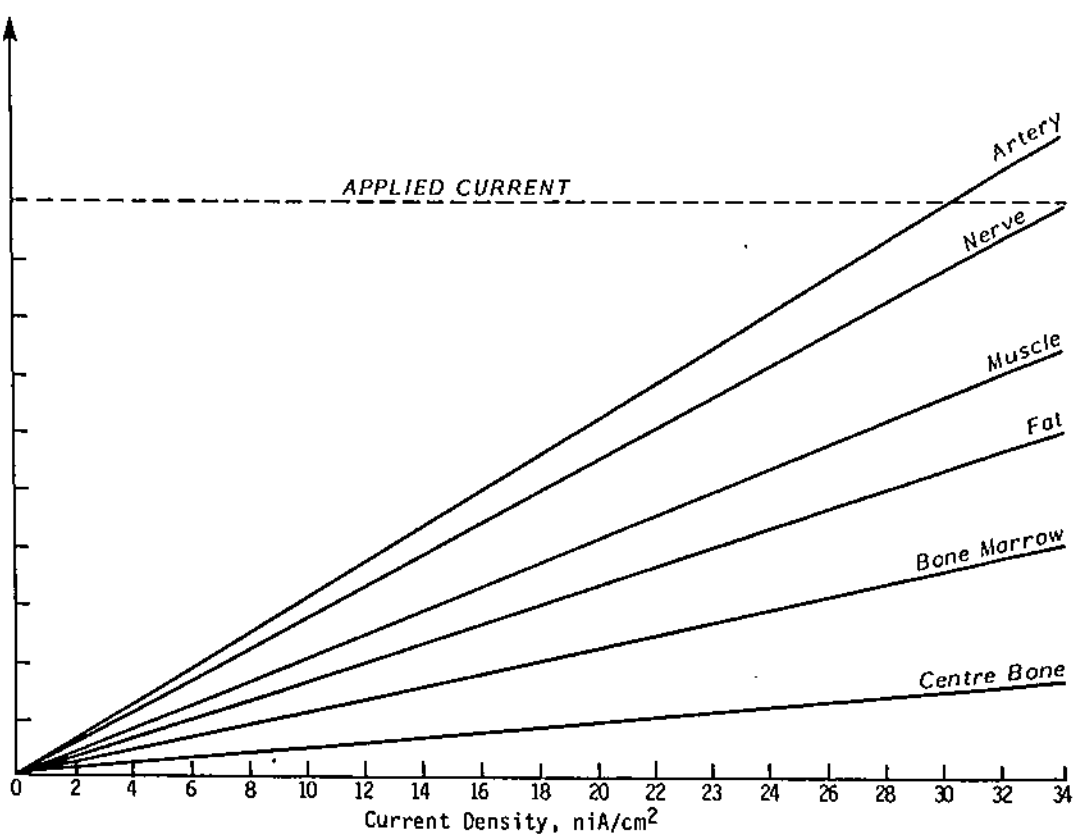


Fig. 3 - Total curve t 0.01 to 1 amp hindlimb to hindlimb.

We also studied unembalmed male human cadavers one to three days following death. Two thousand volts were applied from hand-to-hand, leg-to-leg, or hand-to-leg. The impedances were about twice as great as those measured in the living hog.

We also measured current distribution in the hog's body with current application from the hind limb to the fore limb using the 4 electrode method. Currents were measured in the spine, kidney, lung, and in the heart and other areas (Fig. 4). In the hog, a substantial amount of the current traverses the back, probably because there is a large body of muscle in this region. Consequently, quite a bit goes through the spine and the spinal cord. It may be the same in man with currents from the leg to the upper arm, ie, a substantial amount of current, more than expected based on the average cross-sections, might flow through the spine.

		J	ρ
Intest.		0.71	511 Ω
Back	neck	0.021	1140 Ω
Muscle	M.T.	0.141	
Kidney		0.097	447 Ω
Liver		0.065	570 Ω
Lung		0.058	1650
Heart TtoA		0.073	
Belly		0.065	547
Abdomen		0.026	560

Figure 4 — 100 MA Applied Lf forelimb to Rt hindlimb

Figure 4 shows the current densities in the intestine, the back muscle, the neck, the muscles in the upper thora, mid-thora, upper lumbar, kidney, liver, lung, heart, belly and abdomen. For application of 100 milliamperes it is probably reasonable to linearly extrapolate from a 100 milliamps to 10 A. These studies were conducted below fibrillation threshold for the hogs, so that they could survive. In the hogs we found a fibrillation threshold at about 400 milliamperes of applied current. Thus, if we multiply the heart value of 0.073 milliamperes per centimeter^2 by 4 assuming it is linear, we get approximately 0.3 milliamp per centimeter^2 as the current density in the heart for fibrillation with 400 milliamperes applied. As I recall, Dr. Roy's findings in the isolated heart are similar.

Now I would like to briefly review Kouwenhoven's ring transformer studies in dog hearts. What he found was that fibrillation threshold was between the 6 and 10 mA. If we assume the cross-section of the dog heart is 20 square centimeters, then 10 or 6 divided by 20 is in the range of approximately a half milliamp per centimeter^2. Dr. Roy, I guess your measurement ranged from about 0.3 to 0.5 milliamps per centimeter^2.

Finally, we can put this in perspective with respect to other types of currents that are used therapeutically, such as electrosleep currents. The electrotherapeutic sleep currents are approximately 1 milliamp and are passed across the head. This current can be either a rectangular pulse which is one to two milliseconds in duration with a repetition rate, or a pulsed sinewave burst with a repetition rate of about 100 per second. These currents are used for sleep disorders, and it has been suggested and proven helpful for people with alcoholism, drug and other diseases. Hundreds of thousands of patients are treated in the USSR with these currents. Then we proceed to electrical anesthesia. In it a current is passed across the head. I think it is still performed in the USSR, Czechoslovakia, Yugoslavia, Japan, France, and a number of other places around the

world. Some of the original studies were conducted in the USA. Basically, it is a current of about 100 milliamperes. We have done major surgeries on humans with these currents. The next level is for electroshock currents followed by electrocution and electrical burns.

HEROUX: I'd like to say a few words about the factors that influence the flow of current (excluding electrode effects in electrical burns) produced by electrodes. Why are we interested in this detailed flow? Well, that is because tissue damage, particularly progressive necrosis depends on the details of current flow. It is thought that sufficient current densities circulating in the long, cylindrical limb, such as an arm, will on occasion concentrate at specific anatomical landmarks and initiate damage that will become exposed only days after the shock. One obvious factor affecting conductivity is tissue temperature. As the temperature rises, the ions become more mobile and the conductivity increases but that is not too interesting. A more interesting factor is muscular contraction. If you enter fibrillation, of course you have an immediate problem and, you can solve your problem by coughing. That is if you cough repeatedly, this action maintains sufficient blood circulation to sustain life for some time. Similarly, one would expect a rise in the resistance with the very strong contractions stimulated by the electrocution current. That is at least one factor that might affect muscular conductivity considerably. Another very interesting factor is arterial contraction. The differential conductivity between blood and contracted muscle is expected to generate a transmural potential across arterial walls. Jaffe[4] reported in 1928 that electrically stimulated arterial contractions are markedly irregular and vary in intensity, consequently vessel conductivity varies widely. Those contractions are not related to thrombosis and are reversible. Toda[5] in 1973 observed that transmural stimulation did not contract the cerebral and internal carotid arteries, but that external carotid, common carotid and superior masenteric arteries were contracted in the dog. The behaviour of arteries is dependent on frequency possibly because of an interaction with rapid neurotransmitter release. This indicates that patterns of current passage along an arterial tree can be quite intricate. A third factor is membrane puncture. The polarization of a cell by an electric field induces a membrane potential proportional to field strength and to cell radius in the case of a spherical cell. Mild[6] in 1982 demonstrated that the breakdown voltage for the membrane of the lymphocyte is only 1 V. There is no reason to believe that the value would be very different for a muscle cell or a neuron. Therefore, one can expect that long cells such as muscle cells or neurons would be easily punctured by typical electrocution current. These punctures could markedly affect potential distribution within the body. This situation indicates that body tissues change their properties during current application with the possible exception of bone, and that the significant variable that determines current paths may be a tissue resistance value which is different from the initial resistivity. Crile[7] indicated in 1921 that conductivity is a

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[4] Jaffe, R.H., Willis, D., Bachem, A., "The Effect of Electric Currents on the Arteries", Archives of Pathology (Chicago) 7:244, 1929.

[5] Nobura Toda, Yuzo Fujita, "Responsiveness of Isolated Cerebral and Peripheral Arteries to Serotonin, Norepinephrine and Transmural Electric Stimulation", Circulation Research, 33:98-104, 1973.

[6] K. Hannon Mild, L. Lövdahl, K.G. Lövstrand, S. Lovtrup, "Effects of High Voltage Pulses on Viability of Human Leucocytes in Vitro", Bioelectromagnetics, Vol. 3, No. 2, pp. 213-218; 1982.

[7] Crile, G.W., Hosmer, H.R. Romland, A.F., "The Electrical Conductivity of Animal Tissues Under Normal and Pathological Conditions", American Journal of Physiology, Vol. 60, No. 1, 1921.

sensitive indication of physiologic status of tissue. Laboratory tests at the Medical College of Wisconsin have shown, as we were told this afternoon, that tissue resistivity changes with high density currents and that such resistivity changes could possibly be used to gauge tissue viability. It seems strange that little is known about the ability of blood to handle high current densities without coagulation or bubble formation, which is certainly one thing that should be amenable to very easy experimentation. In conclusion, body tissues may not be viewed as inalterable elements in electrocution. It is probable that a number of even relatively mild shocks can induce reversible membrane changes.

BIEGELMEIER: What did you mean when you said that coughing is helpful during ventricular fibrillation?

HEROUX: Apparently, there was a case in the United States in which an MD went into fibrillation and he was aware of this and the man coughed all the way to the hospital.

VAINBERG: A question to Dr. Sances. In the electrical utility industry we quite often have to measure electrical soil resistivity. A Wenner method similar to a four-probe method you described is often used. We know that it is not very simple to measure and interpret the resistivity measurements. If the soil is uniform for a large depth (up to hundreds of feet) then the soil resistivity can be measured accurately. However, when the soil is non-uniform with, let's say two layers, you would likely have to start changing the spacing of the electrodes and then try to find out what is the resistivity for each layer. In a case of tissue resistivity, using a similar method one has to be very careful, because the media are non-uniform as well as highly anisotropic. So, the question arises as to what is actually measured in these experiments.

SANCES: Thank you for bringing that up, I neglected to cover that aspect. When we were measuring the smaller tissues we used smaller probes and roughly the spacing of the probes should be less than the thickness of the interface that we're attempting to measure. For example when we performed measurements in the intestines we used larger probes and in our paper which was published in the IEEE transactions we indicate that we chose different size probes for these layers. When we measure in brain, for example, we use hemispherical symmetry instead of spherical symmetry. We are aware of the anisotropic phenomena and so what we do for example when we're working in muscle, we have a transverse measurement and a longitudinal and we then correct for this.

BIEGELMEIER: Thank you, I think we have to close slowly the subject of distribution of current in the bodies. Is there somebody in the audience who wants to put a question?

DENO: Prof. Biegelmeier's results on foot-to-foot versus the hand-to-hand currents suggest that a lower current will pass through the heart with the foot-to-foot conduction. The conclusion was that we can allow higher step potentials than touch potentials. Any quantitative statements relating foot-to-foot versus hand-to-hand currents to the heart would be an important contribution. This affects the relaxing of costly power system grounding designs for worst case hand-to-hand fibrillating currents.

BIEGELMEIER: Thank you. I think I can try to give an answer. Freiberger (17) made a large number of measurements on corpses with ring transformers around the heart so that he could measure the current through the heart for various current paths. He says, for instance, that if the current from left hand to right hand is 100% then the current through the heart measured in a ring transformer would be 2.5%. Now for the current path from left foot to right foot, if the total current is 100%, the full current through the heart is below 0.1%. So it is much lower

than for other current paths and this is what I meant. For instance, if you have a current path from right hand to both feet, 8% of the current would go through the heart, compared with 0.1% for left foot, to right foot. For left hand to right foot, 5% of the current would go through the heart.

SHERMAN: I just have a brief comment. Although it is true that significantly less current goes through the heart in leg-to-leg path, one can not in any way conclude that the standards for the grounding design should be relaxed, because the moment that current goes through the leg, the person falls, and you probably can confirm that, one cannot stand with the current going through the leg. Therefore, the whole point becomes irrelevant. The current pathway will then be determined by the way the person is lying on the ground.

BIEGELMEIER: That is of course a question the committee has got to decide.

Thank you Dr. Sherman.

LEE: I would like to support what Dr. Biegelmeier has said from quite another aspect. When we were doing experiments on arrest of respiration, which you said yesterday requires a somewhat lower current than for fibrillation, we found that you can arrest respiration by passing the current through the dog from the upper limb to the opposite lower limb. The required current was somewhere about 20, 30, 40 mA. If you now connect your electrodes to both hind limbs you can jack up the current until you've got amps and you've got smoke coming from where the electrodes are and the respiration isn't affected. This bears out that as a first approximation one can regard the body as a volume conductor. I mean if you regard yourself as nothing more than a leather bag filled with saline you're probably fairly close to the truth. That is point number one. Point number two is that if you look at lightning accidents, you certainly get significant step voltages. Now, lightning can kill by ventricular fibrillation we believe, and I would refer you to the details of a paper by Golde and Lee[8], Berger, Biegelmeier and Karobath[9], in the IEE where we discussed this in some detail. But there are many well documented lightning cases where people have been thrown to the ground from step voltages and after a time, they recover. They don't get respiratory arrest or cardiac arrest.

BIEGELMEIER: Thank you. I think we'll close this topic now. The next topic is models for body impedance measurements. Mr. Smoot agreed to introduce this topic.

SMOOT: The United States Consumer Product Commission asked us to do some work for them because they have the responsibility of passing judgement on the safety of electrical products. As you know there is a lot of information on the general subject of the body impedance and more should be forthcoming, but we cannot wait until all this information is in, so it is necessary at this time to have something that could be useful in representing the human body when taking measurements from appliances. It is also desirable to have some kind of an instrument which would measure these currents in such a way as to be indicative of the physiological effects such as perspiration, let-go or ventricular fibrillation. We used the fairly accepted five component model; that is the internal impedance is essentially purely resistive, and the two skin interfaces are represented by a parallel combination of resistance and capacitance. We measured the voltage across the

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[8] Golde, R.H. and Lee, W.R. (1976). "Death by Lightning". Proc. Instn. elect. Engrs. Reviews 123, 1163-1179.

[9] Berger, K., Biegelmeier, G., and Karobath, H. Über die Wahrscheinlichkeit und den Mechanismus des Todes bei Blitzeinwirkungen Bull. Swis SEV/VSE 69 (1978) No. 8, pp 361..366.

pure resistance in the inner body and then converted it into current. One further step as was told by Mr. Hart would be to introduce a filter network which would have a frequency response characteristic which is proportional to the physiological effect in the human. That would mean a different network for each effect. When this is done, then we'd hope to have an indication of the measuring instrument which would tell us, "okay" or "no go", in other words, it is acceptable or not acceptable. To facilitate the use of a body impedance model in the laboratory, we built a gadget - a cabinet with many resistors and capacitors with switches, so that proper values could be switched in. These values were determined on the basis of a review of the literature taking into account the size ie, height and weight of the person that might interface with the product. The skin resistance would then be a function of area of contact, pressure of contact and, of course, would be a function of the applied voltage and also the duration of the current. In some cases the current is limited by some type of automatic interrupter. Because the capacitance is primarily a function of the area, and the voltage across the skin is primarily not necessarily known in advance we select a value of resistance for the skin interfaces and then using that as a model, we take an actual measurement with the appliance. Then knowing what the current is we have a computer program which allows an adjustment to be made in the resistance values so as to compensate for the new current value. Then by iteration, the adjustments are made to the current value. This procedure allows us to have a loading on the appliance which is comparable to that of the person who may interface with it. This network, which we don't have at this time, would allow us to dispense with the idea of using an equation to determine what the allowable current will be at different frequencies and different waveshapes.

BIEGELMEIER: Thank you. Could you say a few words about the experiments with immersed bodies in water basins you have done some years ago?

SMOOT: It must have been seven years ago or so. We were doing some work not for the purpose of measuring body impedance, but to try to get a distribution of current in the water and in the body of a swimmer in a pool in the event that there was some type of damage to the underwater lighting fixture. What we had to do, of course, was to determine the acceptability of the fixture design when the lens has been broken, which in most cases would also break the enclosure on the bulb. We had to make the judgement whether or not the fixture would be safe under those conditions. So we immersed bodies in the water, limited the current for safety reasons to 5 milliamperes, at 60 Hz. One test situation was to have the body immersed in the water up to the armpits, then reaching out and grab a copper bar with both hands. We then measured the current between the bar and the water. We were able to get 5 milliamperes at about 2 V which comes out to about 400 Ω. For another set of experiments we built a double tank arrangement. The lower tank was high enough to accommodate a standing individual so the water could be at different levels from the waste all the way up to the armpits. The upper tank was arranged so that just the upper part of the body above the armpits would be in the water, and there was a rubber seal so that water didn't leak out. In the upper tank the arms and the shoulders and the neck and most of the head was under water. Then we put electrodes in the two tanks and passed current between the two tanks by way of the body. In that case we were able to measure the voltage distribution over the surface of the body. At 5 milliamperes it turned out that the distribution of voltage was approximately 2/10 of a volt per foot of length of body. So from that you can get some general idea what the impedance might be if you had the body immersed in conductive fluid.

BIEGELMEIER: Thank you very much. I might make a little contribution with that kind of accident. There was the famous Austrian case in which there were three children in a bathtub; the mother took the 4 year old boy out and was drying his hair. Then she went into the kitchen and put the hairdryer into the hands of the

4 year old boy and this boy threw the hairdryer into the bathtub where his two brothers were sitting. Figure 5 illustrates the situation. We investigated that accident very thoroughly because it throws light on this kind of accident in bathtubs and unfortunately they are increasing in number. The water level was low. One boy touched the hairdryer with his back and obviously the current was flowing through the water. On the other side of the bathtub was a conducting pipe. Only one boy was killed because, as we can reconstruct the situation, this boy seeing the hairdryer falling in, wanted to get out of the bathtub so he grasped the waterpipe and at this moment the current was flowing through his heart and that killed him. The other boy in the tub was not hurt and was only crying because he felt the electric shock in his back. This is very typical for accidents in bathtubs. They occur in the cases where people immediately try to grasp an appliance falling into the tub to get it out again. That is a reflex movement. But once the person grasps an appliance, even if it has an insulating handle, up to half an amp will flow through the arm, through the heart, to the bathtub and to the ground causing the fatal accident. Are there any other questions?

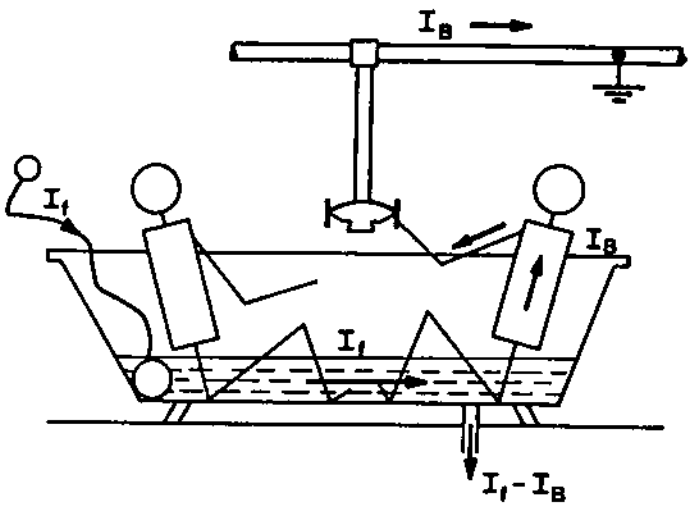

Fig. 5 - Diagram of a bathtub accident.

KRENICKY: Does anybody have any information about influence of skin effect on the distribution of the current passing through the human body.

BIEGELMEIER: You mean at higher frequencies?

KRENICKY: Yes, because skin effect plays a role only at frequencies in kilohertz or megahertz range.

BIEGELMEIER: Anybody on the panel can answer that question?

REILLY: Our information on that is indirect and comes from sensory studies. We do studies in which we subject people to transient electric shocks and also to very high voltages, thousands of volts in some cases of durations running from below one microsecond and longer. Of course with very short duration transient you're talking about a very high frequency spectrum. We find that the sensory response is consistent with a model that says that the high frequency components efficiently stimulate the sensory receptors.

BIEGELMEIER: Thank you Mr. Reilly. Any other questions?

TAYLOR: We just did a study at our laboratory looking at the effects of magnetic induction and the potential hazards from fences near transmission lines to chil-

dren that touch those fences under wet contact conditions. We did some measurements out in the field, but we felt that there is a real need for additional research, not only in terms of the human body impedance but also in terms of the body contact impedance to ground. I suggest that future research be directed along these lines in order to get a better understanding of the full body circuit impedance which totally determines the current.

BIEGELMEIER: Any comment?

SANCES: What impedance could we assume for regular shoes?

BIEGELMEIER: There was a study in the United Kingdom about the insulation resistance of shoes and the values of resistance are very high. One can suppose that dry shoes have a resistance value of tens of kilo-ohms. After shoes have been inserted in water for minutes they have an isolation resistance of kilo-ohms[10,11].

BRIDGES: I have a comment concerning the question of the effect of high frequency currents. I did a very brief study a while back on this subject. There is a body of literature dealing with this topic and with the physiological effects of high frequency current flowing in the body. From the literature that I reviewed, two essential facts have emerged. First of all, as supported by the Dalziel data on perception, the ability to sense a given current flow diminishes as the frequency increases. Therefore, a point finally comes that if you are, for example, grasping a fence near a portable high-frequency transmitter, you may not sense that the current is flowing, and eventually what happens is that the energy dissipated in your fingers exceeds the heat dissipation ability of the tissue, that is the point of a potential danger. Eventually, if the current persists, it may burn the tissue. There's also the possibility of arcs with the radio-frequency potentials and they can be very painful as I have experienced.

BIEGELMEIER: Thank you Mr. Bridges. Any other comments?

WILLS: I have a question for Dr. Biegelmeier. In the case he just described of the children in the tub, was the post-mortem done on the child and if so what was found?

BIEGELMEIER: I don't know.

POMERANZ: You have been all treating the skin as a homogeneous tissue and I'm just wondering if you're aware of some of Dr. Becker's work suggesting that there are points of low resistance at various spots on the body. As I recall, he placed a matrix of electrodes on the surface and mapped out the whole human skin. He found that there were regions where resistance was an order of a magnitude lower than the surrounding tissue. These regions were frequently over motor points where nerves seem to enter muscle, but nobody knows why that correlation was there. Secondly, I've noticed in my own experience using TNS or transcutaneous nerve stimulators that the lower limbs seem to be much less sensitive than the arms, and I'm not sure whether anybody can tell me whether it has anything to do with the nerves being closer to the surface or the skin having different resistivity and the tissues underneath having different pathways. Does anybody have any comments?

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[10] British Central Electricity Generating Board, London: Report on "Protection of post office lines against power system induction and rise of earth potential Project CS4, Decembet 1982.

[11] Irresberger, G. Isolationwiderstand von Schuhen. Swiss Bull. SEV/VSE 46 (1955), p. 159.

SANCES: I guess the thing that is fairly well known, and I'm sure you're familiar with this, is that the distribution of sensory units is less dense in the lower limbs than in the upper limbs. Perhaps that answers your question.

REILLY: In connection with the sensitivity test, we also mapped the body in terms of points of greatest cutaneous sensitivity and we found the lower limbs to be the least sensitive compared with other areas of the body. In relationship to your observation about the mosaic quality of skin impedance, silver staining techniques reveal a mosaic of preferred channels. Approximately one channel per square millimeter has been observed by some experimenters. Also incidentally, that is roughly the spacing for sweat glands on the finger.

BIEGELMEIER: I want to ask if anybody has experience with autopsy after electrical accidents. Can you see whether the heart has fibrillated or not?

LEE: We have done this with animals and you do not find any characteristic features. We've done this with the forensic pathologists, and again you do not find any characteristic features if the animal has died from ventricular fibrillation. What is interesting is that you do not find the ordinary signs of asphyxia if the person has died, or if the animal, has died from sustained respiratory arrest. So given a dead person or a dead animal in the circumstances of an electrical accident you cannot say what was the cause of death. You may find marks on the skin, things like that, but you cannot say that the cause of death was necessarily cardiac or respiratory.

BIEGELMEIER: Thank you Tim. Any comments?

HAUF: We have done in Germany many autopsies and we could not find any changes in the heart if the people had died from heart fibrillation. We find only a large dilated heart but nothing else.

KNICKERBOCKER: I'm going to comment on something totally out of my realm of expertise, but since the group is casting about for fruitful things to look forward to for the future I'd like to share an impression with you. I believe that there has been a low level of expertise applied in autopsy investigations following electric shock. We need some educational programs that would help raise the level of understanding on the part of medical examiners of the issues surrounding electrical incidents.

LEE: I think Guy is right. The cause of death in electric shock in the majority of instances, no matter which mechanism you have is functional and not structural. That's why you don't find anything characteristic because it is a disturbance of function not a disturbance of structure and the pathologist looks for structure.

BIEGELMEIER: Thank you. I would like to thank very much the members of the panel and to wish you a very nice evening.

Chapter 5

Safety and Standards

MECHANISMS FOR HUMAN SENSITIVITY TO TRANSIENT ELECTRIC CURRENTS

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ABSTRACT

A linear sensitivity model is presented for monophasic transients using electrical properties of excitable membranes. Strength/duration relationships derived from the model are in good agreement with our perceptual data using monophasic capacitive discharges. For biphasic stimuli the perceptual model must be extended to account for nonlinear membrane behavior.

KEYWORDS

Electric shock, transient shock, human sensitivity, neuroelectric models.

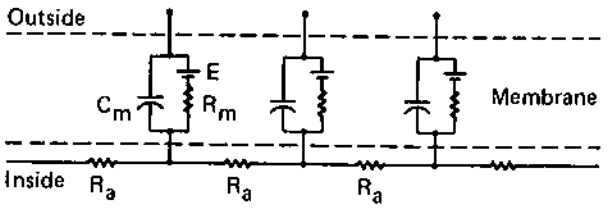
INTRODUCTION

The objective of our research is to quantify human reactions to brief electric currents. One application concerns capacitive discharges that may result from induction in high voltage ac fields, such as with high voltage transmission lines. This paper treats basic neuroelectric mechanisms underlying sensory phenomena.

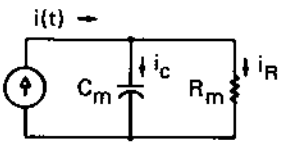
NEUROELECTRIC MODELS

Figure 1(a) represents an electrical model for a nerve fiber. The nodes of a myelinated fiber are individually represented as circuit elements consisting of transmembrane capacitance, C_m, transmembrane resistance, R_m, axoplasm resistance, R_a, and transmembrane resting potential source, E. Figure 2 represents stimulation by a rectangular current pulse injected across the membrane; the transmembrane potential at the point of stimulation responds as shown. Pulses 3 and 4 depolarize the membrane to the point of the action potential, which is propagated along the axon.

The depolarizing effect of transmembrane current injection is frequently analyzed in terms of the simplified circuit model of Fig. 1(b) (cf. Plonsey, 1969). In this circuit, the resting potential, E, is treated as zero, and depolarization is given in terms of the voltage rise across the RC network. In a simplified analysis, R_m is treated as a constant up to the point of the action potential threshold; in actuality, it is relatively constant only up to about 80% of the threshold (McNeal, 1976).



(a) Equivalent circuit representation of myelinated nerve fiber.



(b) Simplified analysis circuit at single node.

Fig. 1 Equivalent circuit models for excitable membranes.

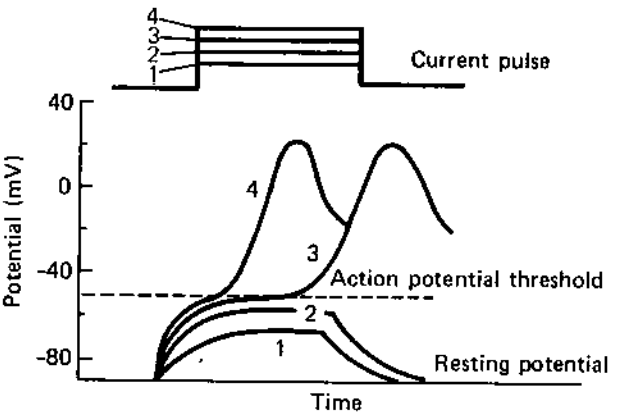


Fig. 2 Transmembrane current initiates an action potential if cell depolarization reaches (3) or exceeds (4) an excitation threshold.

The stimuli used in our experiments can be approximated by exponential current pulses of the form: $i(t) = I \exp(-t/\tau_c)$ for $t \geq 0$, where I is the peak current and τ_c is the stimulus current time constant. The current and charge necessary for depolarization to the action potential threshold, using exponential stimulation, are, respectively (Reilly and Larkin, 1983; Reilly et al., 1982):

$$I/I_{rh} = p^{1/(p-1)} , \tag{1}$$

$$Q/Q_{min} = p^{p/(p-1)} , \tag{2}$$

where I is the peak magnitude of the threshold stimulating pulse, p is the normalized time constant ($p = \tau_c/\tau_m$), τ_m is the membrane time constant (equal to $R_m C_m$), I_{rh} is the rheobasic current (the minimum current required to generate an action potential with an infinitely long rectangular pulse), Q is the threshold charge necessary for initiation of an action potential, and Q_{min} is the minimum threshold charge needed for a very short pulse ($Q_{min} = I_{rh}\tau_m$).

Equations 1 and 2 express strength/duration relationships for current and charge with exponential current stimulation. These relationships are shown by the solid curves in Fig. 3, which show that for short duration pulses ($p < 0.05$), the threshold stimuli are charge-dependent, and for long pulses ($p > 20$), they are current-dependent.

We may compare Eqs. 1 and 2 with corresponding expressions derived by Pearce et al. (1982) for rectangular current pulse waveforms with magnitude I and duration τ_c (the broken lines in Fig. 3):

$$I/I_{rh} = 1/(1 - e^{-p}) , \tag{3}$$

$$Q/Q_{min} = p/(1 - e^{-p}) . \tag{4}$$

The strength/duration relationships shown in Fig. 3 apply when current is injected through a neural membrane. With cutaneous stimulation, the affected membrane is immersed in a three-dimensional electric field. McNeal (1976) models excitation of a myelinated nerve with stimulation by a point electrode 1 mm from a node. He finds that the major effect of membrane depolarization is due to the node-to-node voltage disturbance set up by the stimulating current.

We can readily obtain the steady-state distribution of nodal current in response to a constant-current stimulus with the electrode external to the axon. With reference to Fig. 1(a), the steady-state solution is obtained with the capacitors fully charged. Two quantities are necessary to solve for the current distribution -- the voltage distribution along the axon, and the ratio $R = R_m/R_a$. In our calculations, the voltage distribution applies to a point electrode in a homogeneous medium, namely $V = k/r$, where $k = \rho I/(4\pi)$, r is the radial distance from the electrode, I is the current magnitude from the stimulating electrode, and ρ is the medium's resistivity. R is assumed to be 3, in accordance with assumptions used in other studies (McNeal, 1976).

Figure 4 illustrates the steady-state distribution of nodal current calculated when a point electrode is centered over a node. For a cathodal pulse, the positive y axis represents nodal current efflux, and negative values represent current influx. If the stimulating electrode were anodal, then the plot would be inverted.

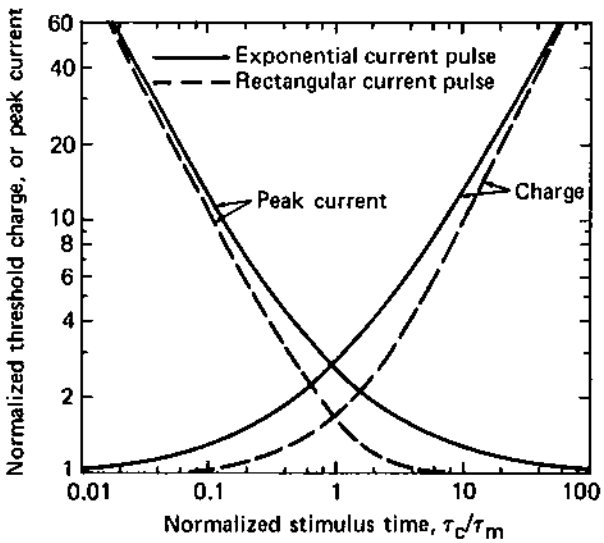


Fig. 3 Normalized strength/duration curve for rectangular and exponential pulses.

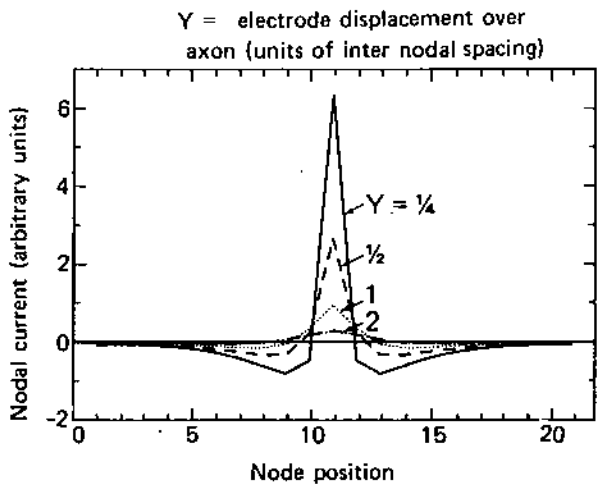


Fig. 4 Steady-state nodal current distribution along a myelinated axon. Stimulating electrode centered over node 11.

An action potential can result only from the depolarizing action of current efflux. We see from Fig. 4 that, if the current magnitude is just adequate to initiate an action potential, cathodal excitation will occur at the node nearest the electrode, and anodal excitation will occur at a more distant node. The plot also indicates a significantly greater sensitivity to cathodal stimulation than to anodal stimulation (about 7:1 for y = 1/4). Our calculations for other electrode/neuron geometries show that polarity selectivity is reduced if the stimulating electrode is centered between nodes or is more distant from the axon.

Many basic models of excitable membrane response assume a constant-current source, with one electrode piercing the membrane. In contrast, a cutaneously applied constant-current source appears as a constant voltage source within the medium at each node. It is instructive to compare models for these two cases.

We find, for example, that whereas the strength/duration relationship for transmembrane current injection depends on the membrane time constant ($\tau_m = R_m C_m$), external electrode stimulation also depends on the axon time constant ($\tau_a = R_a C_m$) (Reilly et al., 1983). It also has been shown that the transmembrane current waveform does not exactly follow the current waveform at the stimulating electrode (McNeal, 1976). Despite these differences, the form of the strength/duration curve derived for a myelinated axon using externally applied current closely follows the model of Fig. 1(b) (McNeal, 1976). Furthermore, as we shall discuss presently, our perceptual data are in reasonable conformance with this model. Also, strength/duration data from direct myocardial stimulation are well modeled by the simple linear model (Pearce et al., 1982). It is therefore persuasive to use the simplified membrane electrical model in comparing cutaneous strength/duration relationships for different waveforms. However, we must remember that the apparent membrane time constant derived from experimental data may include the influence of both membrane and axon time constants, and that the model is restricted to monophasic stimuli.

SENSORY STUDIES WITH MONOPHASIC STIMULATION

This section presents the results of sensory experiments using monophasic capacitive discharge currents, and relates these data to linear models of the previous section. Details of the stimulator, waveform characteristics, and experimental methods have been documented in previous publications (Reilly and Larkin, 1983; Reilly et al., 1982). These points shall be discussed only briefly here.

The stimulator uses a high voltage source to charge a capacitor in either polarity; capacitance and polarity are controlled by the operator. Depending on the procedure, either the operator or the subject may control voltage. The subject discharges the capacitor either through active touching, or by means of an electrode kept in contact with the skin.

Sensitivity measurements were made in individual test sessions of 1 to 2 hours duration. In most procedures, the subject controlled the discharge voltage using the method of self-adjustment and followed a strict protocol that included paced trials, practiced stereotypy of movements or controlled tapping force, and adherence to a detectability criterion.

Figure 5 illustrates perception thresholds using several procedures for delivering positive polarity capacitive discharges. The vertical axis depicts voltage, V, on the charged capacitor corresponding to perception threshold. The horizontal axis gives the capacitance, C. Curve (a) applies to a procedure in which discharges were applied via an electrode that the subject tapped with a "light" force (20 dB on our intensity scale). Tactile sensations due to tap force can significantly alter electrical thresholds. It is therefore very important to monitor and control this parameter in procedures involving active touching (Reilly and Larkin, 1983; Reilly et al., 1982). Curves (b) and (c) apply to a procedure in which the discharge was applied to an electrode held in contact with the skin. Curve (d) applies to discharges to a needle that pierced the corneum. Curves (a) and (c) deviate from a straight line and are approximately parallel. Curves (b) and (d) closely follow an equal charge contour described by $CV = \text{constant} = Q$. (Thresholds for negative polarity stimuli, not shown here, averaged 25 to 30% below those for positive polarity stimuli.)

The contour shapes of Fig. 5 can be related to theoretical strength/duration curves if we account for the variation of stimulus time constants. For discharges to an ideal resistor, the time constant (time for capacitor charge to decay by 1/e) is $\tau = RC$. Although the body does not behave as a simple linear resistance, the time course of discharges will similarly depend on the impedance of the subject. Thus, factors that affect skin impedance will also affect the time constant of the discharge.

Subject impedance to high voltage capacitive discharges has been extensively treated in a previous publication (Reilly et al., 1982). We find that impedance properties are voltage-dependent. Nonlinear effects are especially prominent for capacitive discharges that occur through air breakdown (sparks). These discharges exhibit a limiting plateau voltage of about 550 V, above which sparks can occur, and below which they do not. Thus, the plateau voltage delineates a region above which skin impedance breaks down to spark discharges. Depending on the choice of voltage and capacitance, the stimulus time constant can span a range of 1000:1.

Figure 6 shows strength/duration data for procedures that have been discussed in connection with Fig. 5, namely, a tapped electrode procedure and discharges to a contact electrode. In either case, capacitance was varied from 100 to 6400 pF, and the resulting time constant corresponding to the threshold voltage was measured. In addition, we show data for a test in which capacitance is held fixed, and discharge time constant is varied by adding resistance (up to 2 MΩ) to the discharge circuit (see Reilly et al., 1983). The vertical axis is the normalized threshold charge, Q/Q_{min}, where Q_{min} is the threshold charge determined at the shortest discharge time constant corresponding to the smallest capacitance (100 pF). The solid lines are theoretical values determined from Eq. 2 using various assumed values of τ_m. Taken as a whole, the experimental data are bounded by theoretical curves with τ_m falling between 0.4 and 1.0 ms.

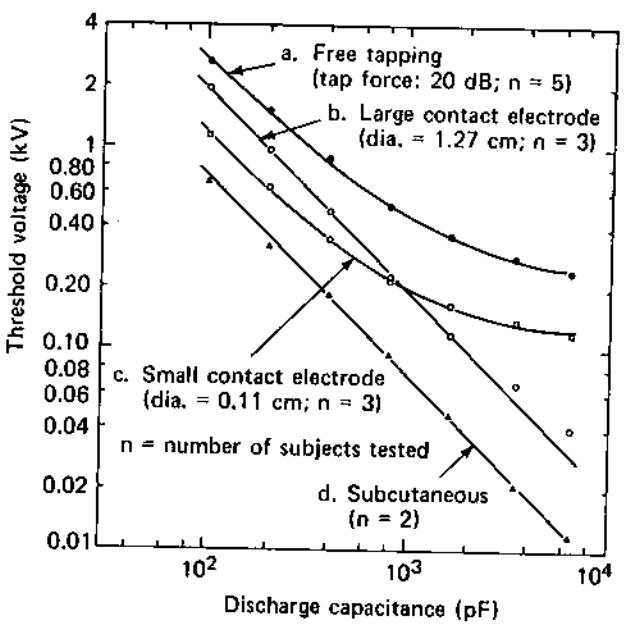


Fig. 5 **Mean sensitivity contours for stimulation of the finger, using capacitive discharges of positive polarity.**

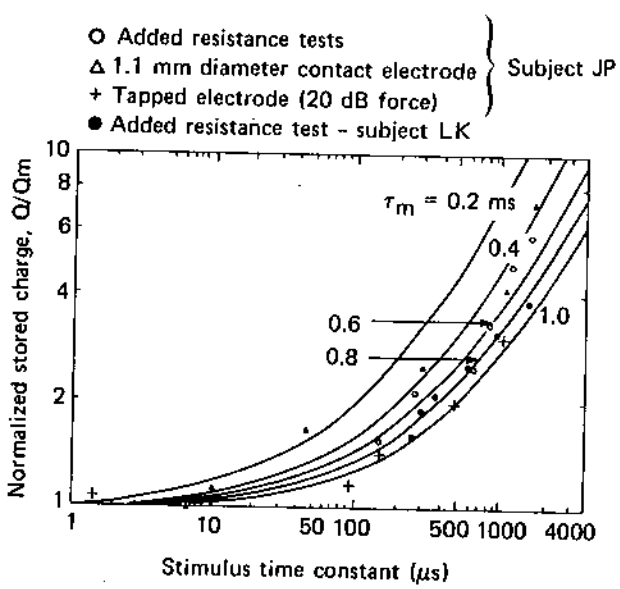


Fig. 6 **Strength/duration data. Points are measurements at perception threshold, normalized by minimum threshold charge.**

In the light of these strength/duration data, we can explain the contour shapes of Fig. 5. Curves (a) and (c) deviate from constant charge contours because of the increased current time constant, which results mainly from increased skin impedance as voltage is reduced. Curves (b) and (d) follow a constant charge contour because electrode impedance (and, therefore, stimulus time constant) is sufficiently small throughout the contour. The low impedance associated with curve (b) results from the large contact area. The low impedance associated with curve (d) results because the subcutaneous electrode bypasses the high impedance corneal layer. The vertical displacements of the curves may be explained by current density effects (Reilly et al., 1983) and by tactile masking (Reilly et al., 1982).

SENSORY STUDIES WITH BIPHASIC STIMULATION

Monophasic capacitive discharges, treated in the preceding paragraphs, are special cases of a more general class of transient waveforms that, although of brief duration and limited charge transfer, may exhibit an oscillatory pattern. We studied biphasic transients by adding inductance to the discharge path. Figure 7 shows an example of the resulting voltage and current waveforms for discharges from a 400 pF capacitor to an 8 mm diameter contact electrode on the fingertip. The measured oscillatory waveforms are similar to damped sinusoidal functions calculated for an ideal circuit consisting of a capacitor discharging through a series resistance and inductance (RLC circuit), in which the damping time constant is given by $\tau_c = 2L/R$, and the oscillatory frequency is $1/(2\pi\sqrt{LC})$.

There are important similarities and differences to note with respect to the monophasic waveforms reported in the previous section and the biphasic waveforms discussed here. For a given initial capacitor voltage and a complete discharge, the net charge, Q, and energy, U, are the same in either case: $Q = CV$ and $U = 0.5\ CV^2$. In contrast to equality of net charge, however, the maximum displaced charge during a monophasic segment of the oscillatory waveform, Q_m, is greater than with the monophasic discharge. The maximum displaced charge is determined by $C\Delta V$, where ΔV is the change in capacitor voltage during the initial phase of the current waveform. In Fig. 7; for example, $Q_m = 0.22\ \mu C$ ($\Delta V = 550$ V), and $Q = 0.14\ \mu C$ ($\Delta V = V = 350$ V).

Figure 8 presents the normalized mean threshold charge for four subjects; a 400 pF capacitor was discharged to an 8 mm diameter electrode contacting the fingertip. Inductance is depicted as an independent variable; however, neuroelectric considerations suggest that the important sensitivity parameters include the oscillation frequency and decay time constant of the stimulus, as well as the nonlinear suprathreshold response of the excited membrane. Oscillation frequency (upper horizontal scale) and decay time constant (geometric means), are also included in the figure.

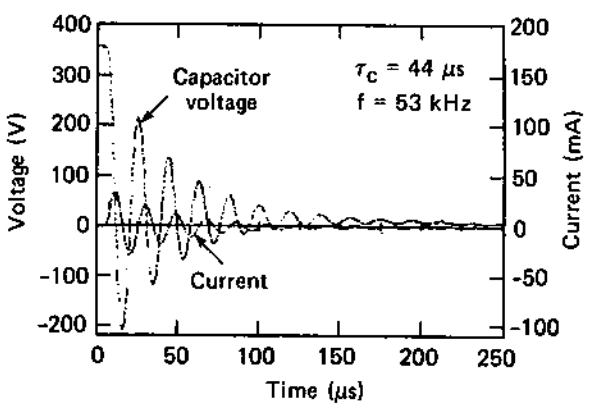


Fig. 7 Oscillatory waveform for discharge to finger from a 400 pF capacitance. Series inductance = 25 mH, contact electrode diameter = 8 mm.

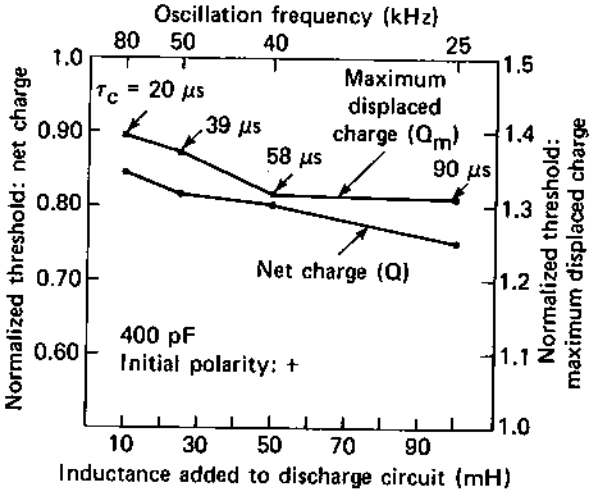


Fig. 8 Effect of rapid current oscillation on sensitivity to transient discharges.

Two normalized charge parameters are depicted: net displaced charge, Q', and maximum displaced charge, Q'_m. For both parameters, the normalization is obtained by dividing the measured quantities by threshold charge for the monophasic stimulus (i.e., the value of Q with L = 0). Neither charge parameter fully accounts for sensitivity: both Q' and Q'_m decrease with added inductance.

Past studies demonstrate that a biphasic pulse is a less effective stimulus than a monophasic pulse of the same current magnitude (Saunders, 1974; Honert and Mortimer, 1979; Szeto and Saunders, 1982; Bütikofer and Lawrence, 1978). The findings of Honert and Mortimer are particularly enlightening with respect to our studies. They directly stimulated myelinated axons with 50 μs rectangular pulses. They demonstrated that if a suprathreshold cathodal pulse is followed by an anodal pulse, the membrane action potential process can be reversed and entirely abolished. The magnitude of the anodal pulse necessary to abolish the action potential was shown to depend on the degree to which the cathodal pulse, taken by itself, was above threshold, and the time delay between anodal and cathodal pulse.

For the biphasic stimuli associated with Fig. 8, the initial half cycle taken alone would exceed the perception threshold by the factor Q'_m. The following half cycle of opposite polarity attenuates the effectiveness of the initial phase. The attenuation factor shown in Fig. 8 lies between 1.3 and 1.4, and is consistent with the factors estimated by Honert and Mortimer (1979).

The response model for monophasic pulses is not appropriate for the biphasic case, because membrane events after the initiation of an action potential are highly nonlinear. Furthermore, any biphasic model must account for polarity asymmetry, as suggested by our perceptual data (Reilly, et al., 1982) and by neural response studies (Oester and Licht, 1971).

DISCUSSION

We have analyzed models describing neuroelectric sensitivity. For monophasic currents, we have evaluated a simple linear model. Strength/duration data from our sensitivity tests are consistent with that model. Our data show that human sensitivity to monophasic transients is governed by a charge criterion for currents that are brief relative to the time constants of the excitable cell membrane. Within this short time frame, sensitivity is not affected by the fine structure of the current waveform. Conditions that extend the stimulus duration beyond this time frame should depress sensitivity, such that an increase in charge is required to reach threshold. With capacitive discharges, the skin impedance is one such factor.

Our data indicate an equivalent membrane time constant between 0.4 and 1.0 ms. However, the apparent time constant determined from cutaneous tests may not be the same as the classical definition based on transmembrane current injection; theoretical considerations suggest that the axon time constant also affects the strength/duration relatonship.

With biphasic stimuli, we do not expect conformance with the linear model unless the oscillations are considerably slower than those studied here. Taking the neural time constant to be on the order of 1 ms, oscillation frequency would need to be well under 1 kHz to correspond with the linear model of Fig. 1(b).

From studies of low-voltage sinusoidal stimulation, we know that most neural fibers are maximally sensitive to stimulus frequencies between 100 and 200 Hz (Liberson, 1971) and that a painful stimulus may be rendered innocous by increasing the frequency beyond a few kHz (Saunders, 1974). Other studies demonstrate that human sensitivity to sinusoidal currents (as measured by perception sensitivity or muscle contraction) demonstrate a region of maximum sensitivity for frequencies below about 300 Hz (Dalziel, 1972). These effects suggest that neural time constants may underlie many observed differences in waveform sensitivity.

ACKNOWLEDGMENTS

This work was supported by the State of Maryland's Power Plant Site Evaluation Program and by the Canadian Electrical Association. We appreciate the work of R. J. Taylor for impedance studies, V. T. Freeman for software development, L. B. Kittler for experimentation with subjects, and M. J. Flynn for hardware support.

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DISCUSSION

ANTONI: I found it very interesting in your presentation that an anodal pulse following a cathodal one can eliminate the effect of the first pulse. I think this is also in agreement with the results by the group of Green*, who found that oscillating thresholds depend on the length of stimulating wave applied to a heart muscle. You mentioned that in general an anodal stimulation needs more current than the cathodal stimulation. But in a cardiac muscle there is a special point which I would like to mention. Consider the action potential. If you stimulate in the late phase of repolarization then it is clear that cathodal drop is smaller than anodal drop. However, in the early phase of repolarization the effect is different: if you stimulate with a cathodal pulse, there is no effect; it's irresponsive, it's refractory. But if you apply an anodal pulse, the heart will repolarize and if you switch off, an action potential can be elicited. This means that with an anodal pulse you can elicit an action potential much earlier in the refractory phase than with a cathodal pulse. This has practical implications. It was observed in clinics with pacemakers that if unipolar cathodal pacemakers were

* see article 7.3, Fig. 9 in these proceedings.

used in the heart and an anode elsewhere, then there was little fibrillatory danger. But if bipolar electrodes were used (in which there is also an anodal stimulus), sometimes it happened that arrhythmias or fibrillation occurred - very probably because of the described effect, (because the anode can stimulate early in the refractory phase, and the anodal threshold is lower than the cathodal one). I think this is very important practically.

REILLY: I thank Dr. Antoni for his comments. Apparently, while many excitation properties of neurons are shared by cardiac muscle, the latter also includes additional complexities due to spatial and temporal patterns. The phenomenon of anodal excitation, described by Dr. Antoni can also be observed in neural excitation during "anodal break", i.e., cessation of an anodal pulse. This effect can be seen in the work of McNeal** (1976). He demonstrates that depolarization of the membrane can be induced at the break of a cutaneously applied anodal stimulus. Furthermore, our studies with anodal/cathodal sensitivity differences (these proceedings, No. 7.1, 1983) show that for specific geometries the neuron can be more sensitive to an anodal than a cathodal stimulus. Possibly, mechanisms which account for these observations may also be found in the cardiac model.

GEDDES: Have you done any studies to determine the time constant at different temperatures of excitable tissues?

REILLY: No I haven't. There is some information that shows that it is an important parameter but we certainly haven't done that.

ANTONI: Your findings concerning a cancelling influence of the anodal current phase on the excitatory effects of the cathodal phase may apply also to a cardiac muscle and may explain some findings of Green and coworkers (see their paper in these proceedings: No. 7.3, Fig. 9). Moreover, in a cardiac muscle it must be taken into account that, if stimuli are applied during the absolute refractory period, an anodal pulse may (in spite of the "refractoriness") be able to induce an action potential by initially hyperpolarization followed by depolarization when the current is switched off.

REILLY: I thank Dr. Antoni for his comments. Apparently, while many excitation properties of neurons are shared by stimulation of cardiac muscle, the later also includes additional complexities due to spatial and temporal patterns. The phenomenon of anodal excitation, described by Dr. Antoni can also be observed in neural excitation during "anodal break", i.e., cessation of an anodal pulse. This effect can be seen in the work of McNeal (1976). He demonstrates that depolarization of the membrane can be induced at the break of a cutaneously applied anodal stimulus. Furthermore, our studies with anodal/cathodal sensitivity differences (these proceedings, No. 7.1, 1983) show that for specific geometries the neuron can be more sensitive to an anodal than a cathodal stimulus. Possibly, mechanisms which account for these observations may also be found in the cardiac model.

** McNeal, D.R. (1976). "Analysis of a Model of Excitation of Myelinated Nerve." IEEE Trans. on biomed. Eng., BME-23 (4), pp 329-337.

BODY IMPEDANCE FOR TRANSIENT HIGH VOLTAGE CURRENTS

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ABSTRACT

High voltage, short duration capacitive discharge measurements of human body impedance have been accomplished for different paths through the body. Skin contact impedance and internal body impedance between various locations on the body were examined. Impedance measurement instrumentation capable of measuring impedance once every 0.05 μs was used. Voltages of 100 to 2000 V were applied giving peak currents of 0.2 to 5.0 A. The voltage and current waveforms had time constants ranging from 0.2 to 5.0 μs. These short time constants are consistent with safety requirements, allowing testing with people. However, these impedance measurements can be interpreted as limiting values for shocks of longer, possibly lethal duration. The initial total body impedance between the palm of the hand and the sole of the foot was found to be about 500 to 530 Ω. The internal body impedance for the same current path was found to be about 430 Ω. The internal body impedance between the wrist and the calf was found to be about 50% of the internal body impedance measured between the palm and the sole of the foot.

KEYWORDS

Human body electrical impedance; initial body impedance; internal body impedance; skin impedance.

INTRODUCTION

The work reported here is part of an ongoing investigation into human reactions to transient high voltage currents (Reilly and others, 1982). Another paper in this volume, by J. P. Reilly and W. Larkin, discusses sensory aspects of this work, while this paper focuses on body impedance under transient high voltage conditions. In order to characterize stimulus waveforms, we studied transient current and voltage waveforms applied to the body. The time constants for a capacitive discharge are critically dependent on the impedance of the discharge circuit of which the human body is a key element (the time constants increase with circuit impedance). Another reason for this work is that understanding human body impedance is important in determining allowable safe voltage levels for exposure to the body.

Body impedance for transient high voltage currents is significantly different from body impedance measured using steady state currents from low voltage ac or dc sources. A low voltage impedance model of the body can help illustrate the difference between transient impedance and steady state ac impedance. Figure 1 depicts a simplified electrical model suggested by Biegelmeier and Rotter (1971), Edelberg (1971), and Tregear (1966). This is a low voltage linear model (component values do not change with voltage or time). The steady state impedance of Fig. 1 is given by Eq. 1:

$$Z_L = R_B + \frac{R_2 \left(R_1 + \frac{1}{j\omega C_1}\right)}{R_1 + R_2 + \frac{1}{j\omega C_1}} . \quad (1)$$

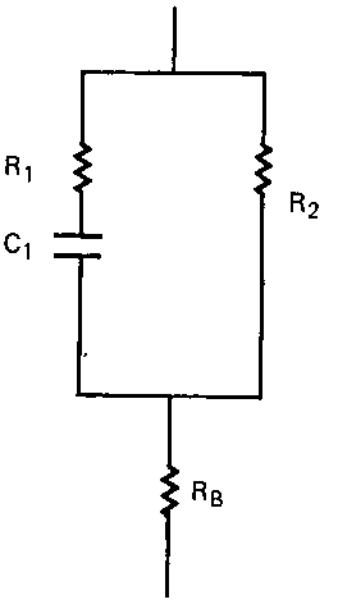

Fig. 1 Simplified impedance model of body.

The long duration or steady state impedance is sometimes called the conventional total body impedance (Biegelmeier, 1978).

Now for transient current, the capacitor C_1 is initially uncharged and the circuit initially behaves as if the capacitor were a low impedance conductor. Thus the initial body impedance, Z_i, should be

$$Z_i = R_B + \frac{R_2 R_1}{R_1 + R_2} . \quad (2)$$

For high voltage discharge we have found the electrical model given in Fig. 1 to be inadequate (this will be discussed further). But the general idea that transient or initial impedance is different than steady state impedance is well illustrated by the model shown in Fig. 1 and by Eqs. 1 and 2.

We examined three aspects of body impedance: skin impedance, internal body impedance, and total body impedance. The skin impedance is determined by contact area and type of contact. The skin impedance is represented by the circuit components R_1, R_2, and C_1 shown in Fig. 1. The internal body impedance is determined by the path through the body (contact locations). The internal impedance is represented by R_B in Fig. 1. R_B may include some contact area dependence and thus a fraction of the ohmic skin impedances. Total body impedance is the sum of the skin impedance and the internal body impedance.

TOTAL BODY IMPEDANCE VERSUS TIME

Total body impedance was measured using capacitive voltage discharge to the subject. Figure 2 contains a diagram of the measurement schematic, and Fig. 3 is an example of the measured total body impedance versus time using a 500 V discharge from an

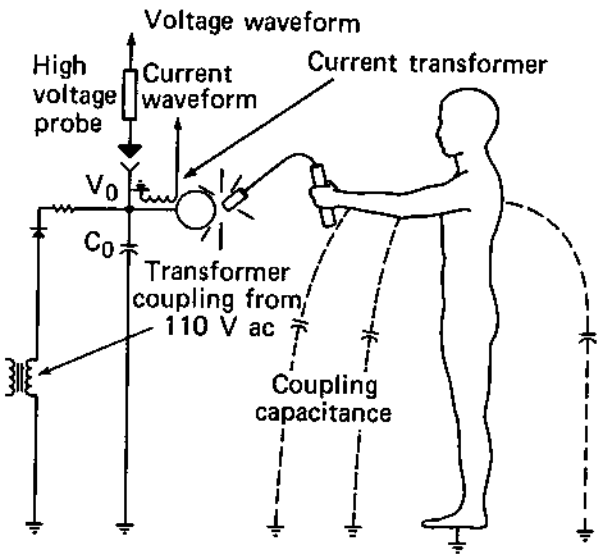

Fig. 2 Body impedance measurement with capacitive coupling of arm and upper portion of the body to ground.

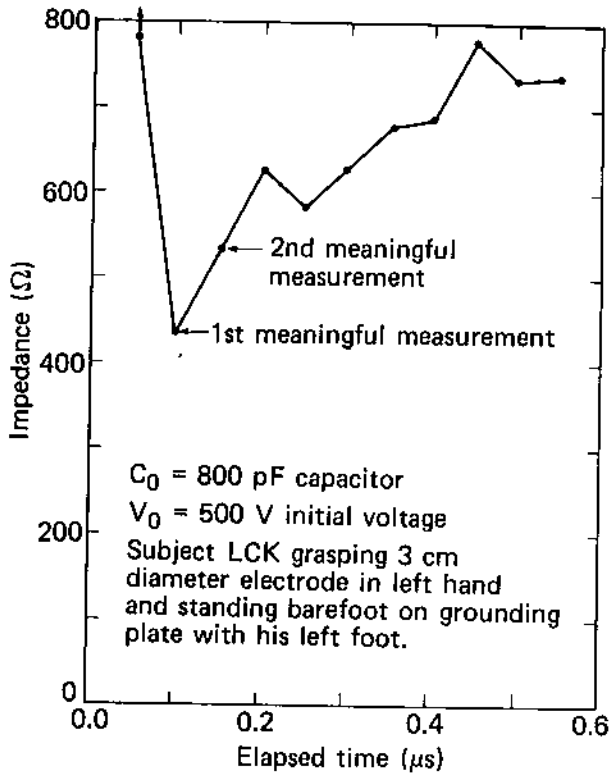

Fig. 3 An example of body impedance measurements versus time. The initial spark discharge occurred between 0.0 μs and 0.05 μs. The time constant for the voltage waveform was 0.7 μs.

800 pF capacitor. Measurements of the current and voltage were done simultaneously once every 0.05 μs using a Nicolet digital oscilloscope. The voltage was measured using a high impedance (500 MΩ), high voltage probe, and the current was measured using a fast rise time (15 ns) current transformer. The subject grasped a 3 cm diameter cylinder in his left hand while standing with his left bare foot on a copper plate.

The impedance measurement at the onset of the discharge is not always meaningful because of the limited current rise time response of our instrumentation. In Fig. 3, the second measured impedance is the first meaningful measurement, 434 Ω (434 V and 1.0 A current). The second meaningful impedance measurement is 538 Ω (400 V and 0.744 A current). Each of these measurements is the average of four separate electrical discharges.

The first meaningful impedance measurement was found to vary as much as 50% as a function of the body's distributed capacitance to ground. Figure 2 also shows a schematic representation of this distributed capacitance. The distributed capacitance requires a surface charge on the body when it is in an electric field. To supply the surface charge, the initial current is increased above the current that passes through the body. As a result, the first impedance measurement is not representative of body impedance alone. The second impedance measurement appears to have very little current supplying the surface charge (only 10% variation with distributed capacitance) and thus is more representative of the true body impedance. For this reason, it is used as "initial" body impedance for this study.

INITIAL TOTAL BODY IMPEDANCE MEASUREMENTS

The arrangement for measuring the initial total body (hand-to-foot) impedance is depicted in Fig. 2. The subject's bare foot was placed on a flat copper sheet (14 by 25 cm), which was the ground electrode. The cylinder used for a grasping hand contact was 3 cm in diameter and 8 cm long. The foot contact area was the area of the footprint (150 to 250 cm^2). The area of the hand contact was approximately the area of the cylinder (75 cm^2). Three separate impedance paths were measured: left hand to left foot, right hand to left foot, and left hand to right hand. In the case of hand-to-hand measurements, the ground conductor was another 3 cm diameter cylinder. Skin preparation was either dry (nothing was placed on the skin, and natural perspiration was not controlled or eliminated) or wet (electrocardiogram electrode paste ["Liqui-cor," Burdick Corp.] was applied to both contact surfaces). Values of the mean and standard deviation of total impedance measurements for seven adult males are given in Table 1.

TABLE 1. Initial Total Body Impedance (Ω)

Path	Mean	Standard Deviation
Dry Skin		
Left hand/left foot	533	52
Right hand/left foot	521	37
Right hand/left hand	508	29
Wet Skin		
Left hand/left foot	516	55
Right hand/left foot	507	36
Right hand/left hand	490	36

Generalizing from Table 1, the hand-to-hand current path appeared to have an initial total body impedance of about 95% of the hand-to-foot current path. The differences between impedances using large area dry contact and large area wet contact were small (the wet was about 97% of the dry impedance). However, it should be noted that significant differences between wet and dry contact impedance do exist for small contact areas as shown in Table 2, which gives data for smaller electrodes (1.14 and 12.6 mm diameters).

TABLE 2. Initial Contact Impedances for Dry and Electrode Paste Contacts to the Body (Ω)

Initial Voltage (V)	Electrode Diameter					
	1.14 mm			12.6 mm		
	Dry	Paste	Ratio	Dry	Paste	Ratio
100	-	-	-	408	183	0.45
200	4870	500	0.10	374	189	0.51
500	4040	415	0.10	326	188	0.58
1000	1360	428	0.31	312	184	0.59

These measurements were done on the calf of the leg with the electrode and ground 10 cm apart. The wet contacts used electrode paste (Liqui-cor) rubbed into the skin in a circle of 4 to 5 cm diameter with enough paste on the skin to keep it wet. Table 2 shows that wet and dry impedances differ by a greater factor for smaller contact areas. Table 2 also shows that the skin impedance has some voltage dependence for small contact areas that disappears for larger areas. No voltage dependence was observed for wet contact with electrodes larger than about 12 mm in diameter.

INTERNAL BODY IMPEDANCE

The internal body impedance determines the minimum impedance one might experience when body contact is made where the skin is broken or damaged. To estimate the internal body impedance, the skin impedance can be subtracted from the total body impedance. The skin impedance for large area contacts was estimated by placing electrodes (about 100 cm^2 each) close together on the body. One location pair used was the top and bottom of the foot. The measured wet skin initial impedance varied from 70 to 100 Ω. For simplicity the internal body impedance for hand-to-foot or hand-to-hand pathways can be estimated from Table 1 by subtracting 85 Ω (approximate average for the wet skin impedance) from the initial total body impedance (wet contacts). This results in a range of internal body impedances of about 400 Ω for the hand-to-hand path and about 430 Ω for the hand-to-foot path. Thus we find the total impedance is dominated by the internal body component, and the skin impedance makes a relatively minor contribution. This may seem surprising, but remember this result is for high voltage, short duration transients with large area contacts to the body.

While the subject stood barefoot on a flat plate ground electrode (14 by 25 cm), a 5 cm^2 contact electrode (with wet contact conditions) was moved to various contact locations on the body and the impedances for the various electrical paths through the body were determined. We also examined the internal body impedance as a function of body contact location. The skin contact impedance was subtracted from these body impedances to give the internal body resistance as a function of body location. These measurements of internal body impedances are shown in Fig. 4 as percentages of the total internal body impedance between the sole of the foot and the palm of the hand. Similarly, the percentage of total internal body impedance between the hands is shown in Fig. 5 for various locations along the arms.

One important conclusion from a safety viewpoint for these measurements is that only 50% of the total internal body impedance is found between the wrist of the arm and the calf of the leg. The other 50% is between the wrist and the palm and between the calf and the sole of the foot. This is important when contacts to the body are between the wrist and the calf. The allowed safe voltage for this case must be half the safe voltage for contacts between the palm and sole of the foot.

Biegelmeier and Rotter (1971) give estimates of internal body impedance in percentages of the total hand-to-foot impedance for lower voltage tests. Their estimate of the foot-to-calf percentage is 32.3% as compared with our estimate of 30%. Their estimate of the palm-to-shoulder impedance is about 44.2%, while our estimate is 40%. Other points of comparison between our estimate and theirs are more difficult because of differences in points of contact, but it appears our estimates are in general agreement with theirs (see Fig. 4).

TRANSIENT ANALYSIS

We compared the theoretical transient behavior of the impedance model shown in Fig. 1 with the measured transient behavior of discharges to the human body. Theoretical

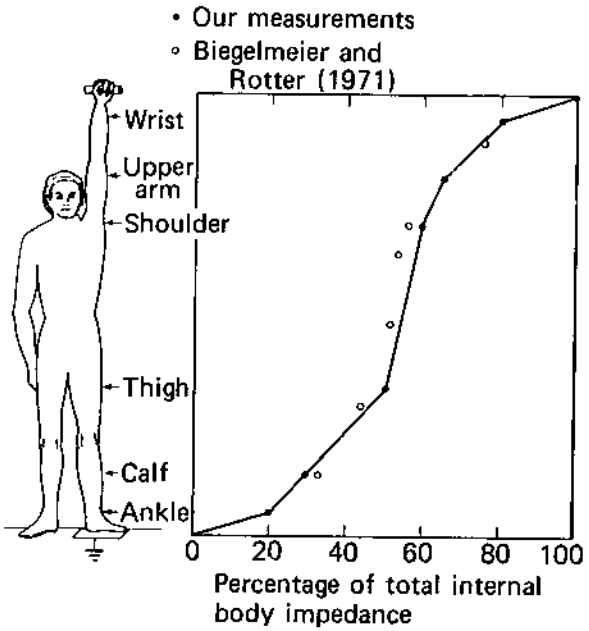

Fig. 4 Internal body impedance between the sole of foot and various locations along the body.

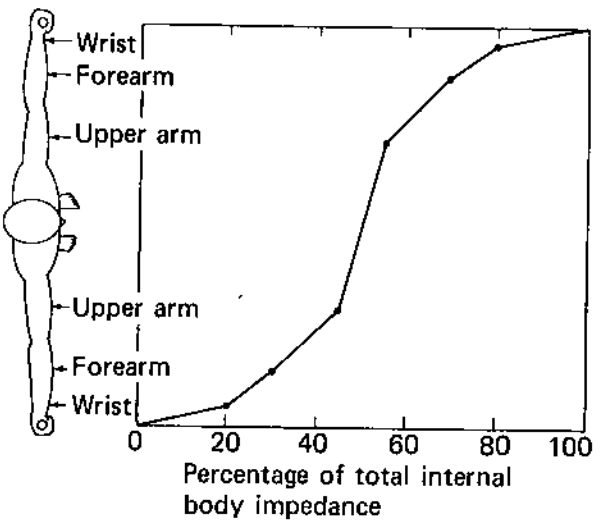

Fig. 5 Internal body impedance from one hand to various locations along the arms.

values of R_1, R_2, R_B, and C_1 were varied until the calculated transient response gave a best fit to the measured subject response. Figure 6 shows the voltage and current of a 1014 V discharge from a 3200 pF capacitor to the calf of the leg using a contact electrode 12.6 mm in diameter and a ground contact 10 cm away. The voltage changes from 1014 to 300 V while the current changes from 3 A to 0.2 A during a 3 μs discharge. Figure 7 shows impedance versus time for the discharge shown in Fig. 6 (the time origin in Fig. 7 starts at the peak current time shown in Fig. 6). The failure of the theoretical model to follow the actual data for more than one μs indicates the limitations of the simple model shown in Fig. 1. However, if the components values in Fig. 1 were voltage or time dependent, a theoretical transient response could be found that would be more in keeping with the measured response. For example, if R_2 were to change from 575 to 800 Ω as the voltage changed from about 1000 V to 300 V, the theoretical transient response should more closely track the measured response.

SUMMARY

The initial value of the transient total body impedance between the palm of the hand and the sole of the foot was found to be about 500 to 530 Ω for large area contact. No steady state body impedance measurements were done during this investigation. The transient skin impedance was found to be very dependent on contact area. The ratio between wet and dry contact impedance was similarly dependent upon contact area. For large area contact (about 100 cm^2), the ratio is about 1 to 1. For about 1 cm^2 contact areas, the ratio is about 1 to 2, and for an area of about 0.01 cm^2, the ratio is about 1 to 10. The internal body impedance for the palm-to-sole current path is about 430 Ω. About 50% of the internal body impedance is between the wrist of the arm and the calf of the leg. The other 50% of the internal body impedance is from the wrist to the palm of the hand and from the calf to the sole of the foot. Also, the components of a simple impedance model of the body must be voltage and/or time dependent for that model to have the transient response one measures for the human body.

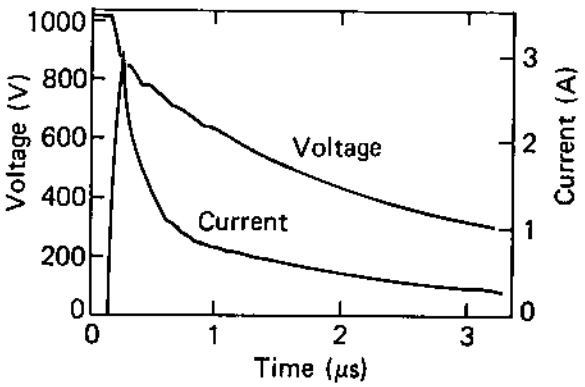

Fig. 6 Voltage and current during discharge from a 3200 pF capacitor into the volar calf. The contact diameter was 12.6 mm.

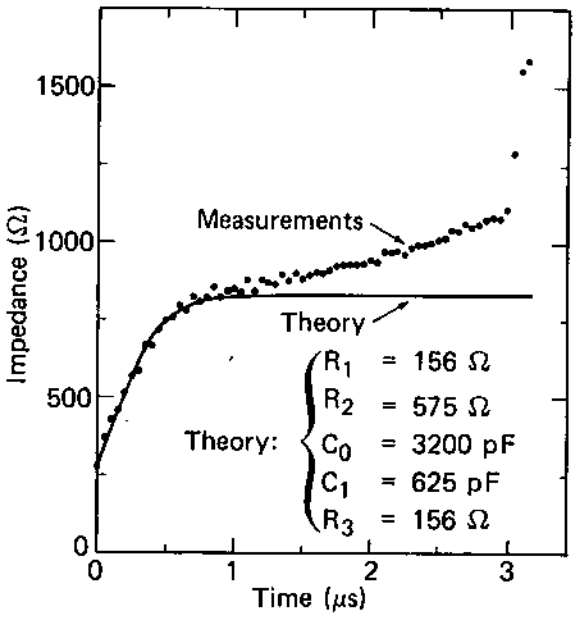

Fig. 7 Impedance versus time for direct contact to the volar calf. The contact diameter was 12.6 mm. See Fig. 6 for voltage and current waveforms.

ACKNOWLEDGMENT

The author would like to express his gratitude to the State of Maryland's Department of Natural Resources and the Canadian Electrical Association for their support of this effort. The conclusions expressed herein do not necessarily reflect the views of these two agencies. Special thanks go to J. P. Reilly of the Applied Physics Laboratory for his direction and advice relative to the work presented here.

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DISCUSSION

J.E. BRIDGES: (1) Was there any difference in the physical arrangement of the apparatus for the first measurement versus the second.? (2) Do you attribute better normalization of the second measurement to body being charged-up? Could it be an electrophysical phenomena?

R. TAYLOR: (1) No. (2) The first measurement was observed to change about 50% as the coupling capacitance to ground was charged. However, the second measurement changed less than 10% for the same changes in coupling capacitance. Apparently, the charging time of this coupling capacitance is less than 50 ns (the time between the first and second measurement).

JACKMAN: Would you expect the model for impedance of the body to hold also for cardiac muscle, and would you also expect the same qualitative change in impedance with time but maybe with different rates?

TAYLOR: One of the key elements in the human body model that we're showing here, is the skin. The skin is acting as a capacitance. I would assume that the heart muscle wouldn't have the same dielectric constants as the skin. Therefore, I think that the model I'm showing here is for the total body with a good part of it being the skin of the body, and I would not expect that model to be applicable to the internal organs.

DANGER LEVELS OF SHORT (1mSec to 15mSec) ELECTRICAL SHOCKS FROM 50Hz SUPPLY

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ABSTRACT

An investigation was undertaken to determine the ventricular fibrillation threshold of anaesthetised dogs subjected to external application of electrical shocks between a foreleg and a hindleg. The shocks were short (1ms to 15ms) sections of 50Hz power waveform with the phase of the current controllable to within 1ms and applied at a known time in the heart cycle (controllable to 1ms from 50ms to 200ms after the cardiac 'R' wave). The object of the experiment was to determine if there was an increase in user safety if power circuit breakers operated faster than the usual 20 - 30ms breaking time. The results showed that no significant improvement in safety would result unless the break time was less than 2ms.

KEY WORDS

Ventricular fibrillation threshold; electric shock; electrical safety; circuit breaker.

BACKGROUND

Fatal electric shock is usually associated with a disruption of normal heart function which is known as Ventricular Fibrillation (VF). This condition is irreversible except by the use of a special device (defibrillator) and if not treated within minutes, the circulation through the brain becomes inadequate to sustain life.

The recent introduction of fast-acting circuit breakers to the commercial market makes it necessary to define the maximum safe levels of short electric shock pulses. These levels were determined in relation to the occurrence of ventricular fibrillation. Very little information is available about the effects of 1ms to 25ms shocks derived from 50Hz AC.

The levels of electric shock which have produced VF are reviewed by Biegelmeier & Lee (1980) for various time lengths of shock down to 8.3ms. Jacobsen, Buntenkotter and Reinhard (1975) have shown that short electrical shocks are

particularly dangerous if the shock is delivered at a time which corresponds to the beginning of the 'T' wave of the electrocardiogram (ECG).

MATERIALS AND METHOD

This report describes a study which was performed to investigate the effects of short current pulses upon cardiac ventricular fibrillation thresholds in normal atmospheric conditions.

In this series of experiments beagle dogs were used as subjects. These animals weighed between 11 and 17kg. The work was performed while the subject was under general anaesthesia (GA).

General anaesthesia was established in two different ways. In one group of dogs sleep was induced with pentobarbitone and maintained with the volatile inhalational agent halothane together with 70% nitrous oxide, a gaseous agent. This sequence was used to enable comparisons to be made with previous work where a similar technique was used (Green, Raftery, Gregory, 1972). Since it was proposed to extend these studies to the hyperbaric environment, where volatile and gaseous agents would prove difficult to control, a second series of experiments was carried out. In this group of dogs anaesthesia was induced with pentobarbitone as before but maintained by slow intravenous injection of pentobarbitone and ketamine. Before the start of the experiments, all dogs were sedated using "Hypnorm", (0.2 ml/Kg) an opiate and major tranquilliser combination and treated with atropine (0.02 mg/Kg).

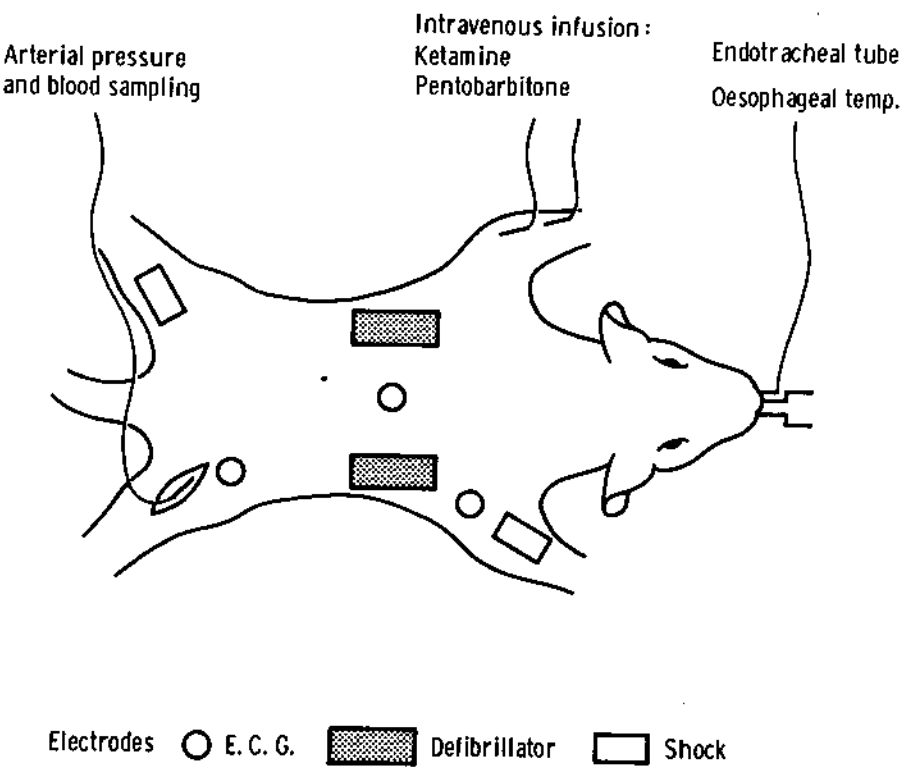

Fig. 1. Placement of shock electrodes and monitoring sensors.

During the procedure every animal breathed spontaneously through an endotracheal tube and the inspired oxygen concentration was kept at 28-30%. The ECG was monitored using non-polarising electrodes (Medicotest). Blood pressure (BP) was measured from a cannula in the femoral artery which also provided arterial blood samples. The pressure transducer used was an Elcomatic type EM 750 and was connected to a "Roche" type 224 signal conditioner.

An impedance pneumograph signal was available from the ECG electrodes via a "Roche" 107 monitor. Estimations of blood pH, carbon dioxide and oxygen were made every 15 minutes and of blood sodium and potassium every 30 minutes during the experiment. Each dog's temperature was monitored using a thermistor probe in the oesophagus and maintained using an electrically heated blanket. The shocks were applied between a foreleg and a hindleg using metal plates (5 x 3 cm) covered with conducting jelly. The impedance of animals varied between 300 and 450Ω. This could not be reduced, even by increasing the size of the electrodes or using both hind limbs and both fore limbs in parallel. Defibrillation was achieved using 60 or 100 joules from a standard DC defibrillator (Cambridge Medical) applied via two metal plates (6 x 7 cm) held onto the chest by elastic bands (Fig. 1).

The test shock was derived from a specially constructed machine (ERA Technology Limited) which was triggered by the ECG 'R' wave. The shock consisted of a short (up to 25ms) section of 50Hz - sine waveform which could be started at any required phase of the 50Hz signal and at an accurately controlled time from the 'R' wave trigger. The generator provides shock impulses (up to 3kV peak) entirely independent of the power mains and once the required delay, phase and durations

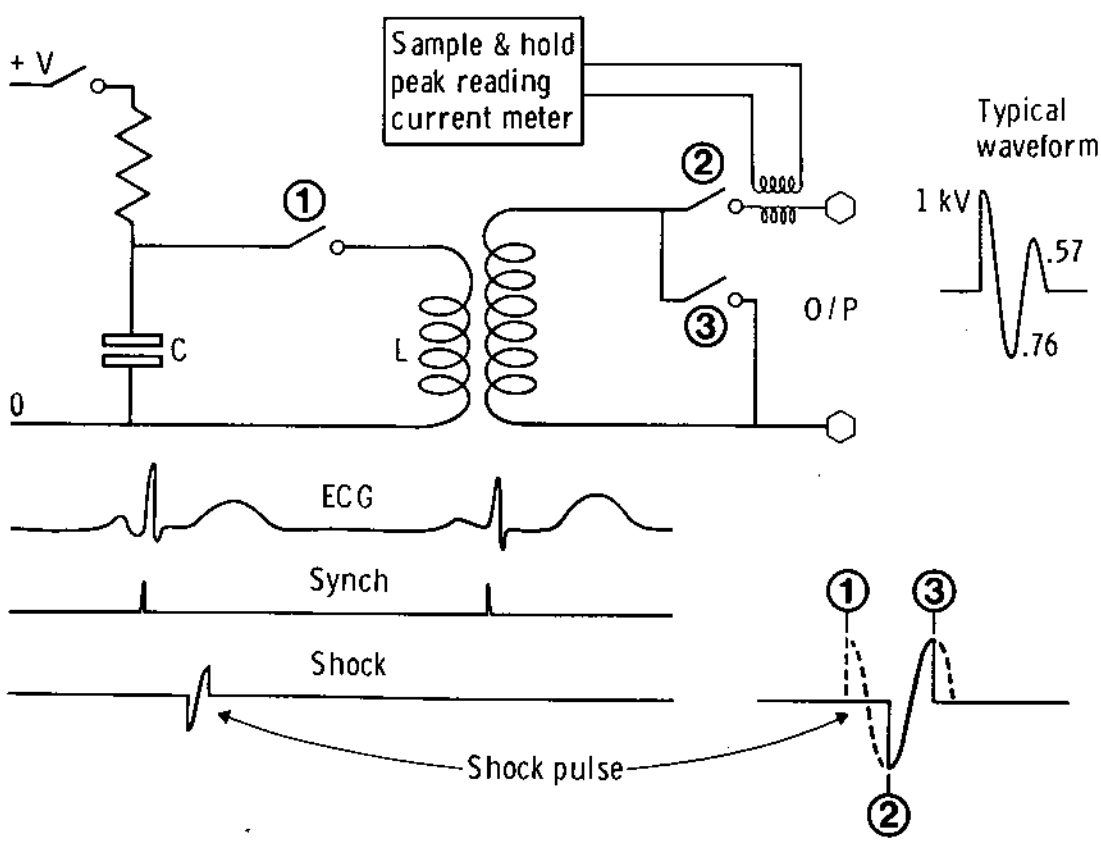

Fig. 2. Block diagram circuit or the shock generator.

have been set on its controls (to 1ms accuracy) it will deliver the shock at the set delay time after the first 'R' wave following pressing the 'fire' button. The actual current flowing through the animal was monitored via an isolating transformer in series. The system used (Fig. 2) consists of an inductance (L) and capacitor (C) which has the capacitor charged to a D.C. voltage level. Connection to the inductor commences a series of oscillations at 50Hz. A secondary winding coupled to L steps up the voltage to the required level, where it is applied to the test electrodes by closing 2 and is then bypassed by 3.

The level of shock current is set by adjusting the value of V+ and since the maximum required level of shock power is high (3000 V at 10A) the energy stored in L and C must be high in order to avoid excessive distortion in the waveform. The switches 1, 2 & 3 are solid state since precise timing is required, and to ensure this the times are derived from a crystal clock driving a digital logic system, which, with internal arithmetic devices, allows the time delay, phase, and duration of the pulse to be pre-set by digital switches. The system then initiates from the heart beat synchronising signal.

The ECG, BP and current stimulus received by the subject were recorded on a chart recorder (Mingograph) and also on a 4-channel FM tape recorder (Racal 'Store 4') for subsequent analysis.

In this work the parameter 'delay time' has been adopted to indicate the point in time when the shock was delivered to the subject. The 'delay time' is related to deflection of the 'R' wave to the onset of the shock. It is necessary to make this definition because the subject is more sensitive to a shock during a particular part of the cardiac cycle (Fig. 3).

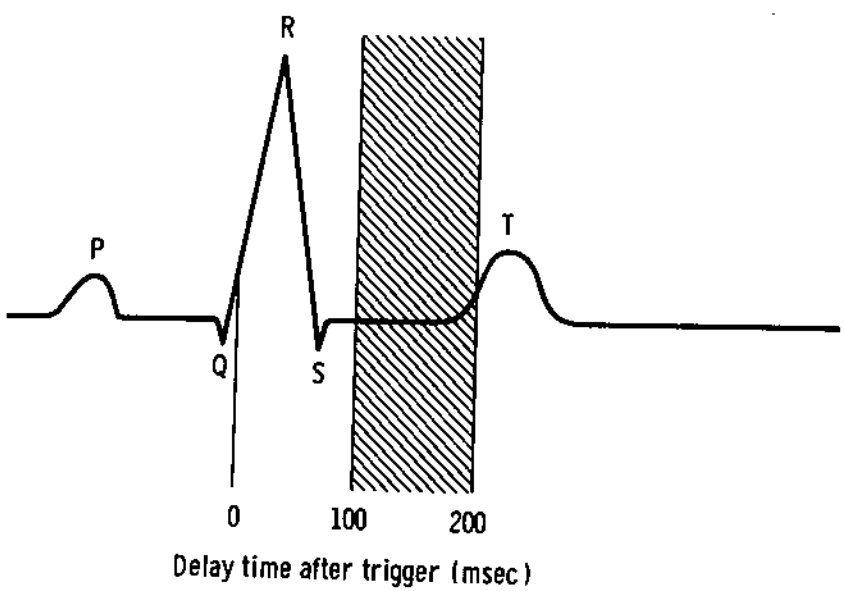

Fig. 3. Showing spread of sensitive timing.

Initially, in order to locate the sensitive time in the cardiac cycle the shock generator was set to deliver 1kV (equivalent to about 3A) for a pulse duration of 4ms, which begins at the peak of a sine wave. The peak of the sine wave was chosen to avoid the zero-crossing where it was suspected there might be anomalous effects, and maximising the delivered energy.

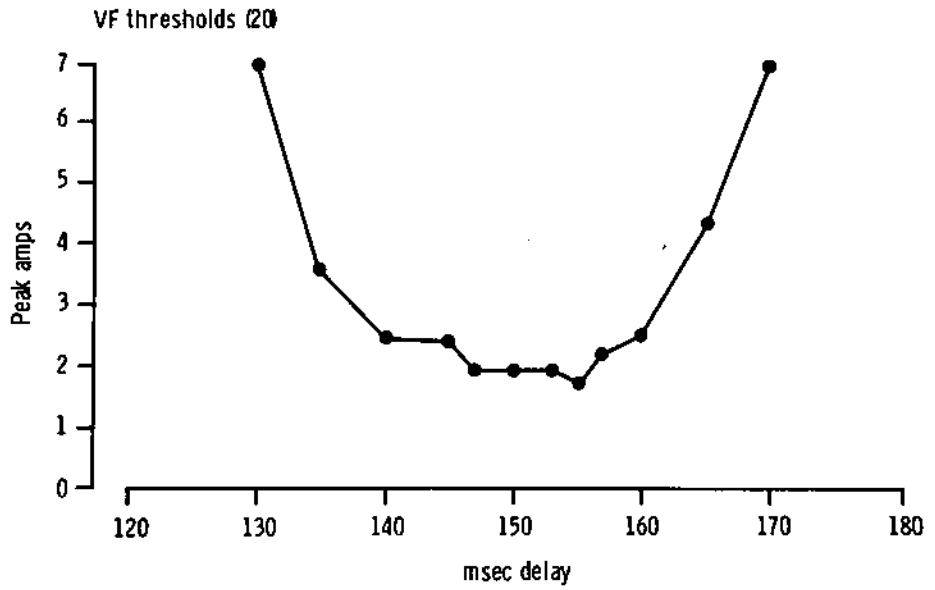

Fig.4. A typical vulnerable window for 4ms shocks starting at a peak.

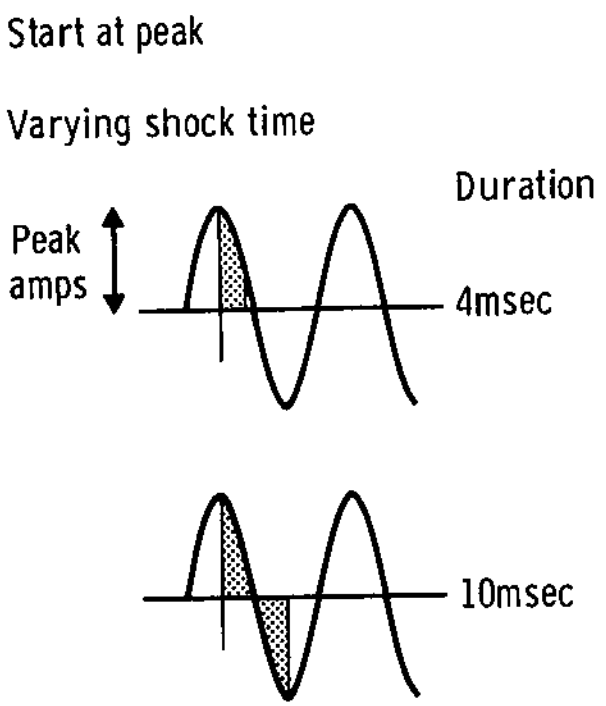

Fig. 5. Shock waveforms which start at peak of A.C. sine wave (50Hz) and vary in length.

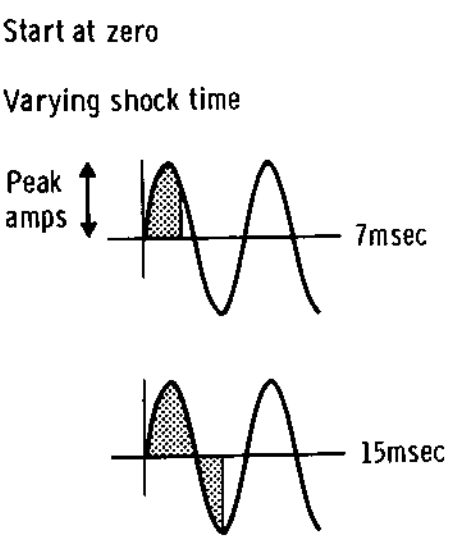

Fig. 6. Varying the start time (phase) of the shocks.

Approximately 160ms delay time was used in the first instance. If the heart fibrillated the animal was immediately defibrillated. A much lower voltage was then used and this was gradually increased to find the minimum level necessary to cause fibrillation. If no fibrillation occurred at 160ms, 140ms was tried and if necessary 180ms. Having found one point in the sensitive period, the delay times just before and just after this were explored, starting at low voltage and increasing by 100V steps until fibrillation occurred. The results may be read on the basis that VF did not occur at 0.3A less than the indicated value. Figure 4 shows a typical result. All the shock sequences contain one peak of the sine waveform and the current level quoted refers to this peak.

Between shock and fibrillation - defibrillation sequences the animal was allowed to restabilise both in pulse rate and BP. This time was usually about 1 - 2 minutes but occasionally took up to 10 minutes.

From the data acquired, the most sensitive delay time was selected to allow the response to longer shocks to be studied.

The subject then received a series of shocks (1-15ms) starting at the selected delay time.

The shock generator can be set in 1ms steps for a duration of 1-25ms, and also in steps of 1ms to start at any required phase of the internally generated 50Hz cycle. Thus the experiments can be repeated with the shock starting 2ms before the peak or starting on a zero. See Fig. 5 and 6.

Some of the experimental sessions had to be terminated early due to signs of cardiac malfunction persisting after defibrillation. An average series of experiments on one animal took 3½ hours for 150 shocks including 40 fibrillations.

RESULTS

The sensitive period of the heart cycle for a given subject when using 4ms pulses is 35-40ms wide at 7A and 20-30ms wide at the 2.5A level. There was some variation between subjects in the timing of this period, although the average centre was 140ms. Thus in a typical subject, the sensitive period could vary from early, 110-150ms, to late 160ms-200ms. There was no relationship between the anaesthetic used and the delay time. The shortest delay time (110ms) occurred in a subject in which the blood oxygen had been allowed to get low (54mm.Hg - normal 100mm.Hg), but the fibrillation levels were not changed from its normal range.

Fig. 7 shows the typical effect of a 3-hour anaesthetic - the minimum value for inducing VF does not change although the vulnerable time increases.

The heart rate of the dogs breathing halothane was 120 — 160 beats per minute (normal range), while the use of the katamine anaesthetic was associated with heart rates of 180 — 200 bpm.

The delay time when minimum current is required to produce fibrillation is not directly dependent upon heart rate because some of the subjects which were most readily fibrillated at shorter delay times had relatively slow heart rates.

By using a longer shock length, 20ms, to plot out the vulnerable period, it can be seen from Fig. 8 that the VF threshold is lower than for 4ms pulses.

Fig. 7. Shows the effect of a 3-hour anaesthetic on the vulnerable period Before ● After ○ Dog 24.

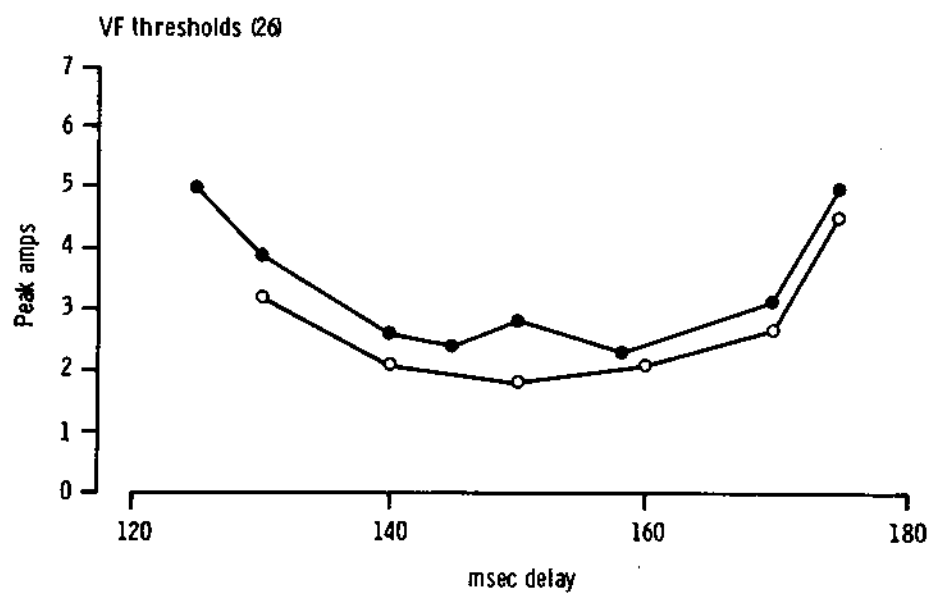

Fig. 8. The change in the vulnerable window due to increasing the shock length ● 4ms, ○ 20ms. (All shocks start at a peak) Dog 26.

The results are given in Table I, and Fig. 9. The current, in amps, is the peak current (measured from zero) at the start of the stimulus, which in the results given, always starts at a peak.

There were no differences between using right or left limbs, or by changing the polarity. The shock was always between one hind limb and one forelimb.

VENTRICULAR FIBRILLATION LEVELS TO 50HZ AC CURRENT STARTING AT A PEAK (PEAK AMPS)

MILLISECONDS DURATION

DOG NO.	1	2	3	4	5	6	8	10	12	15	WEIGHT KG	G A
16	5.91	3.51	2.85	2.52	2.01						11.00	K
18	5.48	3.62	3.36	2.23		2.33	2.85	2.35	3.39	2.39	11.00	H
19	5.70	3.90	3.40	2.30	3.10	4.14	2.60	2.60	2.60	3.50	11.00	H
20	3.33	1.70	1.96	1.70	1.44	1.45	1.18	1.90		1.96	12.00	H
22	5.20	3.90	2.80	2.30	2.80	2.90	3.40	2.60	2.10	2.40	14.00	H
23	6.20	4.60	3.30	3.30	4.10	3.30	3.60	3.60		3.20	16.00	H
25	3.90	2.00		2.00	1.80						15.00	K
26				2.40				2.60			15.00	H
53		3.03		1.97			1.73	1.75	1.86		12.50	K
54		2.50		1.86		2.00	1.97	1.72	1.77	2.01	14.00	K
56		3.75		1.73			3.01	2.53	2.60	2.33	15.00	K
57		2.02		1.97		2.06	1.77	1.48	1.63	1.82	15.50	K
MEAN	5.10	3.14	2.95	2.19	2.54	2.60	2.46	2.31	2.28	2.45	13.50	
S DEV.	1.08	0.95	0.55	0.44	0.99	0.91	0.83	0.62	0.62	0.60	1.89	
S ERROR	0.41	0.29	0.22	0.13	0.40	0.34	0.28	0.20	0.24	0.21		
RMS	3.61	2.22	2.08	1.55	1.80	1.84	1.74	1.64	1.61	1.73		

Three very high results were omitted from the 15ms duration figures - see discussion. The effect of starting the stimulus 5ms before the peak, i.e. at zero is shown in Table II and Fig. 10.

DISCUSSION

It should be noted that when the heart rate changes, the Q-T interval of the ECG does not change in proportion to the change in R-R interval. There is a smaller change in the Q-T interval, and it is non-linear. The typical figures for humans are:-

Heart rate	75	100	150	200	Beats per minute
R-R interval	800	600	400	300	ms
Q-T interval	360	310	250	220	ms (to end of 'T')

In this series of experiments the sensitive period was constant in relation to the R-wave and did not change significantly with Heart Rate.

It is therefore more accurate to define the sensitive time in the heart cycle in terms of delay after 'R' (which bears a constant relationship to 'Q') than in terms of either percentage of cycle time or the 'T' wave, as it is described by Jacobsen, Buntenkotter and Reinhard (1975). The delay time does shorten sometimes by about 20ms after a long anaesthetic and many fibrillation sequences, but the fibrillation levels remain the same.

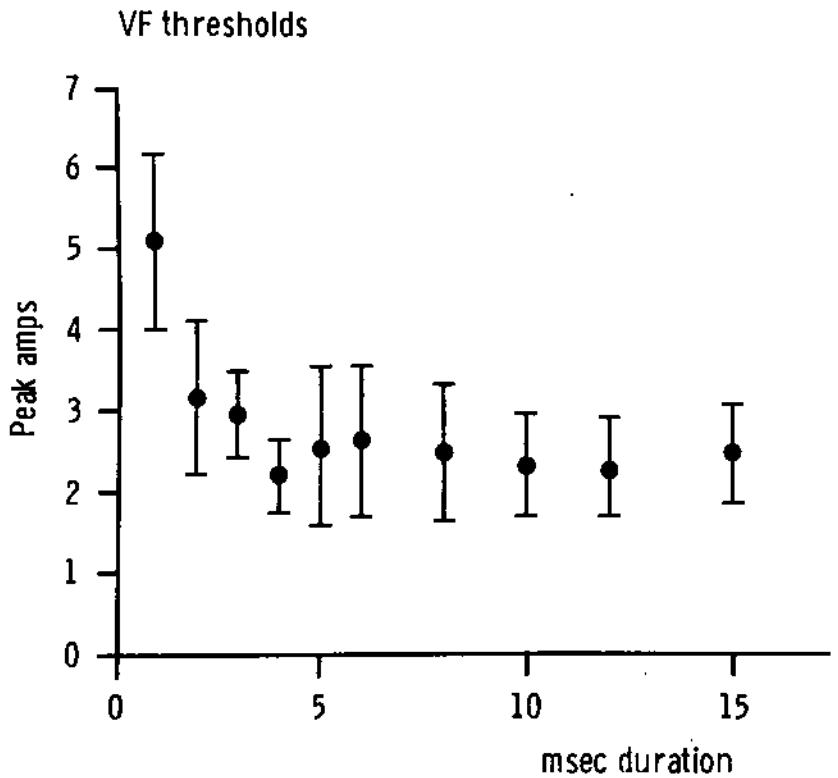

Fig. 9. The results from 12 dogs. Mean values and S.D. for shocks starting at a peak.

TABLE II
VENTRICULAR FIBRILLATION LEVELS TO 50Hz AC CURRENT STARTING AT ZERO (PEAK AMPS)

	MILLISECONDS DURATION										
	4	5	6	7	8	9	10	12	15	WEIGHT KG	G.A
DOG NO.											
29	4.24	3.63	3.22	1.79						11.00	H
31	4.20	1.50	1.50		1.10		1.30	0.84	1.10	14.00	H
32		2.14	2.12	1.06	1.05	1.49	1.47	1.05	1.26	13.50	H
38		2.75					1.80	1.80	2.03	17.00	H
39		2.68	1.96	1.03	1.05	1.48	1.27	1.27	1.02	13.00	H
54		1.50			1.04		1.01	1.27	1.12	14.00	K
56		2.36	2.26		1.27		1.27	1.23		15.00	K
MEAN	4.22	2.37	2.21	1.29	1.10	1.49	1.35	1.24	1.31	13.93	
S DEV.	0.03	0.75	0.63	0.43	0.10	0.01	0.26	0.32	0.41	1.84	
S.E.	0.02	0.28	0.28	0.25	0.04	0.01	0.11	0.13	0.19		
RMS	2.98	1.67	1.56	0.91	0.78	1.05	0.96	0.88	0.92		

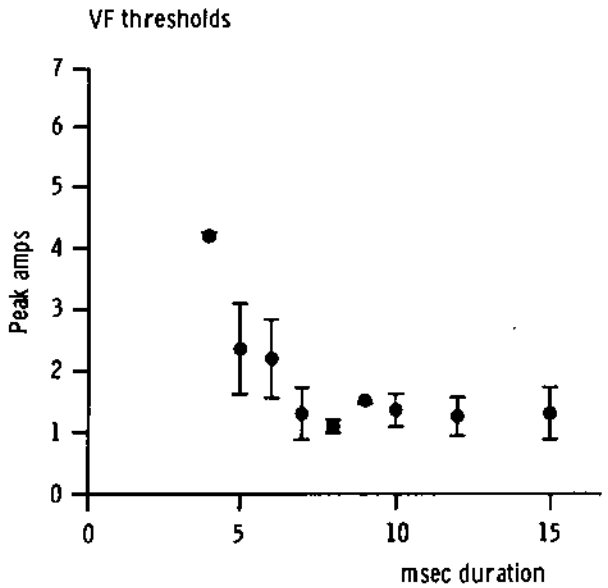

Fig. 10. Mean values and S.D. for shocks starting at zero.

From Fig. 9 it can be seen that the heart is more sensitive at the longer shock periods, and that to get any real improvement in safety of circuit breakers, they must operate at about 2ms or less. Most of the determinations have been done starting at the peak of the sine wave because this is the point at which a fault is most likely to cause an electrical breakdown. A few readings were taken with the waveform starting 2ms before the peak on the basis that this is the next most likely point at which a break-down would occur. No significant difference from a peak start stimulation was noted. With a fault which occurs at about the zero crossing time, the breaker would not sense it until 3 or 4ms later, so some readings have been taken with the stimulus starting at zero.

On occasion in three of the subjects it proved impossible to fibrillate the heart at all, even using 7A, when the duration of the shock was 15ms starting at a peak, i.e. it stops at zero. The fibrillation thresholds within 3ms on either side of this 15ms, i.e. at 12ms, and at 18ms were about 2A. The reason for this is not known - it was not consistent, except in these three subjects. There is a general tendency for the threshold to be higher when the shock stops on a second zero, i.e. after a biphasic stimulus, and does suggest that a shock ending on a second zero is less potentially harmful than a shock stopping on a peak.

Circuit breakers tend to break at zero current due to arcing occurring and only extinguishing at the zero crossover. It would appear from the results obtained that this is a very advantageous situation.

The fibrillation threshold at the longer shock lengths 8-15ms at about 2A peak (1.4A RMS) corresponds with the results quoted by Biegelmeier and Lee (1980). The VF levels between 4ms and 15ms are lower than would have been expected from the relationship I^2t = constant. The start at zero results tend to be lower at shorter shock lengths and more work is required to confirm and extend this set of observations.

Due to the method of generating the shock pulses there is inevitably a decay in the waveform amplitude (20% decay at 10ms). This decay is acceptable up to 15mSec duration but beyond this, the results, although agreeing with previous workers should be confirmed using a different type of shock generator.

In particularly hazardous situations, e.g. under water diving work, it could be worth using a 400Hz supply where possible because the second zero crossing would occur at 2.5ms, and it is also known that high frequency current is less dangerous (Geddes and Baker, 1971).

ACKNOWLEDGEMENT

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DISCUSSION

ROY: Did you notice any amplitude window, within which you were not able to fibrillate? That is, if you have too high a voltage and too high a shock you couldn't fibrillate the heart.

KURN: We did a very high shock level only on one animal. All the others would fibrillate very easily at the high level. The odd animal that did exhibit this characteristic was something that we could offer no explanation for at all. It was a sick animal. It may have been suffering from another dysfunction that was irrelevant to our measurement.

ROY: Did you reverse the current at all?

KURN: Yes indeed. We tried this and it made no difference at all. We made up a change-over switch so that we could do this rapidly. We did that only on three dogs and there was no noticeable difference at all. It was essential that the equipment used was totally floating and had a very low capacity to ground. Otherwise, we would obviously have gotten a ground current. The operating table was totally insulated and it was a long way from any ground electrode.

REILLY: If I correctly interpret your strength-duration relationships, does the current begin to reverse in direction at the point where minimum fibrillation threshold occurred?

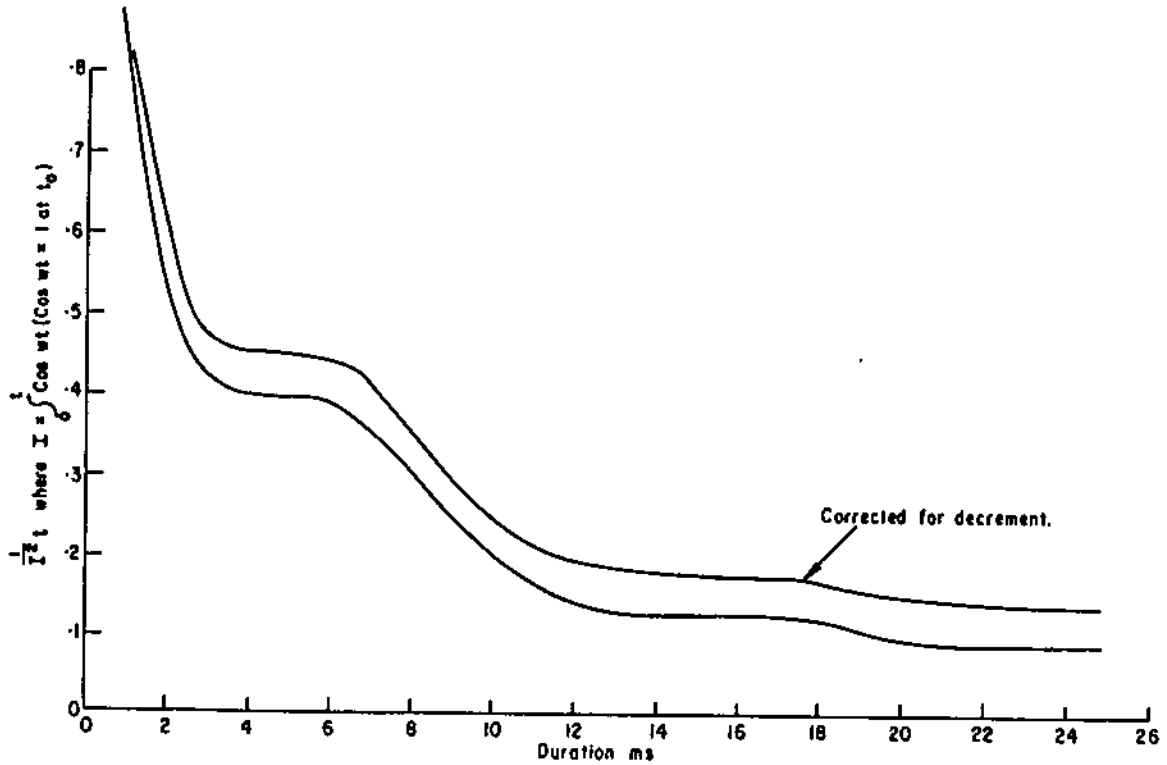

Fig. 11 - Theoretical sensitivity response for I^2t characteristic.

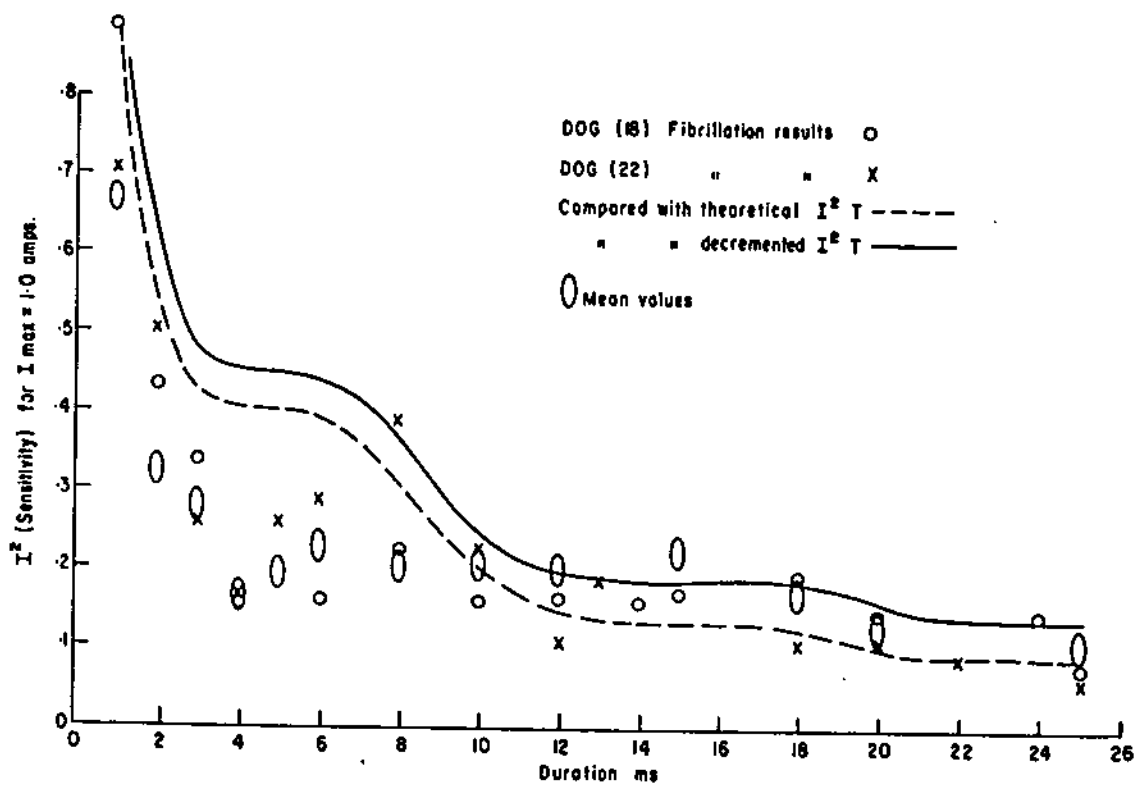

Fig. 12 - Experimental results superimposed on theoretical curves.

KURN: If you take a theoretical I^2t curve, that is, if you have an ac waveform and shock does become a function of I^2t, then, if you draw the resultant current sensitivity, you will obtain the shape similar to the lower curve that is offered in Figure 11. In other words you will have a very high, very short pulse. Coming down it is being modified by the ac waveform until you end up at an integrated curve which is a straight line. But this variation due to the ac "watts" does give a slightly loose step function. The results of the actual experiments on two dogs (No 18 & No 22) are shown in Figure 12. A cross denotes dog No 22 and the ellipse - the mean values. The circle denotes dog No 18. It is quite noticeable that the experimental results divert significantly from the theoretical values in a left part of the curve. It actually fits beautifully to the right of the curve and in the rest of the curve the fit is quite good.

REILLY: May I suggest that the minimum that you see in curves such as in Figure 11 and Figure 12 may be explained by the model I indicated earlier, in which, at the point of current reversal, one can actually inhibit a developing action potential.

KURN: Figures 11 and 12 are the same figures, but in Figure 12 there are just two dogs and in Figure 11 the data is presented for 12 dogs. The experiments were repeated over a number of animals and mean values were offered as well as the standard deviation. All those animals diverged from the theoretical value at this point. So, there was a definite anomaly there which needs some explaining. The result is that we are obviously interested in the cause of this phenomenon.

BIEGELMEIER: Dr. Green's results have been, of course, very important. They allowed the Working Group 4 (IEC TC 64) to draw a line for the fibrillating threshold down to 4 milliseconds and then the curve goes up for durations between 0.01 to 4 milliseconds.

ANTONI: When I first saw these results of Dr. Green's group, I was a little bit doubtful. I corresponded with Dr. Green, and he assured me that there is a statistically significant dip and then rise. And now in the findings of Mr. Reilly, I find a wonderful explanation. As long as the heart rate increases in duration, the threshold falls. If your pulse begins with a peak (5 milliseconds at 50 cycles), and consequently if the current reverses, then as Dr. Reilly has shown, the second half of the pulse can cancel the effect of the first one, and now the threshold rises again. If you begin where the pulse crosses zero, then it shifts by 5 milliseconds, and you have the minimum at 10 milliseconds.

GRIFFIN: First a comment, based on the previous information. I would caution the group from extrapolating too readily data taken from the stimulation threshold of a nerve to that of the fibrillation threshold of an intact mammalian myocardium. Those two may be totally unrelated, and I'm not at all sure you can extrapolate from one to the other.

My question concerns the exact methods of your study. What was the frequency of shock application? Was that frequency held constant from experiment to experiment and from moment to moment within the same experiment? And what was the increment of voltage increase and was that increment held constant during a development of fibrillation in an animal? The reason I ask these questions, is that some of the data that I presented on Wednesday, showed fairly pronounced effects of those more or less technical aspects. And if in any way these are related to the waveshape or other factors, they then may in turn become related to the number that you get. Because, in fact, changes in those increments will effect that number.

KURN: Well, there are many unknowns, but during the experiment obviously we do our best to eliminate those that we can. One of the functions was that after a fibrillation and a defibrillation, the animal was allowed to recover until its heart rate, breathing and blood sugar or blood content were normal. This was out

of my hands and I want you to understand that. But there certainly was a wait for the animal to become normal again before the second fibrillation was attempted. It normally took about 8 minutes.

GRIFFIN: That was not exactly my question. If I understand your experimental methods, did you start with subthreshold voltages and increased those until the fibrillation occurred?

KURN: No, perhaps I ought to be a little more explicit in the procedure we used. First of all we had to determine the window in the particular animal that we were looking at. The window was normally known to be 120 to 180 milliseconds and we always started looking there. We would put a number of shocks at a comparatively low level across that window and look for a fibrillation. And usually there was none. We would then put another number of shocks across that window at a comparatively high level where we would expect a fibrillation. And that would determine the high level shock. We would then reduce the level until we got the minimum level at which we could fibrillate usually twice, sometimes three times.

GRIFFIN: How frequently did you apply those subthreshold and sometimes threshold shocks and was that timing kept constant?

KURN: The time, the interval in the window, was always the same. We were careful about that. The animal was allowed to recover so, that its physiological state, hopefully, was the same each time we applied a shock. That is why it took a long time to conduct the experiments.

GEDDES: I think there's a little piece of Dr. Griffin's question that hasn't been answered, and that is, what amplitude resolution were you using?

KURN: On the scales we were using, it was 100 volts. In other words, our window was 100 volts.

MADER: Just a quick suggestion of a possible explanation for the 100% lowering of the threshold when starting at zero versus starting at peak current. We had a demonstration that the short time interval response of a membrane depends upon charge rather than peak amps. Of course, you're going to get twice the charge starting from zero, then you would be starting from peak. Is this possible? Perhaps the physiology experts could comment further.

INTRICACIES OF THE SAFETY CRITERION AROUND POWER SYSTEM STRUCTURES

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ABSTRACT

In the design of an electrical grounding system, one of the important aspects is the safety of the installation during abnormal operating or fault conditions. During a fault condition current flows into the grounding system and causes differences in potential between various accessible points of any grounded metallic structure and the soil surface in the vicinity of the grounding system, i.e. touch or step potentials.

A grounding analysis produces calculated or measured currents and voltages related to the typical touch or step grounding scenarios. The safety of the electrical grounding system is assessed by comparing the calculated step and touch currents to a reference current fibrillation threshold. This reference value, the tolerable body current, usually specified by national and/or international standards is determined from an electrocution equation. There are essentially four major time dependent electrocution equations. These equations have been developed by Dalziel (1968), Osypka (1966), Geddes (1975), and Biegelmeier (1980). The equations were derived empirically from statistical analyses of data of the fibrillation current versus time for animals and then extrapolated for humans. Experimental data on humans is very limited because of the obvious danger involved.

A detailed review of the various electrocution equations indicates that future work should incorporate parametric investigations of voltage, current, duration of current flowing through the human body, and the body resistance. Investigations should be approached from a physiological basis. For instance, a definitive distribution of the total body current as well as the current density that enters the cardiovascular system is required to ensure validity in extrapolation of animal data to humans. A statistical analysis of the range of body impedances for actual working and recreational situations could be addressed to supplement the laboratory clinical tests and help define the actual incident conditions.

KEYWORDS

Ventricular fibrillation threshold; electrocution equation; electric shock; electrical safety; body impedance.

INTRODUCTION

The grounding design of a power system requires that both the abnormal as well as the normal conditions be considered in order to correctly determine the design requirements and characteristics of power equipment. Of the abnormal electrical conditions which can occur on a power system, the two most frequent are:

(1) Phase-to-ground faults
(2) Lightning strokes

The grounding design may consist of a ground rod, ground grid, or an interconnection of ground grids. The grounding design has a two fold purpose:

(1) Establish a safe environment for personnel as well as the general public in the vicinity of the power system equipment.

(2) Establish a low resistance connection to earth such that protective devices detect and isolate faults quickly and potential rise of the grounding system does not exceed a value which could damage electrical equipment.

ABNORMAL ELECTRICAL OPERATION - PHASE-TO-GROUND FAULTS

In the design of an electrical grounding system, one of the important aspects to be considered is the safety of the installation during fault conditions. During a fault, current flows into or out of the grounding system and causes differences in potential between various accessible points of any grounded metallic structure and the soil surface in the vicinity of the grounding system.

ELECTRIC SHOCK CIRCUIT

Electric shocks are possible when current flows through the body of a human or animal. This necessarily means the existence of a potential difference across at least a portion of the human or animal body. Because of the numerous activities performed by human beings and the variety of electrical apparatus used, the points of contact in an electrical shock can be anywhere on the body. The most common points of contact will be at the hand or foot extremities.

STEP AND TOUCH POTENTIALS

In the case of power system grounding incidents, generally two types of contacts are considered:

(1) Step
(2) Touch

Figure 1 of Dawalibi (1982) illustrates two types of shock contacts both pictorially and as an equivalent electrical circuit. The equivalent electrical circuit can be broken down into four distinct constitutive elements:

(1) Difference in potential (step or touch).

(2) Resistance due to insulating materials (gloves, shoes, or insulating materials covering the soil surface).

(3) Body contact resistance (skin and contact resistances).

(4) Resistances of internal body tissues (heart, hands, legs, etc.).

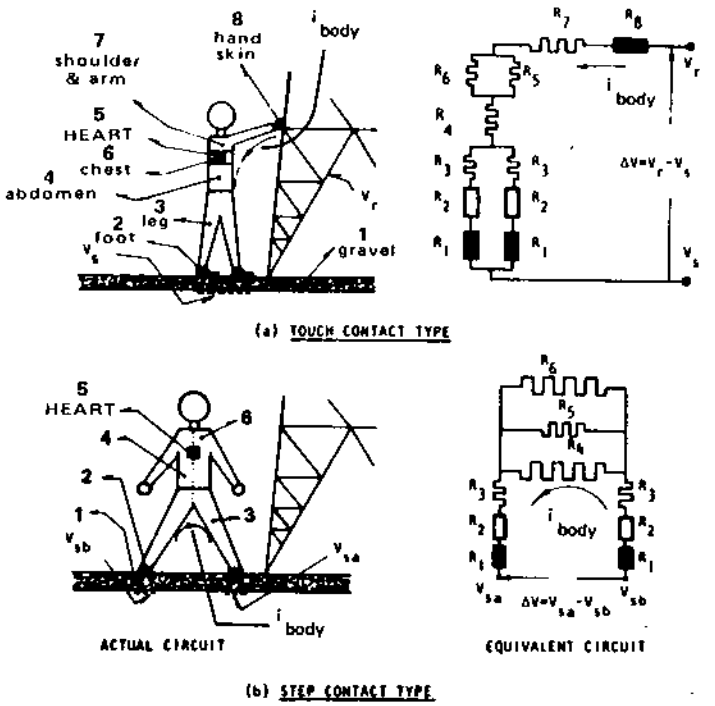

Fig. 1. The electric shock circuit.

If all of the preceding four elements are accurately known, the current flowing in each part of the body can be easily determined. If, in addition, the maximum tolerable currents which can safely flow in the various paths of a body are also known, then it will be a simple matter for the designer to modify his installation so that it conforms to the safety criteria.

The potential difference, generally the step or touch voltage, can be calculated very accurately. Recently published analytical works on power system grounding describe computer based computational techniques for the total analysis of grounding systems. The electrical performance of very complex grounding systems can be determined. For additional information on these techniques see Dawalibi (1982) and the bibliographical list of Chapter 5 of the referenced document.

The various resistances listed under insulating materials and body contact can be determined by direct measurements under various conditions. Although these measurements can easily be made, there are no comprehensive tables listing the resistance values from which the ones applicable to a specific problem can be extracted.

Information regarding the resistivity of internal body tissues, although quite extensively known, is not really the main concern. What is needed rather, is the equivalent resistances which should be used in order to accurately model the distribution of current among the various parts of the body. It is argued here

that if one can establish more precisely the density of current which traverses the heart tissues then it will be much easier to establish the risk of ventricular fibrillation. Unfortunately, no literature has been found concerning research on the distribution of shock currents through the human body or the resistances of current paths through the human body. Consequently, the detailed equivalent circuits of Fig. 1 are of academic interest only. In practice, it is assumed that the body path is represented by one lumped equivalent resistance and the total body current not specifically the heart current. This simple assumption, although somewhat inaccurate, remains a reasonable choice until more conclusive research work becomes available. Figure 2 shows a simplified equivalent circuit of the electric shock path for both the step and touch conditions.

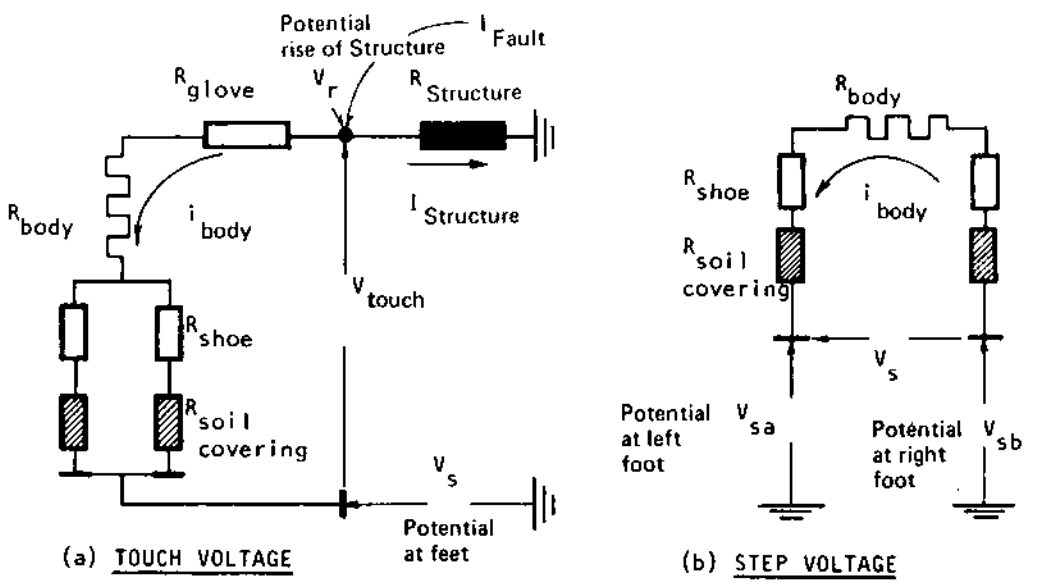

Fig. 2. Simplified equivalent electric shock circuit.

When one reviews the detailed equivalent circuit of Fig. 1, it becomes obvious that the assumed lumped body resistance of Fig. 2 for both the step and touch contacts would not necessarily be the same value. The vulnerable current through the heart is also a different value for both the step and touch contacts.

SAFETY CRITERION

Three variables, body path characteristics, current frequency, and current duration have been shown by experimentation to be a function of the safe body current magnitude. Therefore, the general form of the electrocution equation can be written as:

$$i_{body} = F(p,f,t) \tag{1}$$

where

i_{body} is the maximum permissible body current in amperes rms (for a given body path p) which will not cause ventricular fibrillation to more than X% of a population sample having similar body path characteristics.

This current is also designated as the ventricular fibrillation threshold.

p is one or several parameters characterizing the paths followed by the current in the body as discussed in the preceding paragraphs.

f is the current frequency in Hz.

t is the duration of the fault in seconds.

The electrocution equation, as applicable to humans, is usually determined empirically by extrapolating experimental data obtained from tests on four-legged animals and primates. Four major time dependent electrocution equations developed by Dalziel (1968), Osypka (1966), Geddes (1975) and Biegelmeier (1980) were derived empirically from a statistical analysis of the fibrillation current versus time data. A recent paper by Bridges (1981) provides a good summary of these four major concepts and their related equations.

Figure 3 shows the safe body current as a function of its duration according to equations of Dalziel, Osypka and Biegelmeier. Geddes interprets his data from a physiological viewpoint relating the responses of irritable (nervous) tissue to pulses of various widths; therefore, it was not plotted.

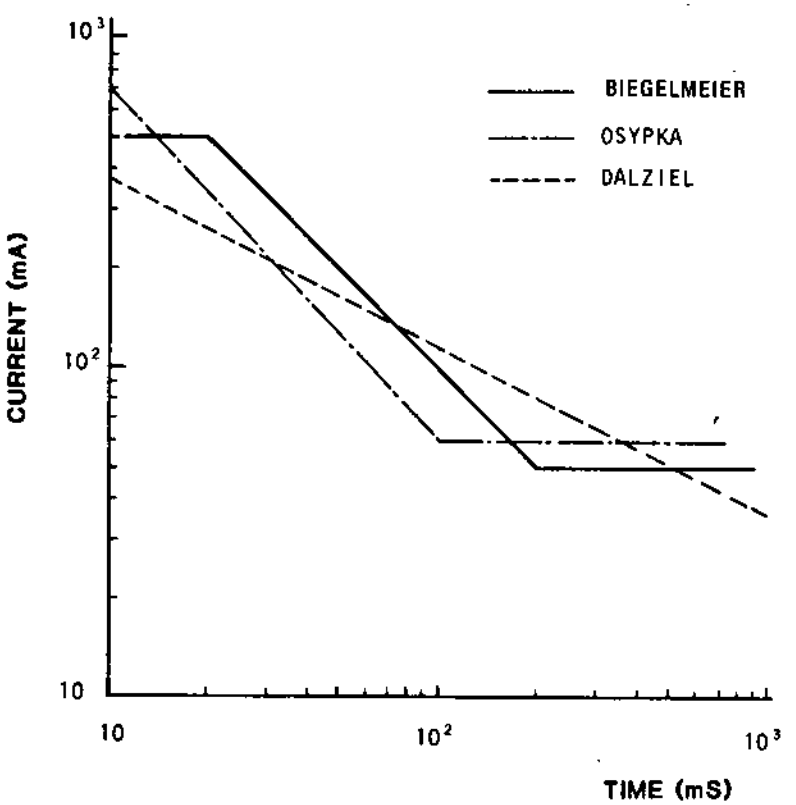

Fig. 3. Safe body current versus time.

Since the ventricular fibrillation threshold is a statistical result, the maximum safe body current is selected such that X% or less of the population, consisting of "standard" persons of a defined body weight, will be subject to fibrillation (for example, IEEE Guide 80 (1976) proposes 0.5% of 50 Kg persons). The curves of Fig. 3 are valid for a narrow range of frequencies (around 50 - 60 Hz) and the current paths in the body are not specifically designated.

It is useful to consider qualitatively the effects of the various body resistances of Fig. 1. It is clear that the path resistance of the body through legs or hands is inversely proportional to the cross-section of the paths. This leads to the conclusion that body resistances of a child are higher than those of an adult. This is an important fact observed experimentally by Whitaker (1939) and means that for the same voltage across the contact areas, less current will flow through the body of a child. Despite the lack of conclusive data relating to children, it may be argued that although the fibrillating threshold current for a child is less than for an adult, the same voltage limits might apply to both the adult and the child, because of the inherently higher child body resistance. The preceding considerations raise an important but still unresolved question. What is the relationship between body weight and fibrillation threshold current?

According to Dalziel (1972), this current is proportional to weight. In contrast, Geddes has concluded that the fibrillation current varies with the square root of the body weight. However, based on electrophysiological concepts, one can conclude that for bodies of the same general proportions, the response of excitable tissue is identical provided that the current density in the tissue is identical. The current density criterion, Bridges (1981), appears more appropriate for extrapolation purposes and leads to a fibrillating current proportional to the 2/3 power of body weight. The 2/3 power relationship is derived from the observation that for a given shape of different weights, cross-sectional area varies as the 2/3 power of the weight. Since most experiments were made on quadrupeds, extrapolation of the results to bipeds based on the body weight criterion will introduce unknown errors.

The IEEE Guide for Safety in Substation Grounding (1976) has adopted Dalziel's electrocution equation based on average adult body weight of 50 Kg and has assumed the following:

$$i_{body} = 0.116/\sqrt{t} \qquad (2)$$

From this empirically derived body current threshold, one must derive the associated tolerable step and touch voltages of Fig. 2. In order to do this one must know both the body and contact resistances for both step and touch contacts:

$$E_{tolerable\ step} = \left[R_{body} + 2(R_{shoe}+R_{soil})\right]\left[i_{body}\right] \qquad (3)$$

$$E_{tolerable\ touch} = \left[R_{glove} + R_{body}+\tfrac{1}{2}(R_{shoe}+R_{soil})\right]\left[i_{body}\right] \qquad (4)$$

The IEEE Guide (1976) has assumed the following:

(1) The equivalent body resistance (R_{body}) is equal to 1000 ohms.

(2) The soil contact resistance of each foot (R_{soil}) equals 3.0 times the soil surface resistivity in ohm meters (ρ_s) based on an equivalent 16 cm diameter plate.

(3) The contact resistance of both the hands and the shoes (R_{glove}, R_{shoe}) are zero ohms.

The combination of the above results in the following tolerable voltages:

$$E_{tolerable\ step} = (1000 + 6\rho_s)\ (0.116/\sqrt{t}) \quad (5)$$

$$E_{tolerable\ touch} = (1000 + 1.5\rho_s)\ (0.116/\sqrt{t}) \quad (6)$$

LIGHTNING STROKES - IMPULSE OR SURGE CURRENTS

Essentially, the approach regarding safe current levels applies thus far equally well to very short (microseconds) or long duration currents (seconds) with few exceptions. Unfortunately, the values of the biological constants which affect the electrocution equation are not well known when impulse, lightning or power system surge currents are involved.

Several direct and indirect lightning strike and power system surge electrocution incidents indicate that a person can survive very short duration currents (1 to 1000 μ s) of 20 to 100 amperes as evidenced by the work reported by Dalziel (1953). From a limited number of electric shock incidents involving the discharge of high voltage capacitors, Dalziel concluded that the energy criterion, I^2t=constant, is applicable for impulse or surge currents.

An uncertainty exists concerning the appropriate value of body impedance when subject to high magnitude surge voltages. Not only is the body impedance reduced because of the high voltage level, but it is also shunted by a capacitance. The value of this capacitance is not well known although values range in the low hundreds of pF. This capacitance appears to play a mitigating role by diverting some portion of the current which would otherwise flow through the body tissues. There is clearly an urgent need for extensive research concerning electric shocks caused by surge or impulse currents. However, until better information is available it seems prudent to adopt conservative low body resistance values.

CONCLUSION

The severity of electric shock to humans from power grounding systems under electrical fault conditions is dependent on many variables. Some of these factors include the body current magnitude and duration, voltage and frequency of the circuit, the current path traversed in the body, the weight of the body, and both the contact and the internal resistance of the body. Several investigators have predicted safe voltage and current limits that humans can withstand based on animal studies.

In spite of the considerable progress since the beginning of this century, the data related to electrocutions are still very experimental in nature and cannot be accurately correlated with actual electrocution cases. The major difficulty is that the most meaningful shock data have been obtained under experimental conditions where the current stimulus was directed toward the target, (i.e. the heart). In actual electrocution accidents, contact is generally made through the extremities (hands or feet) and only an unknown fraction of the total current reaches the vulnerable tissues of the body. Unfortunately, it appears that there has been no work directed at a determination of the current paths through both the test animal and the human body. There is no indication that efforts have

been made to extrapolate any test data available from quadrupeds to humans.

Hammam and Baishiki's review (1982) pointed out that the cardiac cycle period of all animals and humans are not the same. Therefore for animals tested, the vulnerable period (the transition from systole to diastole), should be correlated to that of a human's cardiac cycle. Other observations are that the body resistance is actually better represented by an ohmic range for a specific body current magnitude, duration, voltage, and frequency of the source. Further experimentation should reflect a range of body and contact resistances for actual working and recreational situations. Factors such as stress, fatigue, age, physical condition should also be addressed when acquiring further statistical data. This future work could be extended to improvement of design criteria as a means of preventing electrical accidents.

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DISCUSSION

LEE: A comment with respect to curves of Dalziel & Lee and Biegelmeier & Lee. The Dalziel & Lee equation was produced in the late 1960's and represented the data then available - it did not set out to provide a physiological model. The later curve by Biegelmeier & Lee took account of further results which had become available. (The subsequent work of Green & his colleagues substantially fits this proposal).

Further, because the experiments leading to this curves used the forelimb (arm) to hindlimb (leg) route, it is unwise to use these for step voltage.

DAWALIBI: Indeed, the recent EPRI Transmission Line Grounding Report has introduced the more recent Biegelmeier & Lee equation as the preferred reference "electrocution equation". However, we believe that a major effort, similar to that made by Dalziel and his colleagues during the early sixties, should be carried out in order to bring all the new physiological experimental evidence into a form suitable for the design engineer. This includes an appropriate electrocution equation which will not only be a function of time and weight but rather a function of current path, frequency, duration and voltage. It is also necessary to develop a threshold limit for uncontrollable movements due to step potentials to establish the safe limits which will prevent a man from falling to ground in locations where single or multiple reclosure practices are applied by electrical utilities. It appears that electrical engineers use the current threshold for fibrillation as the limiting current which also prevents a person from falling if subjected to a step voltage. Obviously, more realistic data are required to establish the maximum current which can traverse the feet of a man without causing him to fall.

FORTIN: Although you consider in your paper that glove and shoe resistances are nil, it is compulsory for our workers to wear high resistance shoes and leather gloves. These surely represent an important factor and provide at least some protection. One may argue that the resistance of these may be drastically reduced by wetting. But a comment heard during the symposium pointed out that shoes, although wetted, still have a high resistance. In the case of a boom truck under a distribution line, it may be possible for a utility to keep public and children away, and I would like to know if we can include the resistance of shoes in assessing electrocution risk to lineman.

DAWALIBI: We agree that all meaningful parameters which intervene in the electrocution equation should be considered. However, one must be careful not to consider boots or gloves when dealing with installations which can be accessible to the public or personnel not adequately protected by insulating materials.

If public access is not possible, then we strongly recommend that boots or gloves be taken into consideration in the electrocution equation, provided that reasonably conservative values be used for the characteristics of the protective equipment (boots/gloves, etc). In addition proper inspection procedures must be routinely applied to the protective equipment.

M. VAINBERG: In your figures with V_{step} and V_{touch} it appears that the definition of these values include a voltage drop between feet and the remote ground (soil resistance included in the model R_{soil}). Could you, please comment?

BAISHIKI: The figures are for illustration purposes and therefore do not represent truly the nature of our equations. We do not include the remote ground resistance, but the resistance of the thin insulating material underneath the foot (see EPRI Report on Transmission Line Grounding). However, in the IEEE Guide 80 feet resistance values refer to the remote ground resistance. We also believe that this is not an accurate representation of the real conditions.

SAFETY CRITERIA FOR INTENDED OR EXPECTED NON-LETHAL ELECTRICAL SHOCKS

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ABSTRACT

Safety criteria are developed for intended or expected electrical shocks based on a comparison of the electric shock outputs to levels considered non-hazardous, such as that from an electric fence controller or from a continuous 6 mA, 60 Hz shock. The true r.m.s. value of the current for a periodic pulse type shock cannot always be compared to the effect of the same 60 Hz r.m.s. current because higher frequency components of the pulse output have a lesser effect on the human body. Periodic pulse type shocks are evaluated by obtaining an effective value for the current taking into account the attenuation of the effect of frequency components above 1 kHz on the human body.

KEYWORDS

Electrical shock; electrocution; electrical safety; non-lethal electrical shock; ventricular fibrillation.

INTRODUCTION

The design of most electrical equipment ensures that an individual should rarely contact energized parts and be subjected to electric shock. For such equipment electrical safety is provided primarily by insulation or guarding to prevent contact and by suitable grounding. Any contact with energized parts is considered hazardous. There are other equipment where, even though it may not be intended, contact with energized parts is expected so that the electrical safety must be provided by ensuring that any possible electric shock will not be hazardous or lethal. Examples of such electrical devices are the electric fence, gun, welder, cattle prod, and fly electrocuter.

This paper evaluates various types of electric output waveforms as to their safety. The types of waveforms include direct current, sinusoidal, trains of pulses, trains of damped sinusoids, and half-wave rectified sinusoids. Parameters considered included the frequency, amplitude, and waveshape.

SINUSOIDAL, 60 Hz SHOCKS

Threshold of Perception

Electrical shocks involving alternating current have been investigated since before 1890 (Bernstein, 1975). Most of the recent studies have involved sinusoidal, 50 or 60 Hz currents though the effects of other frequencies have also been studied. For 60 Hz shocks, the lowest level of current that can be a problem is the threshold of perception level. This level, where some people may feel a slight tingle but should have no extreme startle reaction, is usually considered to be 0.5 mA rms for 60 Hz currents and is the maximum allowable leakage current for appliances (ANSI, 1973). Dalziel and Mansfield (1950) have determined that the median threshold of perception current at 60 Hz was 1.067 mA for 28 men and 1.18 mA for four women. Shocks near but above the threshold of perception current may be a hazard because of injury caused by the startle reaction producing a dangerous body motion.

Ventricular Fibrillation

At the other extreme is the level of current where the heart may be thrown into ventricular fibrillation. For the group below 0.5% of the population this level of current at 60 Hz is given by the expression (Dalziel and Lee, 1968)

$$I = 116/\sqrt{T} \text{ mA r.m.s} \qquad (1)$$

where T is in seconds. This expression is valid for $8.3 \text{ ms} \leq T \leq 5 \text{ s}$. For T between 5 and 20 seconds the value of current to cause fibrillation is about the same as the value at 5 seconds.

Biegelmeier and Lee (1980) have re-evaluated experimental data on ventricular fibrillation induced by electrical shock in animals and related the results to the physiological response to electrical shocks. For short duration shocks shorter than a cardiac cycle, the electrical current to cause fibrillation must be large and occur during the vulnerable period, T wave. Shocks longer than a cardiac cycle can cause premature ventricular contractions that lower the shock threshold current to a minimum after 4 or 5 premature ventricular contractions. Using these concepts, a safe current limit has been proposed as 500 mA for shocks less than 0.2 seconds in duration and 50 mA for shocks longer than 2 seconds. For shocks between 0.2 and 2 seconds, the safe current is given by the expression

$$I = 100/T \text{ mA r.m.s.} \qquad (2)$$

where T is in seconds and $0.2 \text{ s} \leq T \leq 2 \text{ s}$.

Let-Go Current

The let-go current level of shock is not immediately lethal as is the ventricular fibrillation level. At this level of shock, with a current path through the arm, the individual cannot let go of an energized conductor. This level is hazardous in that a person is receiving a very painful shock from electrical equipment that he cannot release. Such a long duration shock may eventually become hazardous because of evoked heart arrhythmias or a decrease in contact resistance because of perspiration or burns allows greater currents. Dalziel and Massoglia (1956) have determined that the 60 Hz let-go current level where 0.5% of the individuals cannot let-go is 9 mA for men and 6 mA for women. The median let-go level is 16 mA for men and 10.5 mA for women. The let-go level where 99.5% of the

individuals cannot let-go is 23 mA for men and 15 mA for women. Underwriters Laboratories (1972) requires that the ground fault circuit interrrupter trip with long duration shocks greater than 6 mA as most people can let-go at currents less than 6 mA. Currents above an individual's let-go current level could be hazardous and painful because the individual would be frozen to the circuit.

DIRECT CURRENT SHOCKS

Direct current shocks are not as lethal as are 60 Hz shocks; that is, for a given duration shock the current for direct current shocks must be of higher amplitude than the r.m.s. value of the 60 Hz current. As an example, the median threshold of perception for direct current was found to be 5.2 mA for men and 3.5 mA for women (Dalziel and Mansfield, 1950) as compared to a value of approximately 1 mA for both at 60 Hz. The direct current release current levels were given by Dalziel (1971) for the case where 0.5% of the individuals will not release as 62 mA for men and 41 mA for women. The median release level is 76 mA for men and 51 mA for women while the release level where 99% of the individuals will not release is 90 mA for men and 60 mA for women. The term release current rather than let-go current is used because with direct current the test subjects could let-go of the circuit but refused because of the very severe shock on release.

The level of direct current shock that can cause ventricular fibrillation is given by Dalziel (1971) as 500 mA for a 3 second shock.

SINGLE PULSE SHOCKS

Dalziel (1971) has made a study relating to capacitor discharge type shocks. A shock with an energy content of 50 J or less may be startling or disagreeable but not lethal; one with with an energy content of 0.25 J is definitely objectionable though harmless. The effect can be gauged by noting that an individual walking on a carpet can receive an electrostatic shock with about 10 mJ of energy when touching a grounded object. This assumes a typical (Brundrett, 1976/1977) body capacitance of 200 pF and a body voltage of 10 kV.

EFFECT OF FREQUENCY

The frequency of the electrical current is important in determining the effect on the human body of a given magnitude of current. It has been shown in the section on direct current shocks that to produce a given effect a greater level of direct current is required than for a 60 Hz shock acting for the same period. The effects of other frequencies must also be considered.

When testing appliances or medical devices for leakage current, test loads have been devised which are supposed to simulate the response of the human body to the various frequency components in the leakage current. In order to do this, an electronic voltmeter is connected across the simulated load in such a fashion that a given reading of the voltmeter at any frequency is equivalent to the same effect shock. Underwriters Laboratories (1976) specifies a test load to measure leakage current such that the allowable leakage current is the same for all frequencies to 1 kHz. The allowable leakage current is increased directly proportional to the frequency for frequencies higher than 1 kHz up to 100 kHz. Above 100 kHz the allowable leakage current is the same as at 100 kHz - 100 times the value at 1 kHz. The equivalent dc shock current for the same effect is taken as 40% larger than the 60 Hz current. The ANSI/AAMI (1978) test load is similar.

EVALUATION OF SHOCK HAZARDS

Train of Pulse Shocks

The electric fence controller (Underwriters Laboratories, 1980) provides a basis for determining what is considered a safe electric shock for a train of pulses. The electric fence has been used for many years with the realization that humans will contact the fence but must not be injured. The controller delivers a pulse type output with the output during the "on time" being of the peak discharge-type output or of the 60 Hz sinusoidal-type output. All tests for the controller are performed with a 500 ohm load.

The "off period" for the controller must be greater than 0.9 s for a sinusoidal type output or greater than 0.75 s for a peak discharge-type output. This "off period" is essential to allow an individual to get off the fence as the output during the "on period" is greater than the let-go current level. Continuous output is not permitted. Any single failure in the controller must not produce a continuous current greater than 5 mA.

The "on period" for peak discharge-type controllers must be less than 0.2 seconds. For this peak discharge-type controller, the output delivered to a 500 ohm load during the "on time" is limited to a given value of milliampere-seconds, charge, depending on the length of the "on period." The curve for the "on period" for peak discharge-type controllers provides allowable milliampere-second values for the time period from 0.03 s to 0.1 s. For "on periods" from 0.1 to 0.2 seconds the allowable output is 4 mA-s. The allowable output is reduced to 2 mA-s for a 0.03 second "on period."

For sinusoidal-type output the "on period" must be less than 0.2 s. For "on periods" between 0.025 s and 0.2 s, the allowable current must be less than

$$I = 75 - 350T \text{ mA r.m.s.} \quad (3)$$

where T is the "on period" in seconds. For "on period" between 0.025 s and 0.2 s, equation (3) allows sinusoidal type r.m.s. currents between 65 and 5 mA. These values are well below the 500 mA level considered dangerous for a single shock of such duration. It is important to note, however, that the fence controller produces a train of pulses rather than a single pulse.

Noting that the pulse repetition frequency for the sinusoidal-type pulse is approximately 1 Hz, the true r.m.s. current can be calculated for different pulse "on periods" when the r.m.s. value of the current during the pulse is given by equation (3). The results for pulse width between 0.025 s and 0.2 s are given in Table 1.

This indicates that the highest output current is about 13 mA which is above the 60 Hz let-go current for some individuals. The current should not electrocute a person at this level. There still is a question as to whether the true r.m.s. current given in Table 1 can be equated to the effect of 60 Hz currents. The pulse train will have frequency components above 1 kHz.

To study the frequency components for the pulse train the Fourier spectrum (Cooper, 1967) for a single pulse is calculated. Because the pulses are periodic with a frequency of 1 Hz, the amplitudes for the individual harmonics are proportional to the value of the Fourier spectrum at discrete frequencies - starting at 1 Hz and at all higher frequencies separated by 1 Hz. The peak discrete frequency component is $2/\tau$ times the Fourier spectrum value at that frequency where τ is the period for the pulses in seconds. Above 1 kHz the

TABLE 1 True R.M.S. Current Related to Pulse Width

Pulse Width (T) (s)	True r.m.s. Current (mA)
0.025	10.47
0.05	12.84
0.07	13.34 (max)
0.10	12.62
0.15	8.65
0.2	1.9

effect of the frequency components decrease inversely proportional to the frequency. Using the Fourier spectrum and the decrease in effect of the shock for frequencies above 1 kHz, the effective r.m.s. current for the n'th harmonic is given in equation (4)

$$I_n = (75\text{-}350T)\ T\left[\frac{\sin(n-60)\ \pi T}{(n-60)\ \pi T} + \frac{\sin(n+60)\pi T}{(n+60)\pi T}\right] \cdot \frac{[1+(n/10^5)^2]^{1/2}}{[1+(n/10^3)^2]^{1/2}}\ \text{mA r.m.s.} \qquad (4)$$

where n is the harmonic and, in this case, its frequency (n = 1,2,3, ---); T is the "on period" in seconds; and the frequency of the sinusoidal output during the pulse is 60 Hz. Above 1 kHz, equation (4) indicates that the harmonics are small and falling off rapidly so that the frequency components below 1 kHz are the most prominent. Thus, the true r.m.s. current values in Table 1 are equivalent to the 60 Hz values as far as effect on the human body is concerned.

Half-Wave Rectified Sine Wave Voltages

The effect of electrical shocks from half-wave rectified sine wave voltages can be evaluated by analyzing the effects of the frequency components for this waveform. Consider the r.m.s. voltage of a half-wave rectified sine waveform derived from a full-wave sinusoidal voltage.

$$V_{r.m.s.}\ (\text{half wave}) = \sqrt{2}/2\ V_{r.m.s.}\ (\text{full wave})\ V \qquad (5)$$

The Fourier series expansion for the half-wave rectified sine wave is given by the following expression where V_{avg} is the half-wave rectified average value.

$$v(t) = V_{avg}\left[1 + \frac{\pi}{2}\cos\theta + \frac{2}{3}\cos2\theta - \frac{2}{15}\cos4\theta + \frac{2}{35}\cos6\theta - \frac{2}{63}\cos8\theta + \frac{2}{99}\cos10\theta + \ldots\right] \qquad (6)$$

Equation (6) can be used to evaluate the hazard of the half wave rectified voltage and compare it to full wave voltages. The half wave rectified voltage obtained from a full wave,*60 Hz, sinusoidal voltage has a true r.m.s. value of 84.85V. This is certainly a dangerous voltage providing that this true r.m.s. voltage is made up primarily of frequency components below 1 kHz. From equation (6) it is seen that the frequency components above the 10th harmonic, 600 Hz, have very small magnitudes so that the true r.m.s. value is made up primarily of

*120 V r.m.s.

frequency components below 600 Hz. Evaluating the r.m.s. value by taking the square root of the sum of the squares for the r.m.s. values for the first 10 harmonics provide an r.m.s. value for the first 10 harmonics of 84.82V which is practically the true r.m.s. So a shock from a half wave rectified voltage source where the full wave voltage was 120 V r.m. is as hazardous as an approximate 85 V r.m.s. full-wave voltage.

The Electric Gun

An electric gun has been developed where two darts, trailing wires connected to the gun, are fired into an individual. When the darts are embedded, electric shocks are delivered to incapacitate the person. The shock delivered consists of a train of high frequency damped sinusoidal pulses with a repetition frequency of 13 Hz.

With the darts fully inserted into the tissue, the exposed dart area per dart is about 5.5 mm. Geddes and Baker (1975) find that the impedances between pairs of needle electrodes to be approximately 1000 ohms for 5.6 mm^2 exposed area electrodes and approximately 300 ohms for 73 mm^2 electrodes. Since the electrodes have barbs and are forcefully inserted, it would appear that 500 to 1000 ohms would be reasonable electrode resistance values. The value of electrode resistance is important as the current output of the gun power supply depends on the load resistance.

With a 500 ohm load, the gun power supply has an output voltage waveform consisting of a train of damped sinusoidal pulses where each pulse is of the form

$$v(t) = V_0 e^{-t/\tau} \sin \omega_d t \text{ V} \tag{7}$$

where

$$V_0 = 3692\text{V}, \ \tau = 15 \ \mu\text{s}, \text{ and } \omega_d = 4.83 \times 10^5 \text{ rad/s} .$$

The pulse repetition frequency is 13 Hz so the period is 77 ms.

The true r.m.s. value for the current in a 500 ohm load can readily be calculated from equation (7) and is found to be

$$I = 51.1 \text{ mA r.m.s.} \tag{8}$$

This certainly would be a hazardous value if this current were equivalent to a 60 Hz shock.

The Fourier series frequency components for the train of damped sinusoidal pulses are obtained from the Fourier spectrum (Cooper, 1967) for the single damped sinusoidal pulse of equation (7) and is:

$$F(jw) = V_0\omega_d/\{(j\omega)^2 + 2a(j\omega) + (a^2 + \omega_d^2)\} \tag{9}$$

where $a = 1/\tau = 6.67 \times 10^{-4} \text{ s}^{-1}$. This can be recognized as a second order system with the following parameters

$$\text{Undamped natural frequency } (\omega_n) = (a^2+\omega_d^2)^{1/2} = 4.88 \times 10^5 \text{ rad/s or}$$
$$\text{Undamped natural frequency } (f_n) = 77.7 \text{ kHz} \tag{10}$$

$$\text{and Damping ratio } (\zeta) = a/\omega_n = 0.14 \tag{11}$$

Since the bandwidth for such a system is approximately, 120 kHz, the spectrum has significant high frequency component up to the bandwidth - well above the 1 kHz frequency where the effects of electric shock on the human body for a given magnitude current are reduced.

Because the damped sinusoidal pulses are periodic with a frequency of 13 Hz, the r.m.s. values for the Fourier series harmonics are proportional to the value of the Fourier spectrum at the harmonic frequency. For this case the Fourier series has its fundamental frequency of 13 Hz with the higher harmonics all the multiples of 13 Hz.

Using equation (9), the r.m.s. value for the harmonic at each discrete harmonic frequency, ω, is

$$I(j\omega) = \left[\frac{2}{\sqrt{2}RT}\right]\left[\frac{V_o\omega_d}{a^2+\omega_d^2}\right]\left[\frac{1}{\{1-[\omega^2/(a^2+\omega_d^2)]\}+j\{2a\omega/(a^2+\omega_d^2)\}}\right] \text{ A r.m.s.} \qquad (12)$$

where

$T = 1/13$ s $\qquad V_o = 3692$ V

$\omega_d = 4.83 \times 10^5$ rad/s $\qquad a = 1/\tau = 6.67 \times 10^4$ s^{-1}

$R = 500$ ohms

and ω has discrete values at $\omega = 2\pi(13n)$ where $n = 1,2,3,$ ---.

The magnitude for the n'th harmonic where the frequency for the harmonic is f = 13n Hz is:

$$I(n) = 2.76 \times 10^{-4}/[(1-2.8 \times 10^{-8}n^2)^2 + (4.59 \times 10^{-5}n)^2]^{1/2} \text{A r.m.s.} \qquad (13)$$

The true r.m.s. value for the current including the first n harmonics is the square root of the sum of the squares for the first n harmonic values from equation (13).

The harmonics from equation (13) must be reduced by introducing the frequency response for the human body when the effects for shock currents are reduced proportional to frequency for frequencies between 1 kHz and 100 kHz. This can be accomplished by multiplying the magnitude for a given harmonic, n, found in equation (13) by the factor:

$$G(jw) = [1 + (f/10^5)^2]^{1/2}/[1 + (f/10^3)^2]^{1/2}$$
$$= (1 + 1.69 \times 10^{-8}n^2)^{1/2}/(1 + 1.69 \times 10^{-4}n^2)^{1/2} \qquad (14)$$

Combining equations (13) and (14) the following r.m.s. values for current to the n'th harmonic have been calculated and are shown in Table 2.

The results shown in Table 2 indicate that the output of the electric gun would be as hazardous as an approximate 3 mA, 60 Hz electric shock with a current path between the barbs. This should not be hazardous as it is well below the ventricular fibrillation level. It is a nasty shock somewhat like one at the let-go current level.

TABLE 2 Effective r.m.s. Current on Human Body to n'th Harmonic

Harmonic, n	Frequency for Harmonic,n (kHz)	Effective Current (mA r.m.s.)
1000	13	2.96
2000	26	3.00
7750	100.75	3.13

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DISCUSSION

BEATTIE: You took account of the repetitive nature of several shock type signals by computing the RMS value of current. What rationale is there for using this figure for phenomena that are primarily threshold initiated and exhibit non-linear temporal characteristics?

REILLY: The approach used by the author is similar to that of Dr. Menendez in a previous paper (5.3). I would like to get the author's response to the question I raised at that time. How can linear circuit analysis be used for the extremely nonlinear process that is involved when we electrically stimulate excitable membranes with oscillating currents?

BERNSTEIN: Both Mr. Reilly and Dr. Beattie raise the same valid point as to how linear circuit analysis can be used for the harmonics of a periodic pulse shock waveform.

At the present time there is no other way to attempt to evaluate the hazard related to such periodic waveforms. The calculations provide results that would be the same as measured using the AAMI or UL test loads. The calculations also seem to fit Dr. Knickerbocker's experimental results with combined dc and ac shocks.

More experimentation is necessary on combined alternating current shocks of different frequencies before a better answer can be provided.

DAWALIBI: The author has decomposed the signal into its Fourier components to establish an equivalent RMS value for safety evaluation. Did the author take into consideration the frequency dependent nature of the threshold current or response of human to electrical current?

BERNSTEIN: The effect of frequency on the Fourier components was included as shown by the last factor in Equation (4) and in Equation (14). The effect of frequency components above 1 kHz is reduced in proportion to frequency for up to 100 kHz. Above 100 kHz the frequency components are reduced in magnitude to 10^{-2} of those that are calculated for the waveform itself.

VAINBERG: Do you know if anyone tried to compare the data on fibrillation thresholds and values of body impedance obtained from legal electrocutions with the data presented at the symposium during the last two days?

BERNSTEIN: Well it is turning out that the impedance from the head electrode to the calf is about 250 Ω. They've been making the measurements ever since the first electrocution in 1890. And as far as fibrillation is concerned, I think that the trouble with the Alabama system was that they kept it at 1800 V. Then they brought it down to 800 Volts and then they went back up again for a reason that nobody knows why. I think they defibrillated the subject every time they brought the voltage back up.

HART: I have a comment regarding work that I have done with mixed frequency currents and preliminary work with square waves. It has been shown that the weighted peak relates to the let-go levels and the perception levels of Dalziel.

KURN: I have a question about electric fences. We know what they do to humans, and obviously these fences are controlled so that there is no harm to people. But a human is 500 Ω. What happens to the animal when it touches the fence? I find it difficult to understand that the animal even feels it, I'm thinking of cattle with fur on. Is there something to be learned from the statistics of dead animals

found around the electric fences? Is there a size function that can be perhaps learnt from, I imagine, hundreds of miles of these fences?

BERNSTEIN: I have not done any studies on the effect of electric fence controllers for animals of various sizes and shapes and I am not aware of any studies going on at present.

GUSTAFSON: I'd like to respond to this question. We are working with animals basically at lower levels because of 2 and 3 V problems in livestock facilities. We have some data on dairy cow's resistance for several pathways. For example, a mouth to all four hooves pathway would have a mean resistance of about 360 Ω. The response of some cows to electric fences is dramatically different. Some cows actually scratch their backs on those and others jump far away. So, there is a lot of variability. In summary, there exists some data, but it is very limited.

KNICKERBOCKER: Would the author care to comment on whether or not the results of a study I carried out,* which I believe shows that RMS current may not be an appropriate "description" of fibrillating levels for computer waveforms, encourages him to look for alternative ways of characterizing the magnitude of complex waveforms?

BERNSTEIN: The paper cited by Dr. Knickerbocker is quite useful in that it attempts to determine an equivalent 20 Hz electrical shock current with the same duration as the combined dc and 20 Hz electrical shock that causes fibrillation in dogs. For shocks longer than 0.5 s, it is suggested in the paper that the equivalent, sinusoidal, alternating current has a peak-to-peak value the same as the peak-to-peak of the combined alternating and direct current.

For a one second shock the mean pure dc shock current was 340 mA while the mean pure 20 Hz shock current was 100 mA. This gave a ratio of 3.4. For a two second shock the same values were 275 mA pure dc, 75 mA pure ac, and the ratio was 3.67. Using this data I propose a dc-to-ac ratio of 3.5 and propose that the effective pure alternating current for a shock of the same duration as that for a combined alternating and direct current as given by the expression

$$(1) \qquad I_{rms} = [(I_{AC\ rms})^2 + (I_{DC}/3.5)^2]^{1/2}$$

Equation (1) was used to calculate the equivalent alternating current shock currents for one and two second shocks and compared to the results shown in Knickerbocker's Figures 15 and 16. Calculations were also made using Knickerbocker's criterion for comparison. The results are shown in the following table.

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* Knickerbocker, G.G., "Fibrillating Parameters of Direct and Alternating (20 Hz) Currents Separately and in Combination - An Experimental Study". IEEE Transactions on Communication V COM-21 #9 Sept/73.

Mean Effective Fibrillating Current

One Second Shocks

Test Data		Calculated Equivalent Pure ac Shocks			
		Knickerbocker		Equation 1	
I_{AC}(mA rms)	I_{DC}(mA)	Current (mA)	% Error	Current (mA)	% Error
100	0	100	0	100	0
85	25	85	-15	85.3	-14.7
100	50	100	0	101	1
100	100	100	0	104	4
90	160	101.6	1.6	100.9	0.9
75	280	136.6	36.6	109.7	9.7
0	340	120.2	20.2	97.1	-2.9

Two Second Shocks

Test Data		Calculated Equivalent Pure ac Shocks			
		Knickerbocker		Equation 1	
I_{AC}(mA rms)	I_{DC}(mA)	Current (mA)	% Error	Current (mA)	% Error
75	0	75	0	75	0
80	25	80	6.7	80.3	7.1
80	50	80	6.7	81.3	8.4
80	80	80	6.7	83.2	10.9
80	150	93	24	90.8	21.1
50	185	90.4	20.5	72.8	-2.93
0	275	97.2	29.6	78.6	4.8

These results seem to indicate that at least for a combined alternating and direct current shock the concept of using an equivalent effective current based on the weighted effective values may be valid.

METHODS OF CALCULATING ELECTRICAL BODY IMPEDANCE AND EQUIPMENT FOR MEASURING LEAKAGE CURRENTS

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ABSTRACT

The impedance of the human body is represented by a five-component model, consisting of a resistor in series with two parallel combinations of a resistor and a capacitor. The values of the components can be calculated by equations as functions of the pathway and duration of the current through the body, height and weight of the body, area and pressure of contact, and the voltage across the body. On the basis of a literature review, suggested limits are given in order to prevent injuries from the physiological effects of the passage of electric current through the human body such as: inability to let go of the electrode, stoppage of breathing, ventricular fibrillation of the heart, electric burns and paralysis. This paper is limited to consideration of circuit voltages of not more than 250 V RMS.

KEYWORDS

Body impedance; skin impedance; let go; ventricular fibrillation; shock hazard.

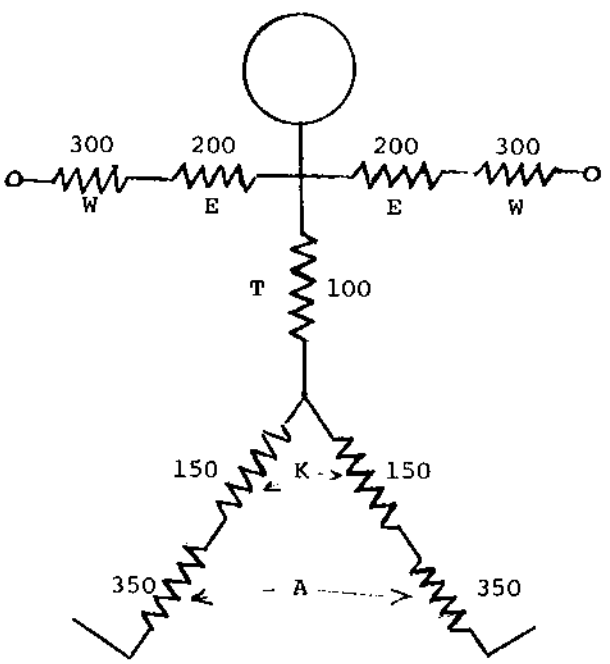
INTRODUCTION

Regulatory agencies that have the responsibility of making judgment of the safety of electric products should have well-defined rules for determining the risk of physiological effects from the passage of current from the product through the human body. These rules should be based on the best information available. One source of information is a review of the shock hazard literature. The space does not permit listing all the references; however, we would like to mention a few authors with the most significant work relating to this paper: Dr. G. Biegelmeier, C. F. Dalziel, L. P. Ferris, H. Freiberger, A. P. Kiselev, D. L. Underwood. There should be limits for current from the product that might pass through the human body, and specifications for methods of measuring the current. The impedance of the instrument measuring the current should be representative of the impedance of the human body under the most severe likely conditions during the interface of the person with the product. The established limits should be conservative because of the limited experimental data. More research work is needed in several areas in order to establish less conservative limits with sufficiently high confidence level. The views expressed in this paper are not necessarily the views of the Consumer Product Safety Commission or of Underwriters Laboratories.

BODY IMPEDANCE

The human body impedance can be described as having three distinct parts: the internal body impedance and the two skin impedances associated with the two electrodes applied to the body. The internal body impedance is reported to be essentially resistive with no reactive components. The skin reportedly behaves like a leaky capacitor that has a relatively low resistance(1).

Internal body resistance - In Freiberger's investigation the average or "reference" body height was 1.65m and the weight 56 kg. The internal body resistance of the reference person can be represented by Fig. 1.



Internal body resistances in ohms concentrated about the:

Wrist (W)
Elbows (E)
Torso (T)
Knees (K) and
Ankles (A)

Fig. 1

When the pathway of current through the body has been determined, the "reference" internal body impedance is calculated by combining the resistance values in that path. If we assume that a person's internal body resistance varies directly as the square of his height, and inversely as his weight, the internal resistance of a person having a height and weight differing from the "reference" body can be determined by multiplying the "reference" internal body impedance by the factor of 20.6 (H^2/W), where H is height in meters and W is weight in kilograms.

Skin impedance - Skin impedance may be represented by a parallel combination of a resistor and a capacitor(2). With two areas of electrode contact, two parallel combinations of resistor and capacitor are added to the model. The capacitance associated with the skin is estimated to be 0.05 uF for each cm^2 of area in contact with the electrode. The resistance of the electrode-skin interface is affected by many variables. Because there is always the probability that the skin may be wet, the resistance of the skin is calculated on the assumption that it is wet with a one percent solution of sodium chloride. The resistance of the skin decreases with increase in area of contact, or the conductance increases with increase in area of contact.

This can be expressed as

$$G = KA \tag{1}$$

where: G is the conductance, in mhos, at one skin-electrode interface; K is a parameter that is proportional to area, in mhos per cm^2; A is the area of contact in cm^2.

The effects of fringing at the edges of the electrode are not negligible when the contact area is small relative to the thickness of the skin(3). This can be accounted for in the value assigned to K in equation (1). For areas larger than about 0.1 cm^2, the value of K can be approximated by 80 umhos/cm^2.

With the assumption that the skin is wet and the voltage across the body is 120 volts, the results of investigations of skin resistance points to a value for K in equation (1) that can be expressed as:

$$K = 10^{(0.06A^{-0.434} - 4.1)} \tag{2}$$

from (1) and (2): $\frac{1}{G} = R_A = A^{-1}10^{-(0.06A^{-0.434} - 4.1)}$ (3)

Where R_A = the estimated worst-case (lowest) resistance of one wet skin-electrode contact, with 120 volts across the body, in ohms; A = the area of the wet skin-electrode contact in cm^2 (A not less than 0.001).

The pressure between the skin and the electrode has a relatively minor effect on skin resistance. Equation (3) was developed assuming a contact pressure of 0.5 kg/cm^2. If other values of pressure are employed, each skin resistance can be calculated by multiplying the value obtained in equation (3) by M_1, which is

$$M_1 = 0.899\ P^{-0.163} \tag{4}$$

where P is contact pressure in kg/cm^2 for one skin-electrode interface.

The investigators of body impedance(1) report that the magnitude of the voltage across the body has no effect on the internal body resistance, but does have effect on the skin resistance. The higher the voltage, the lower the skin resistance. The equations (3) and (4) are based on 120 volts across the body, with equal skin-electrode interfaces; and the data for developing the equations indicate that, with this body voltage, approximately 37 volts appear across each skin-electrode interface. For other values of voltage across the skin, the resistance value calculated by equations (3) and (4) is multiplied by M_2, which is

$$M_2 = 1.183e^{-E/220} \tag{5}$$

where: e = base of natural logarithms; E = voltage across each skin-electrode interface.

Since the multiplying factor is a function of the voltage across the skin, and the voltage across each skin is a function of the skin resistance, a process of iteration is used to gradually approach the proper value. When a voltage is applied to the body, the resistance of the skin reduces, but the process takes a certain amount of time(4). If the duration of the current is very short, the calculated values of skin resistance (based on long durations of current) should be adjusted upward.

BODY IMPEDANCE MODEL

The electrical impedance model of the body can be represented by the network shown in Fig. 2, where R_1 and C_1 represent one skin-electrode interface, R_2 and C_2 represent the other skin-electrode interface and R_3 represents the internal body resistance.

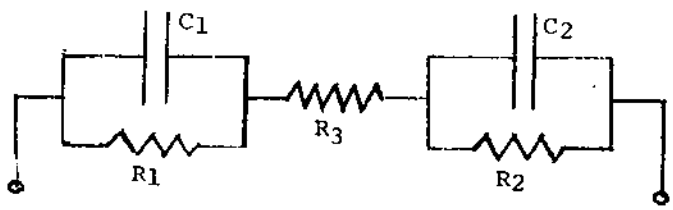


Fig. 2

When measuring current available from the product that might flow through a person's body, the network shown in Fig. 2 is used as the load in the electric circuit. The voltage measured across R_3, or any part of R_3, is proportional to the current that might flow through a person's body under the same conditions used for calculating the parameters of the network.

Based on the network shown in Fig. 2 an instrument called the Body Impedance Model (BIM) was developed by the Underwriters Laboratories (UL) for the U.S. Consumer Product Safety Commission (CPSC). The values of the parameters can be calculated and easily set to the prevailing conditions. The BIM is being used presently by CPSC for measuring leakage currents on electrical consumer products whenever the presence of excessive leakage current is suspected.

RECOMMENDED CURRENT LIMITS

Physiological Effects of Current - Electric current through the human body produces many different kinds of physiological effects. Among these effects are perception, reaction, let-go, stoppage of breathing, ventricular fibrillation of the heart, electric burns, and paralysis. These effects are listed approximately in the order of increasing current. To avoid potentially lethal and otherwise injurious current levels, the recommended current limits should be based on electric burns, let-go, and ventricular fibrillation. When these effects are prevented, the harmful effects of the other physiological effects are prevented.

In judging the risk of injurious electric shock associated with a particular electric product, the accessible parts of the product that serve as a source of current should be examined, and a judgment made regarding the ability of a person to release contact with the product, assuming that the current through the hand and the arm of the person is above the level of "let-go". If it is judged that the person would be unable to release contact and there is no automatic interruption of the circuit, the steps relating to "let-go" limits should be taken. If it is judged that the person would be able to release contact, the steps relating to "ventricular fibrillation" should be taken.

The threshold of electric tissue burns involves many parameters, including duration of contact. If the person involved is able to release himself from the circuit in a short time, the probability of a tissue burn is remote, unless the current is very high, probably higher than the threshold of ventricular fibrillation. The

probability of a tissue burn may be greater at high frequency because the sensation of the shock is not as great as at low frequency.

Let-go. The threshold of perception of electric current, with electrodes held in the hands, is approximately 1 mA. If the current is increased beyond this point, the muscles of the fingers, hands, and the arms are involuntarily tightened; and the person may be unable to release his grip. Currents of sufficient magnitude to "freeze" the subject to the electrodes produce severe pain and they are considered dangerous. Fainting can result and recovery may not take place(5).

Consideration should be given to the character and use of the product being tested in order to determine the types of persons (man, woman or child) that might interface with the product. The recommended let-go limits for direct or sinusoidal currents are shown in Table 1. For currents containing both dc and ac components (between 15 and 70 Hz) the limits will be between the values established for DC and AC, and have to be calculated. Currents with other than sinusoidal waveforms will generally have the same thresholds, if the peak values of the waveforms are equivalent.

TABLE 1 Direct and Sinusoidal Let-Go Current Limits (rms mA)

Frequency(Hz)	Man	Woman	Child
DC	60	40	30
5	14.5	9.6	7.2
10	9.8	6.5	4.9
15-70	9.0	6.0	4.5

VENTRICULAR FIBRILLATION

If the current is increased beyond the threshold of let-go and to values somewhat greater than those just necessary to stop respiration, a condition of the heart, known as ventricular fibrillation occurs. Death usually occurs within a matter of minutes unless the heart is quickly defibrillated. The experiments indicate that the threshold depends on the body weight, the duration of the current, and the type of current (dc, ac and wave shape).

Body Weight - Most of the experimental work in determining thresholds of ventricular fibrillation was performed on several species of animals having different body weights. The data showed that there was almost a linear relationship between the threshold of ventricular fibrillation and the average body weights of the several species. In some experiments, there was no indication that the threshold of ventricular fibrillation was related to the weight of the animals within a species. It appears that all the animals within a species were full-grown and there was no great variation in the weights of the animals.

Several of the investigators used the relationship between threshold of fibrillation and average body weights of the species of animals tested to propose fibrillating current levels for human beings. To provide protection for human beings of all sizes, the recommended limits are shown in the last column of Table 2).

Effect of Duration - Investigation of the effect of duration of current on the threshold of ventricular fibrillation for animals showed that as the duration is decreased below approximately one second, the threshold of ventricular fibrillation current is increased(6). The data from four investigators are plotted in Fig. 3. On the same graph, there is plotted a curve that illustrates the recommendation for

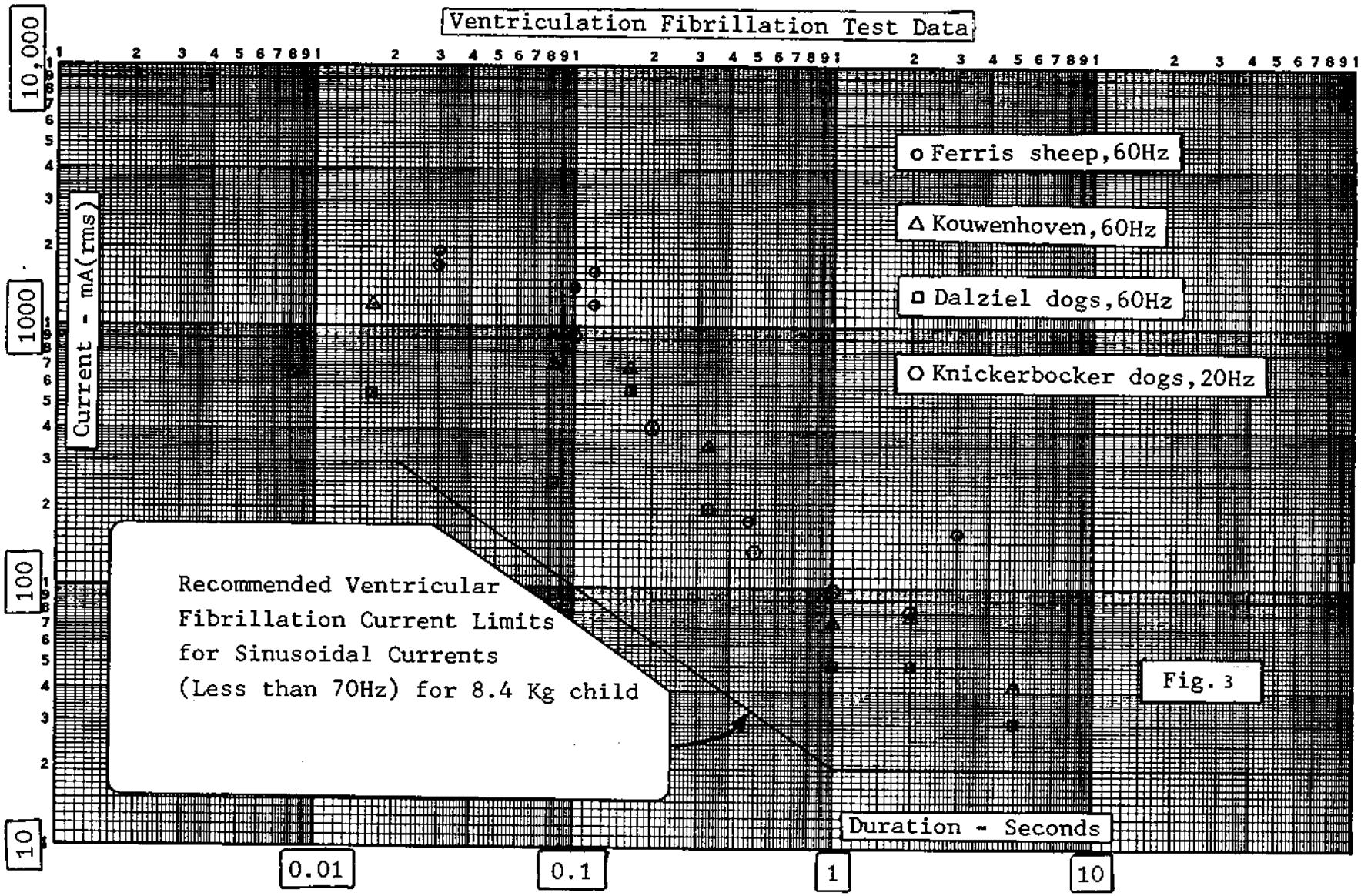

Ventriculation Fibrillation Test Data
Current - mA(rms)
10,000
1000
100
10
0.01
0.1
1
10
Duration - Seconds
o Ferris sheep,60Hz
Δ Kouwenhoven,60Hz
□ Dalziel dogs,60Hz
O Knickerbocker dogs,20Hz
Recommended Ventricular
Fibrillation Current Limits
for Sinusoidal Currents
(Less than 70Hz) for 8.4 Kg child

Fig. 3

Fig. 3

maximum current for a 8.4 kg child. 8.4 kg is the 5th percentile rank by weight of male and female children having ages between 12 and 15 months (7). Table 2 shows the recommended limiting current values for people with different body weights.

TABLE 2 60 Hz RMS Limits of Sinusoidal Currents for Protection from Ventricular Fibrillation

Body Weight (kg)	Type of Person	Shock duration (T) (Seconds) Less than 0.0209	0.0209 to 1	Greater than 1
70	Man	I=1245 mA	$I=83T^{-0.7}$ mA	I=83 mA
55		I=1125 mA	$I=75T^{-0.7}$ mA	I=75 mA
43.8	Woman	I=915 mA	$I=61T^{-0.7}$ mA	I=61 mA
25		I=585 mA	$I=39T^{-0.7}$ mA	I=39 mA
8.4	Child	I=300 mA	$I=20T^{-0.7}$ mA	I=20 mA

Composite dc and Sinusoidal ac - As a result of an investigation on dogs, it was determined that for combinations of ac and dc, where the ac component has a frequency of 70 hertz or less, the fibrillation hazard may be taken as being approximately the same as the hazard of the equivalent pure ac shock. The equivalent pure ac shock is one of the same duration and of the same peak-to-peak current as parameter A, if the shock duration is 0.5 second or longer; or of the same peak current as parameter B, if the shock duration is 0.2 second or less. See Fig. 4.

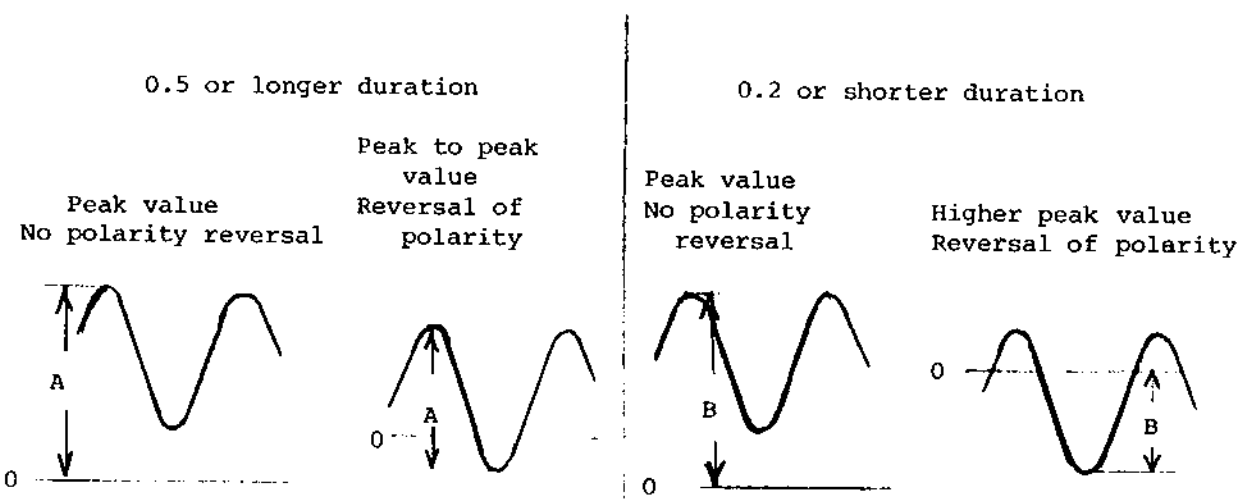


Fig. 4. Parameter for amplitude measurement

For full-wave and half-wave rectified sinusoidal alternating current at frequencies between 40 and 70 hertz, the maximum recommended levels for prevention of ventricular fibrillation are shown in Table 3.

TABLE 3 Maximum Acceptable Full-Wave and Half-Wave Rectified Sinusoidal Alternating Current (mA) At Power Line Frequencies for Protection From Ventricular Fibrillation

Body Weight (kg)	Duration	
	Less than 0.05s	Greater than 1s
	Current Limit (mA)	
70	946 peak	221 peak
55	855 peak	200 peak
43.8	695 peak	162 peak
25	445 peak	104 peak
8.4	228 peak	53 peak

RECOMMENDATIONS FOR FUTURE ACTIONS

Body Impedance - The review of the literature did not reveal sufficient information to permit the construction of a body impedance model that would incorporate all of the variables present in real life. The variables that should be further investigated include the effect of moisture, skin puncture and scars, nonlinearity of the skin resistance, the effect of various different electrode shapes and materials, skin thickness and type, the variation of the skin resistance as a function of time at different current values, and the effect of voltage across the skin on the resistance of the skin.

Current Limits - The recommendations for current limits are based upon the information contained in the technical literature on the subject. In some cases, the investigation of the effects of a particular parameter of the current upon the body was carried out by only one group of investigators. In order to obtain better confidence in the results, other investigators should conduct similar experiments covering the same parameters.

The effect of different wave shapes on the let-go current level has been investigated, but it is desirable to have information on the effect of other wave shapes, including narrow pulse trains, interrupted direct current, and phase-cut sinusoidal current. The effect of frequency has been determined for frequencies up to approximately 10,000 Hz. Because present day products operate at higher frequencies, frequencies beyond 10,000 hertz should be used in the investigations.

In the investigation of safe levels of current that will not cause ventricular fibrillation, there is always the problem of using animal data in order to judge the safe current levels for human beings. Further investigation should be conducted on the effect of age within an animal species on the threshold of ventricular fibrillation. The effect of body weight within a species and the effect of the health of the animal should also be investigated.

Shock durations less than 8 milliseconds should be employed to induce fibrillation in animals in order to determine the relationship between these very narrow pulses of current and the threshold of fibrillation. During this investigation, currents from the discharge of a capacitor through the body may be investigated as this type of body current is common in real life situations.

In recent years considerable medical research has been done on the effect of electric current on the human heart. In the medical experiments, the current is applied directly to the heart with no body impedance in the current path. The medical literature should be studied and the results correlated.

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DISCUSSION

F. DAWALIBI: (1) Under constant voltage conditions a child will be subject to less current than an adult, because of higher body impedance. Is this fact being taken into consideration? (2) if yes, what impedance values are recommended?

A.W. SMOOT: (1) Yes. (2) The body impedance model values will be determined by the applicable equations in accordance with the body weight, height, current pathway, contact area pressure, etc. This will result in a higher overall body impedance and a lower measured current from a constant voltage source.

P. SANDELL: What is the position of UL and the USA, concerning the use of the curves adopted by the IEC in its Sub-Committee 23E concerning the "Ground Fault Current Interrupter (GFCI)" as IEC Report No 755.

A.W. SMOOT: We are of the opinion that the trip level of GFCIs for long time exposures should be low enough to protect against inability to let go. The US has therefore adopted the 5 mA level in the UL Std for GFCIs. There is little difference between the IEC and Figure 9 for short time shocks.

BRIDGES: What is the status of the recommended fibrillation and let-go values, which you've discussed in the paper? Are these being made as a part of Underwriters Laboratory (UL) report or recommendations on the part of CPSC (Consumer Product Safety Commission).

MOGAN: Concerning CPSC, whenever a problem arises, we have a published limit based on the values which are represented in the study. Mr. Smoot can make a comment on a position of the UL.

SMOOT: The results of the study are being incorporated into several standards at this time and it will take a little time for them to appear in the printed standards.

KANODE: My question relates to the fact that we (Hewlett Packard) sell products in the US and, probably, sell a few products that come under the authority of the CPSC. The authors specified that the results of the paper will be used as a determinant in case of a problem. Could we then build a scenario and suggest that if we have a problem and someone has been harmed, then the CPSC will use the suggested numbers to identify guilt on the part of the manufacturer?

MOGAN: We use this number to determine whether or not a certain product is considered safe or unsafe.

GRIFFIN: Just one brief comment. As you consider the difference between adults and children, we should keep in mind that the body composition of children is completely different. Such things as water content may be almost double in children as compared to adults. In addition to that the distribution of fat and the composition of bone and blood may be significantly different.

MOGAN: Right now this was the best value we could come up with based on the available literature. As a result of the symposium we hope to update our data and bring it in line with the up to date results.

KANODE: I'd like to address this question to Mr. Smoot. In view of the comment made by Mr. Mogan from CPSC and in view of the numbers that have been presented I now find that the products that have been approved by Underwriters Laboratories under the business equipment and office equipment standards UL114 or UL478, are now considered unsafe for children, because they allow a leakage current of 5

milliamps and as I recall the graphs said 4 and a half milliamps. I'd like UL's opinion on this.

SMOOT: For those two categories, there is going to be more work done in order to make changes in the limits which will appear in the standard. Right now we're not exactly sure just what those new limits will be, but there will be work done.

KANODE: I'd like to address one more question to Mr. Mogan of the CPSC. My concern is for products that have been manufactured and have been out in the field for many years, have been designed and tested to a standard in the US that was assumed to evaluate a product for safety. The standard allowed 5 milliamps leakage current. The information that now UL has presented to CPSC says that for children, the leakage current limits should be 4.5 milliamps. We find these products used in the homes regularly, where grounding is not always available, producing this leakage current to any accessible metal parts. The cause for this has been the RFI requirements put out by the FCC, requiring us to actually increase filtering technique and produce some of this leakage current. The question is, will the CPSC apply this requirement of 4.5 milliamps to products that are in the field and products that are being manufactured today before UL changes their standard. That's a yes or a no I guess.

MOGAN: This is just one case where the difference between the numbers is so small that it is very difficult to differentiate between 4.5 and 5 ma.

SVERAK: Then what is your recommendation on body weight scaling, especially for children?

SMOOT: The recommendation has to do with two parts. One is the current limit for let-go or ventricular fibrillation. The current limit for the child is going to be lower than the limit for the adult. But for certain types of sources, (low-voltage sources, constant-voltage sources, in particular), the amount of current that's taken by that person, will be influenced by the size of the components in the body impedance model. So as was pointed out, the adult would probably have a lower body impedance and therefore would draw more current from the same supply as compared to the child. So, the body impedance will be different for and the current limits will also be different.

GAMS: I have a conceptual problem with the model. On the slide the child was identified as having a 8-1/2 kg body weight that makes a fairly small child. I cannot picture any manufacturer producing even an extremely simple electric device to be used by a one-year old child. Therefore, I assume that the home appliances which are available in any store are the object of this project. But, the manufacturer cannot design one object with the one-year old child in mind, and another object in the same product family for a 22 year old adult. So, in reality you only have one set of values with the child in mind. Am I right?

SMOOT: We're talking really about the people who will interface with the product, and in homes it is difficult to say that you could isolate children from electrical products. I think everybody has to agree that most of the products will at some time be touched by a one-year old child because that child can crawl and walk. In certain areas you will not find children. In certain industrial areas a one-year old child will not be present. In certain types of industrial equipment I would say we would not consider the child as being a person to interface with the industrial product and, therefore, the limits will be different, and the size of the components in the body impedance model will be different.

REQUIREMENTS FOR GROUNDING PRACTICES AND STANDARDS - THE REVISION OF IEC REPORT 479

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ABSTRACT

International co-operation in the field of electrotechnology demands harmonization of standards for protection and security. All of the necessary electropathological and electrophysiological basic essentials are given in IEC Report 479. It covers nearly all forms of electric shock, which are of technical interest, with shock durations from 0.1 ms to 10 s.

KEYWORDS

Electrical safety requirements; electrical standards; IEC Report 479; electrical accident prevention; electrical ventricular fibrillation; effects of electrical current.

INTRODUCTION

As a result of advanced modern developments of electrotechnology and increasing applications of electrical energy in all domains of life, measures for protection and security have been improved in conformance with the standards of technology. Safety specifications and instructions have been developed independently by different industrial countries and for this reason differences appeared which complicated international trade and co-operation. Moreover, man's requirements for protection and safety demanded a verification of the electropathological and electrophysiological basic structures. In view of the need for international co-operation and the best possible safety, it became an urgent demand to harmonize the differing electrotechnical standards of the various states. The International Electrotechnical Commission (IEC) is attending to the task of solving this problem.

Within the Technical Committee 64 (TC 64) of the IEC which is working out specifications for electrical installations in buildings, the working group "Effects of current passing through the human body" was established in November 1970 to elaborate on medical basic essentials in order to define the technical requirements for safety and protection.

In order to prepare proposals on how to achieve the highest possible degree of safety the Working Group defined its scope as follows:

- Collect information available on the pathophysiological effects of electric current on human body and on livestock.

- Propose curves of current values as a function of time which could be considered conventionally as being lower than the "pathophysiologically dangerous current". The proposals should be based on the information gained according to the collected information and should cover all kinds of current for durations exceeding half a cycle in the case of ac and 10 ms in the case of dc.

- Collect the information available, eventually in all countries concerned, on electrical accidents that occurred at voltages below 50 V ac or 75 V dc and caused severe injury or death.

- Propose values of voltages considered conventionally as not giving rise to pathophysiologically dangerous currents under specified environmental conditions.

IEC REPORT 479

In accordance with the scope, the Working Group has made an exhaustive study of the available literature. First of all, a current-time curve, which could be considered to be lower than the pathophysiologically dangerous currents, had to be plotted. The submitted experimental test results were based on animal experiments and referred to the fibrillating current. The animal species and weight had to be taken into account in interpreting the results. The findings could only be applied conditionally to human beings. Only the let-go current had been tested on living persons. It was known that in electrical accidents death could be caused by the direct effect of current on the heart muscle, by the effect of current on the autonomic nerves and by asphyxia. Apart from the experiments on animals, the Working Group could also rely on the findings of accident analyses. The available material did not give an exact current-time curve of the pathophysiologically dangerous limit values. Further, taking individual factors into consideration, a range of values was to be obtained. There were still considerable discrepancies in the literature regarding the limit values for the onset of ventricular fibrillation. At the present state of knowledge, the proposed current-time curve could, with the greatest probability, be considered as the current-time relationship which will not produce serious pathophysiological effects in adult men. The safety factor, necessarily included in it, could not be stated exactly, exactly, but only the safety factor in relation to the various known fibrillating curves. The safety factor decreases in the case of short durations and increases in the case of longer durations, because asphyxia and autonomic reactions have to be taken into account. Hopefully the resulting curve will be useful. It was plotted under electropathological aspects and concerned the body current in a pathway through the extremities. The Working Group was conscious that this curve could initially only provide guiding values in protection and safety questions in electrical

engineering. In practice, technical alternatives, economy and probability would have to be taken into account. Values below the curve could be taken as safe. For values above the curve, certain risks could exist, but if these are unavoidable in certain circumstances, then the risk must be considered (Fig. 1).

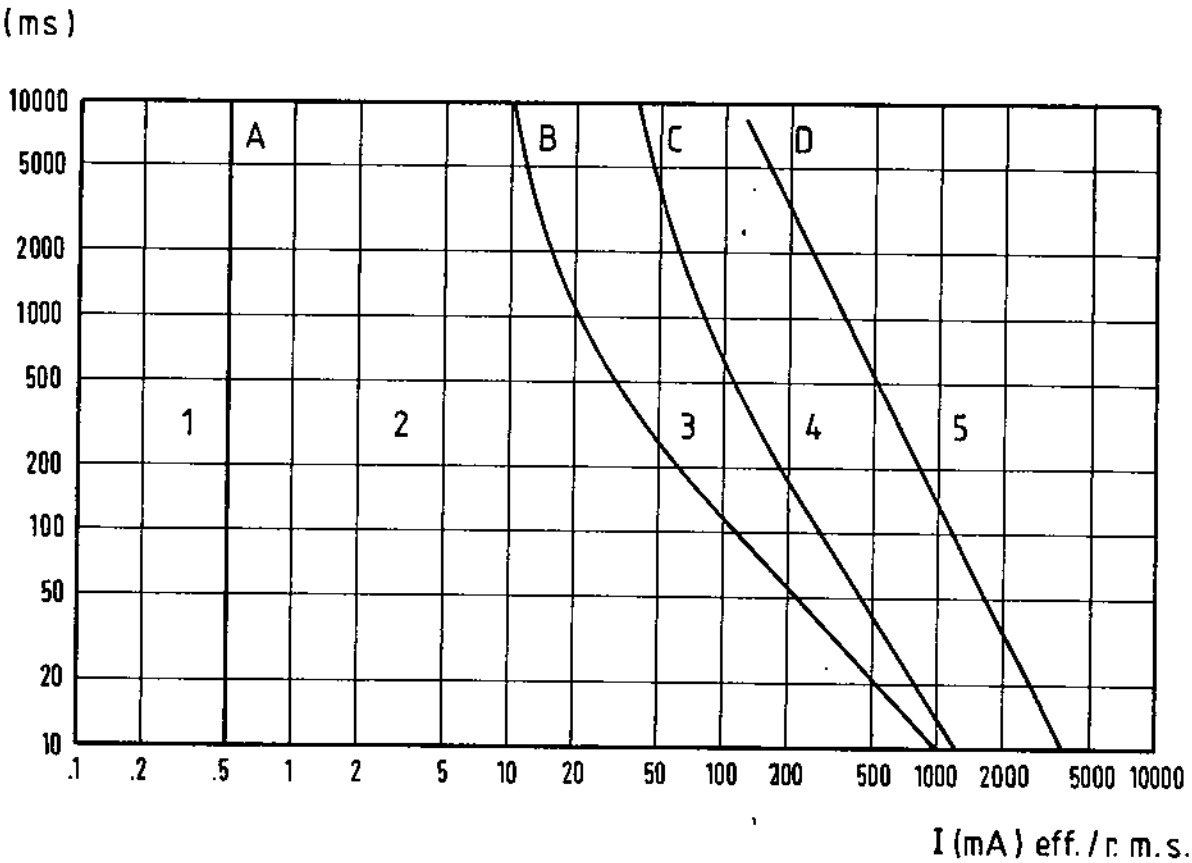

Fig. 1 Zones of effects of ac currents (50/60 Hz) on adult persons.

Zone 1: Usually no reaction effect

Zone 2: Usually no pathophysiologically dangerous effect

Zone 3: Usually no danger of fibrillation

Zone 4: Fibrillation possible (up to 50% probability)

Zone 5: Fibrillation danger (more than 50% probability)

For alternating current a multitude of data collected by numerous authors was available; however, for direct current the task of establishing a diagram of the effects of currents was much more difficult. Due to the fact that the best data were, in general, not directly comparable, they could not be plotted on a common diagram in order to define the different zones. The threshold of perception is 2 mA, as is well proven in the literature. To establish limits of a zone with usually no pathophysiologically dangerous effects, a number of factors were taken into account.

Specifically, a comparison between the risk of alternating current and direct current showed that the ratio of direct current values to alternating current values causing the same risk was high in the range of comparatively low currents and long times (about 4 at 10 s) and low in the range of high currents and short times (about 1 at 10 ms). According to this information it was possible to transform the corresponding curve of the alternating current diagram into the direct current diagram. There was not enough material to give approximate data separating a zone where ventricular fibrillation becomes likely from a zone where less harmful effects were to be expected. But there were data referring to dogs with an average weight between 10 and 16 kg given by Knickerbocker (1972) in his paper "Fibrillating parameters of direct and alternating (20 Hz) currents separately and in combination". They could be considered to be on the safe side for man (Fig. 2).

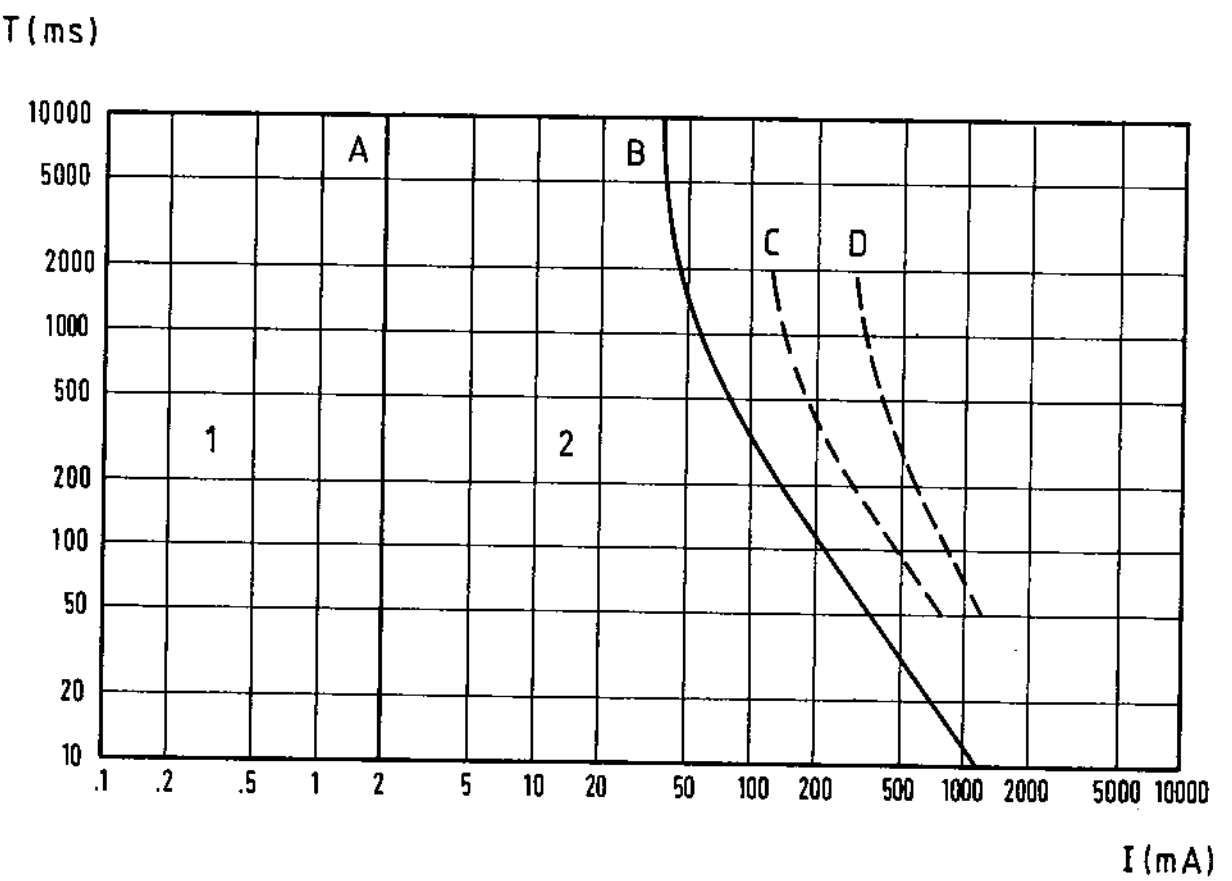

Fig. 2 Zones of effects of dc currents on adult persons.

Zone 1: Usually no reaction effect

Zone 2: Usually no pathophysiologically dangerous effect

Curves C and D: Tests with dogs by G. Knickerbocker
Curve C: 0.5% probability of fibrillation
Curve D: 50% probability of fibrillation

In the resulting diagram it was necessary to make clear that any curve which could be given did not present an absolute limit between two homogeneous zones but rather there was a steady transition between the different zones. In this sense, the Working Group when evaluating the numerous data contained in the literature deemed it useful not to restrict the presentation of the effects of current passing through the body to a single curve separating a dangerous from a nondangerous zone. On the contrary the data collected made it possible to give a more subtle presentation of the effects. This was particularly valid for alternating current at 50/60 Hz.

For a given current path through the human body, the danger to persons depends mainly on the magnitude and duration of the current. However, in many cases the time-current zones are not directly applicable in practice for designating protection against electric shock; the necessary criterion being the safe limit of touch voltage as a function of time. The relation between current and voltage is not linear because the resistance of the human body varies with the touch voltage, and data on this relationship are required accordingly. For this reason it was necessary to get data on the impedances of the human body.

There was no essential disagreement in the literature in regards to the dependence of the total body impedance on the voltage. The internal body impedance is constant and lies between 630 and 1300 Ω for the current path through the extremities. The contact impedance depends on: voltage, state of the skin, contact area, contact pressure and duration of contact. The results of Freiberger (1934) were mostly confirmed. The Group had also been guided by them in the proposals. In publication 479 the given values presupposed the most unfavourable conditions and were therefore minimum values.

Fifty volts ac and 75 V dc were recommended as allowable shock voltages under normal conditions. This shows a discrepancy with the curve in the case of longer durations. Under the most unfavourable resistance conditions, the current would be 25 mA, ie, higher than the let-go current. Theoretically, therefore, asphysxia and finally death could result if the subject remained in the circuit for a longer time. However, in practice, these most adverse conditions do not arise normally. This was also confirmed by an inquiry.

The results of the work of Working Group 4 were summarized in a document and submitted to IEC and National Committees for comments and approval. After this the document was issued in 1974 as an IEC Report, Publication 479.

PRACTICAL USE OF IEC REPORT 479

IEC documents are carefully prepared by experts and are of great international importance for technical co-operation for the following reasons:

1. The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special

interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2. They have the form of recommendations for international use and are accepted by the National Committee in that sense.

3. In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules insofar as national conditions will permit. Any divergence between the IEC recommendations and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

The form of the report has been adopted, as it summarizes results achieved so far and which are being used by Technical Committee No 64 as a basis for shock protection requirements. These results are considered important enough to justify an IEC publication, which may also serve as a guide to other IEC Committees and to countries in need for such information.

For the interpretation of this report, it must be emphasized that the data given herein represent a purely medical aspect of effects of current passing through a body. This data is intended to serve as a basis for establishing safety requirements from an engineering point of view. However this data is only one of the aspects to be taken into account; others may be probability of faults, probability of contact with live or faulty parts, ratio between prospective touch voltage and fault voltage, experience gained, technical alternatives and economics. These parameters have to be carefully considered and weighed when considering safety requirements.

The information given in Publication 479 could be interpreted as a survey of the present knowledge on pathophysiological effects of sinusoidal alternating current and sustained direct current on an adult person but could be subject to certain alterations in the future as further investigation bring in new findings. The possibility of a future revision was considered.

Since the first edition, no fatal electrical accident has been reported, with the physical parameters located in the zones considered to be safe zones.

PROPOSED REVISION OF IEC REPORT 479

New research work has been conducted on this subject in the meantime. Its analysis and more intense study of the preceding publications have allowed a better understanding of the effects of electric current on living organisms and, in particular, on man.

This specifically applies to the limits allowed for ventricular fibrillation which is the main cause of deaths caused by an electric current. The analysis of all results of recent research work on cardiac physiology and on the fibrillation threshold taken together, has made it possible to better appreciate the

influence of the main physical parameters, and especially of the duration of the current flow.

In fact, the fibrillation threshold does change as a function of the duration of the current flow:

- The intensity of the current necessary to cause fibrillation is high for a short duration of the current flow. This means that for a duration of less than a third of the cardiac cycle, fibrillation occurs only if the stimulus falls within the vulnerable period. This is a very specific part of the depolarization/repolarization of the heart and in the course of which the inhomogeneity of the excitatory state of the cardiac muscle makes fibrillation possible.

- The intensity necessary to cause fibrillation is much lower for a long duration of the current flow, ie, a duration exceeding several cardiac cycles, as in this case a current is too small to cause fibrillation for short durations, brings about extrasystoles which lower the fibrillation threshold quite substantially.

The modification of Curve C (Fig. 3) has been based on these physiological facts. This curve defines the fibrillation threshold as a function of the duration of the current flow.

Recent research work has also been conducted on the other physical parameters, especially the waveform and frequency of the current and the impedance of the human body. Therefore a revision of Publication 479 was deemed necessary. This revision should be viewed as a logical development and continuation of the initial publication.

The new edition of Publication 479 has been divided into six parts:

Part 1: Effects of alternating current in the frequency range of 15 to 100 Hz

Part 2: Effects of alternating current above 100 Hz

Part 3: Effects of direct current

Part 4: Effects of alternating current with direct current components including alternating current with phase angle control and burst firing control.

Part 5: Effects of impulse current

Part 6: Impedance of the human body

In order to avoid errors in the interpretation of this report it must be emphasized that the data given herein are based on experiments with animals and on information available from clinical observations and electrical accidents. Only few experiments with shock currents of short duration have been carried out on living human beings.

Based on information available at the present time, the conclusions of the report may be applied to humans but the data may have to be modified later as further knowledge is gained on the relative effects of currents on humans as compared to animals.

An important section of this publication is Part 1 "Effects of alternating current in the range of 15 to 100 Hz". An electric accident is determined by the factors: frequency, voltage, current, impedance, current path and time. Sinusoidal alternating current of 50/60 Hz is the most dangerous frequency for man. For a given current path through the human body, the danger to a person depends mainly on the magnitude and duration of the current. This part of the report shows the relationship between both of these factors and considers mainly the risk of ventricular fibrillation which, in that range of frequencies, is the main cause of fatal accidents. The report is primarily based on the findings related to effects of currents at frequencies of 50/60 Hz which are the most common in electrical installations. Of course, not only ventricular fibrillation but also other effects must be taken into account in the establishment of electrical safety requirements. Therefore the report describes these effects and gives in a diagram form the thresold limits as well zones in which other effects are encountered (Fig. 3).

In comparison to the first edition, Curve C as a limit to the zone in which fatal accidents may happen, is changed and a curve is constructed following the threshold of fibrillation with a security factor. This curve is so far on the safe side that on the evidence available, women and children are included. It is valid for a current path from left hand to feet.

TABLE 1

Heart-Current Factor for Different Current-Paths

Current-Path	Heart-Current Factor
Left hand to left foot, right foot or feet, both hands to feet	1.0
Left hand to right hand	0.4
Right hand to left foot, right foot or feet	0.8
Back to right hand	0.3
Back to left hand	0.7
Chest to right hand	1.3
Chest to left hand	1.5
Seat to left hand, right hand or hands	0.7

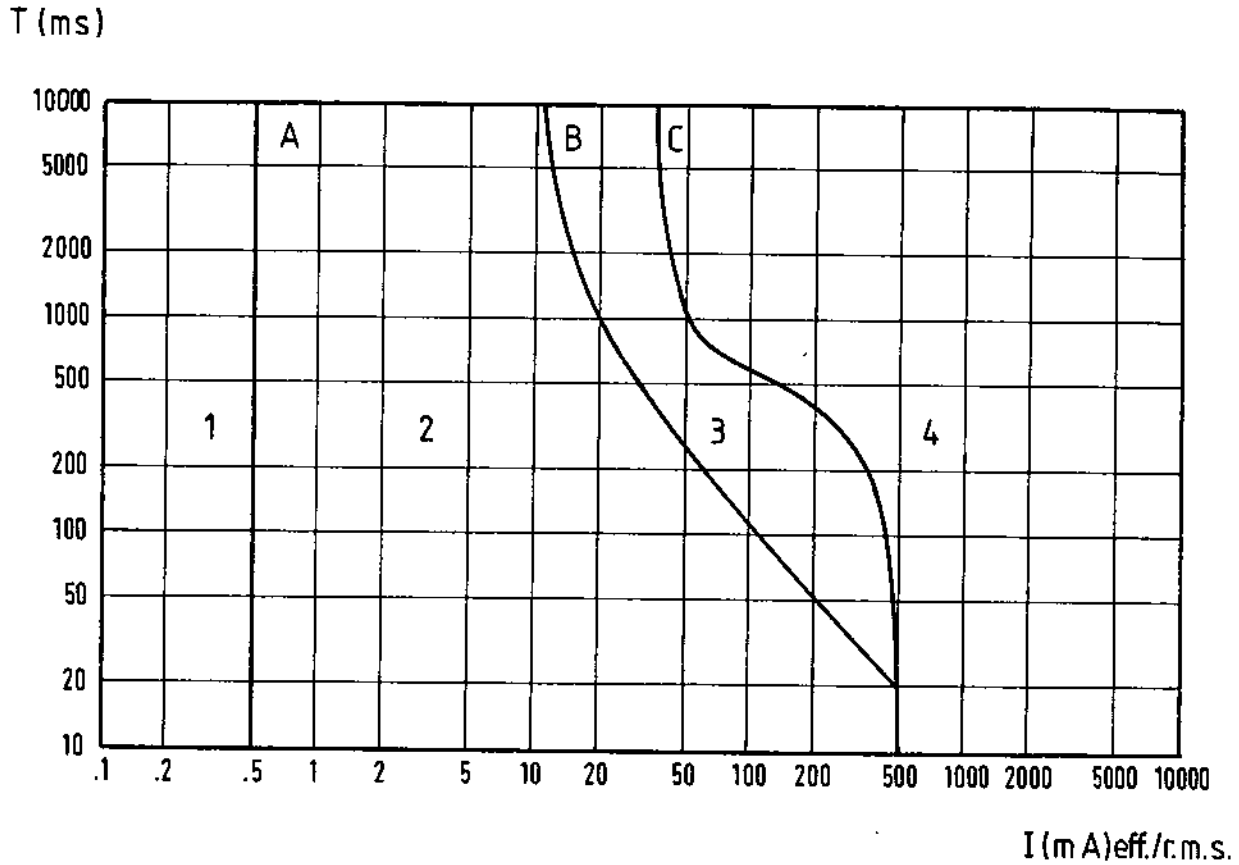

Fig. 3 Time/current zones for ac (50/60 Hz) effects on adult persons. (new proposal)

Regarding ventricular fibrillation, this figure relates to the effects of current which flows in the path - "left hand to feet".

Zone 1: Usually no reaction effects up to the threshold of perception (Curve A).

Zone 2: Includes limit of let-go of about 10 mA. Usually no harmful physiological effects.

Zone 3: Usually no organic damage to be expected. Increasing with current intensity and time muscular contractions and difficulty in breathing, reversible disturbances of formation and conduction of impulses in the heart, including atrial fibrillation and transient cardiac arrest without ventricular fibrillation are likely.

Zone 4: In addition to the effects of Zone 3, ventricular fibrillation likely. Increasing with current intensity and time, pathophysiological effects such as cardiac arrest, breathing arrest, and heavy burns.

For other paths a heart-current factor gives a rough estimation of the relative danger of the various current paths with regard to ventricular fibrillation. In Table 1 the heart-current factors are given for different current paths.

For example, a current of 200 mA for a current path from hand-to-hand has the same effect, regarding ventricular fibrillation, as a current of 80 mA for the path from left hand to feet.

To calculate the risk of higher frequencies, Part 2 shows the relation between the threshold values of effects of currents with frequencies of 50/60 Hz and the threshold values of effects of currents with higher frequencies. Alternating current of higher frequency is increasingly being used in modern electrical equipment, for example, aircraft (400 Hz), power tools and electric welding (mostly up to 450 Hz), electrotherapy (4000 to 5000 Hz) and so on. Higher frequencies are less dangerous regarding ventricular fibrillation. The fibrillation threshold has a minimum at about 50/60 Hz and rises by a factor of 14 at 1000 Hz.

Part 3, effects of ripple free direct current, includes more exact data than in the first edition because results of new research have become available. Accidents with direct current are much less frequent than would be expected from the number of direct current applications, and fatal accidents occur only under very unfavourable conditions. This is partly due to the fact that with direct current, let-go is less difficult and that for shock durations longer than the period of the cardiac cycle, the fibrillating threshold remains considerably higher than for alternating current.

The main differences between the effects of alternating current and direct current on the human body result from the fact that excitatory actions of the current (stimulation of nerves and muscles, induction of cardiac atrial or ventricular fibrillation) are linked to the changes of the current intensity especially when linking and breaking the current. Direct current flow of constant strength induces excitatory effects only at 2 to 4 times higher intensities than alternating current.

The fibrillation threshold for a decreasing current is about twice as high as for an increasing current. For a current path from hand-to-hand, ventricular fibrillation is unlikely to occur. For shock durations longer than the cardiac cycle, the threshold of fibrillation for direct current is several times higher than for alternating current. For shock durations shorter than 200 ms the threshold of fibrillation is approximately the same as for alternating current, measured in rms values.

As with the time/current zones for alternating current, a curve was constructed separating the zone where fibrillation becomes likely from the zone where less harmfull effects may be expected. This curve applies to increasing current flowing longitudinally in the body. With a decreasing current flowing longitudinally in the body , the curve has to be shifted to higher current intensity by a factor of about two. For safety requirements it is necessary to take into account the most unfavourable conditions (Fig. 4).

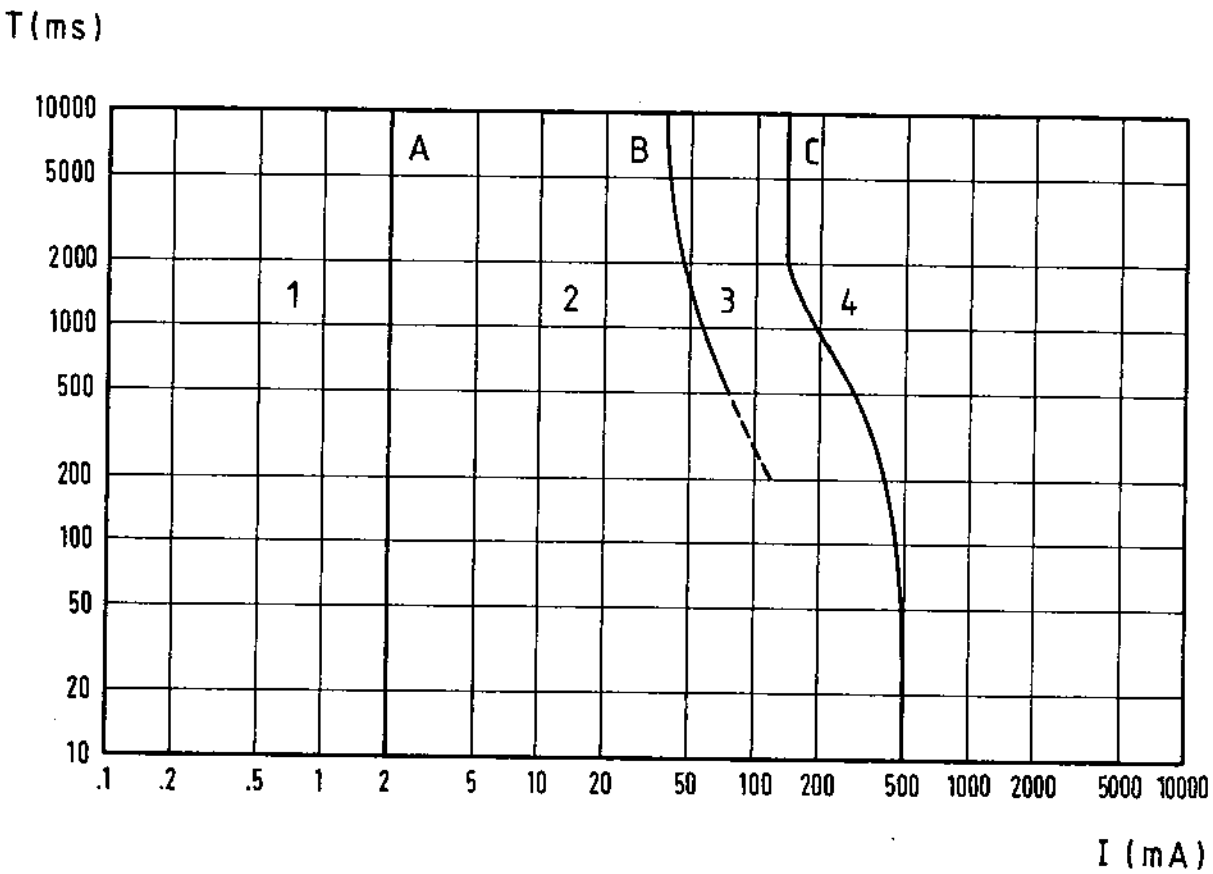

Fig. 4 Time/current zones for dc (new proposal)

Curve C applies to the condition of a longitudinal increasing current in adult persons.

Zone 1: Usually no reaction effects.

Zone 2: Usually no harmful physiological effects.

Zone 3: Usually no organic damage is to be expected. Increasing with current intensity and time, reversible disturbances of formation and conduction of impulses in the heart are likely.

Zone 4: Ventricular fibrillation likely. Increasing with current intensity and time other pathophysiological effects, eg, heavy burns, are to be expected in addition to the effects of Zone 3.

Note: Boundary between Zones 2 and 3 unknown for times less than 500 ms.

Alternating currents with direct current components, as described in Part 4, are of increasing interest because of the rising number of applications of electric controls causing such types of currents in the case of an insulation fault. This is also true for equipment using alternating currents with phase control and burst firing control.

As expected and shown in the few available references, the effects of such currents on the human body have been established between direct and alternating 50/60 Hz current effects for equivalent current intensities with regard to ventricular fibrillation. This means that under the same conditions, the danger is lower than for alternating, 50 Hz current. The values given are also deemed to be applicable for frequencies of alternating current up to 100 Hz, though the experimental alternating current data is based on measurements with 20 Hz and 50 Hz only.

Part 5 describes the effects of unidirectional rectangular impulses, sinusoidal impulses and impulses resulting from capacitor discharges with shock durations from 0.1 ms to 10 ms. These impulses may be a source of danger in the case of an insulation fault of an electric appliance containing electronic components or when touching live parts of such equipment. Similar waveforms are also used in electric fences. Therefore it is also important to establish the danger limits for these types of currents.

New research and new knowledge have provided more information on the impedance of the human body described in Part 6. Part 6 indicates values for the electrical impedance of the human body as a function of touch voltage, the frequency, the degree of moisture of the skin and the current path. Values are given diagramatically for the total body impedance of adult persons under dry conditions for a current path from hand-to-hand or from hand-to-foot, frequency 50/60 Hz and large contact areas. The curves represent a percentile ranks of 5%, 50% and 95%.

The revised IEC report 479 will cover nearly all forms of electric shock, which are of technical interest for shock durations from 0.1 ms up to 10 s.

SUMMARY

International co-operation and exchange in the field of electrotechnology have demanded adjustment and harmonization measures for protection and security according to present day necessities regarding life and health.

Efforts by the International Electrotechnial Commission (IEC) led after careful preparation. to the publication of IEC-Report 479 in 1974 This report gives all of the electropathological and electrophysiological basic essentials which must be considered with other points of view to establish measures necessary for electrotechnological security.

Recently, the results of new research work and results of practical scientific experience have demanded revisions and additions to the report. The Working Group that was formed for this purpose has worked out proposals which are ready for discussion and should be published in the near future.

DISCUSSION

SANDELL: In addition to Professor Hauf's presentation, here is a presentation of the work of GTS of CEG4 of IEC. GTS has established a curve for current versus time for application on electrical installations. This curve is located under the curve of ventricular fibrillation, with a certain safety margin to take into account some variation in estimating the current.

In fact, this curve has been broken down into curves showing duration time to open the circuit versus assumed voltage.

Two curves have been drawn:

1. For normal situations, with a limit of 50 V, and infinite duration.

2. For exposed situations, as outside site, with a limit of 25 V and infinite duration.

The 364-4-41 standard of IEC gives the practical way to apply different schemes of grounding.

Reference: IEC 64 (Secretariat) 375

SESSLER: It may be helpful to note the practical experience of telephone workers using bare hand practices on small terminals at dc voltages up to 130 V dc. The experience indicates that the dc values cited in this paper are at least conservative. Our experience in the Bell System indicates no electrocutions or even freeze-on at any of the dc voltages used in the system even though such contacts may take place in adverse, wet conditions such as in a manhole or splicing pit.

HAUF: I can confirm your experiences. In about 30 years working in Electropathology I have not seen any cases of serious injuries caused by dc voltages below 130 V.

KRENICKY: The new safety standards of IEC and IEEE (re HV equipment) do not mention at all the "transient potential groundrise" as described in some papers. The discusser carried out some practical tests and is convinced that TGPR must be an almost negligible risk. This seems to be proven by the fact that nobody was seriously injured due to TGPR. Adequate remarks should be made in the IEC and IEEE standards (for conventional and GIS high voltage equipment).

HAUF: The remarks are noted and will be the subject of further considerations.

KANODE: The figures indicate "adult persons". Does the information given by the figures apply to children as well as adults, and if so, is there an asymptote value for line B at longer time limits?

HAUF: It is a conclusion of WG4 that "On the evidence available, the report applies to persons including children irrespective of age and weight". This sentence can be doubted and further considerations should be given. The ac-curve B has an asymptote value with the threshold of let-go for long duration of current flow of 10 mA. In the first edition this curve was formulated for adult persons.

HAUF: We have discussed in our working group part 2 of the publication 479 titled: "The effects of the alternating current in the frequency range of 15 to 100 Hz". We found out that there was no sufficient data available to formulate a draft. Therefore we will ask the National IEC Committees and you to relate to us if any useful research is known and published.

HIGHLIGHTS OF THE PROPOSED REVISION OF IEEE STANDARD 80

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ABSTRACT

After more than twenty years since its first edition, the IEEE Std. 80, "Guide for Safety in Substation Grounding" is undergoing its first major revision. This paper describes the major areas of improvement, with emphasis on the procedures and criteria used to make the substation grounding installations safe during a fault. The importance of the changes made and refinements in application of the basic criteria for determining the safe step and touch voltage are also reviewed.

KEYWORDS

Grounding, step voltage, touch voltage, body current, grid geometry, gas-insulated substation, enclosures, protective surface layer, electrical gradient field, model, computer simulation.

INTRODUCTION

Presently, the IEEE Standard 80, "Guide for Safety in Substation Grounding", is undergoing major revision. The work on this new (currently third) edition is about done. The resulting document, prepared by Working Group 78.1 of the Distribution Substations Subcommittee, is presently being balloted by the Substation Committee of IEEE. An early version of the proposed text of Parts I and II has already been disclosed in two report papers by WG 78.1 (1981, 1982). Reports on the remaining Parts III and IV have not been published yet, but most of the theoretical effort concerning the development of key equations and graphs is described in two recent papers (Sverak, 1983; Joy and co-workers, 1983).

In principle, while there is a definite continuity in the approach and methods used, most of the proposed material is either new or, even when the text appears similar to the old one, the outcome of the calculations is different. This is in contrast to the previous revision of 1976, which mostly retained the original AIEE version of the Guide, despite the fact a new

era of VHV and UHV transmission (765 kV and 735 kV systems in the USA and Canada; 1200 kV Walz Mill test project by AEP and ASEA) became reality, and compact gas-insulated substations (GIS) had been increasingly used in Europe. One reason could have been historical: The Guide, following its first publication in 1961, has gained considerable popularity not only in the U.S. industry, but throughout the world.

However, in the late seventies it was realized that unless the electrical gradient field model is refined, the simplified equations for calculating the step and touch potentials above a ground grid - in unrestrained use - can eventually lead to unsafe design. Also, with the emergence of GIS facilities, the simplistic assumptions that were adequate for small conventional stations are often impractical or at least unrealistic for designing a grounding system that serves compact but electrically large power installation.

BASIC APPROACH TO SAFE GROUNDING IN SUBSTATIONS

Fundamental Aspects

Nearly always the practical approach to safety in substation grounding is, by definition, a compromise. Since a safe grounding design has two main objectives, namely,

1. to provide means to carry and dissipate electric currents into ground under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service; and

2. to assure such a degree of human safety that a person working or walking in the vicinity of grounded facilities is not exposed to the danger of a critical electric shock;

it is necessary to balance the interaction of two grounding systems: the permanent one which consists of buried electrodes, and the accidental one, produced by a person walking in the exposed area or standing there and touching a grounded object.

In practice, this means that once the particular operating constraints for a given design and established, usually in the form of equation (1) below,

$$R_g = GPR / I_g \qquad (1)$$

where

R_g is ground grid resistance with respect to remote ground, in ohms

I_g is a portion of the total fault current diverted by the grid into the ground, estimated from the results of a large-scale system short circuit study, in amperes

GPR is the maximum ground potential rise allowed for a given equipment, in volts

the design shall also meet the following two criteria:

$$V_t(p,I,G_t) \leq V_{ts}(p_o,t,B_{ts}) \quad (2)$$

$$V_s(p,I,G_s) \leq V_{ss}(p_o,t,B_{ss}) \quad (3)$$

where V_t is calculated highest touch voltage found in the most critical area (for an equally spaced grid it is found near the center of a corner mesh), volts

p is soil resistivity, in ohm-meters

G_t is electrical gradient field model of a given grid for determining the highest touch voltage V_t above the grid,

V_{ts} is the safely tolerable value of touch voltage, in volts

p_o is resistivity of the surface material covering the exposed area, in ohm-meters

t is fault duration, in seconds

B_{ts} is body circuit equivalent for determining V_{ts}

V_s is calculated step voltage in the most critical area, in volts

G_s is electrical gradient field model of a given grid for determining the highest step voltage above the grid V_s

V_{ss} is the maximum safely allowable value of step voltage, in volts

B_{ss} is body current circuit equivalent for determining V_{ss}

With respect to the previous editions of the Guide, changes have been made in all three fundamental equations (1), (2), (3), and in each equation in the expressions on both the left and right sides.

For the purposes of this publication, first the essence of the left-side changes will be outlined, and then the specifics of the right-side (safety) expressions will be discussed in more detail.

Calculation of Touch Voltage Above a Grid

The maximum touch voltage is determined as the value of so called mesh voltage Vm above the center of a "corner mesh", formed by the first two conductors of an N-conductor model which represents the given grid; Fig. 1. In the past, the simplified equation for

Vt often produced results which were 20 to 40 percent low, and for denser grids and high N's even yielded negative results. Part of the difficulty undoubtedly stemmed from a certain misconception as to what were the true limits of such a model.

IEEE GRADIENT METHOD

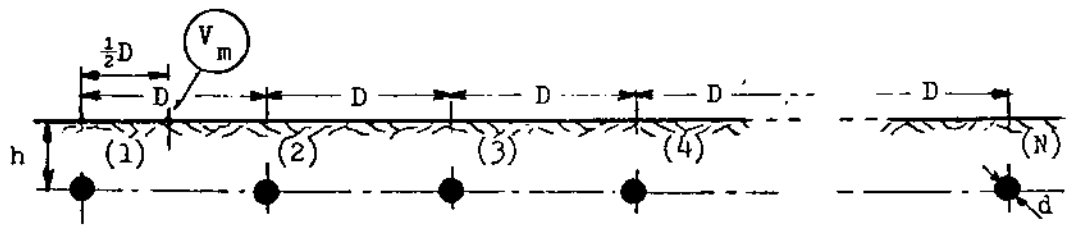

Fig. 1. Set of N parallel conductors in depth h below ground surface, representing a rectangular grid formed by N conductors + M interconnections, assuming N ≥ M.

However, most of the application problems resulted from the fact that in the simplified equations, the depth of grid burial h was inadequately accounted for, and the simplication process used led to a highly asymmetrical model of Figure 2.

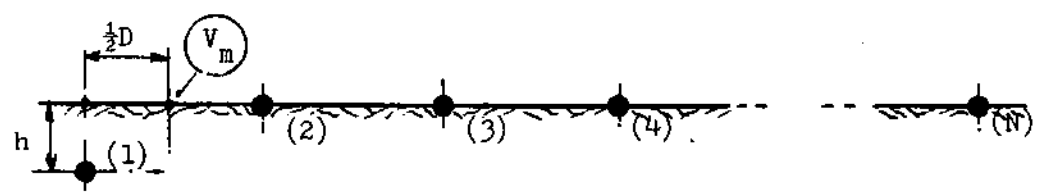

Fig. 2. Simplified model of N parallel conductors per formula (17) of IEEE Std. 80-1976.

To remedy this problem, new simplified equations have been developed which are now based on a symmetrical model of Figure 3. As shown, the first two peripheral conductors are placed in exact depth h, while for the remaining N - 2 conductors the depth is approximated with a small conservative error bias; Fig. 3.

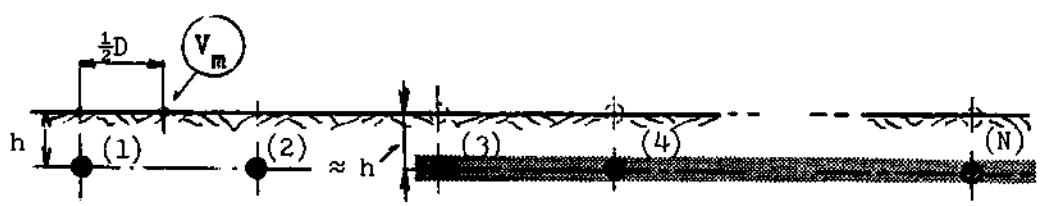

Fig. 3. Refined model for calculating touch voltages.

Calculation of Step Voltage Above a Grid

A similar disregard for the role of the depth parameter, as mentioned previously, has an opposite effect on the calculation of step voltages. The old formula (22) of the 1976 edition has been known to produce too high step voltage values for grids buried 0.5 m below the ground surface, or deeper. In this case, the application of the old formula has been restricted to $0 \leq h \leq 0.25$ m, for grids buried in the depth h of $0.25 \text{ m} \leq h \leq 2.5$ m, a new equation has been developed.

Calculation of Ground Resistance

Since the old resistance formula (20) neither did include the depth of grid burial nor fully accounted for the presence of ground rods, for simplified calculations, this well-known Niemann's formula has been combined with Laurent's approximate expression for the resistance of a circular plate in non-zero depth, with very good results. Finally, a more elaborate formula by Schwarz (1955) has been modified for certain applications in a two-layer soil environment and included into the proposed draft.

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Most of the mathematical analysis which has led to the descirbed refinements, as well as the results of comparative series of calculations on computer related to this development, are described in Sverak (1983). Consequently, the new Guide will provide both a full Fortran algorithm for a refined gradient model of Appendix I, and a set of new simplified equations shown below.

NEW EQUATIONS PROPOSED

$$R_g = \rho \left[\frac{1}{L} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \tag{4}$$

$$V_s = \rho \frac{I}{\pi L} K_i \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} \left[1 - \left(\tfrac{1}{2} \right)^{N-2} \right] \right] \tag{5}$$

$$V_m = \rho \frac{I}{2\pi L} K_i \left[\ell n \left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right) + K_h \, \ell n \left(\frac{8}{\pi(2N-1)} \right) K_{ii} \right] \tag{6}$$

and where in addition to the previously defined symbols,

d is diameter of grid conductors, in meters

D is spacing of grid conductors, in meters

L is total length of buried conductors, in meters, calculated as follows: $L = L_1 + mL_2$;

L_1 is length of horizontal grid conductors, including cross-connections, in meters

L_2 is total length of ground rods, in meters

m is corrective multiplier for the relative effectiveness of ground rods with respect to an equivalent length of grid conductors; m = 1.15 if all ground rods are placed along the grid perimeter, and m = 1 for the rods evenly spread within the entire grid area

A is grid area, in meters^2

h is depth of burial, in meters

V_s is step voltage, in volts

V_m is corner mesh voltage, in volts

$$K_i = 0.172N + 0.656$$

$$K_h = \frac{1}{\sqrt{1 + h/h_o}} \quad ; \quad h_o = 1 \text{ meter}$$

K_{ii} = 1 for grids with all ground rods along perimeter, and

$K_{ii} = (2N)^{-2/N}$ for all other cases

N is number of parallel conductors in one direction, for square grids or for rectangular grids having the same number of conductors in the north-sourth and in the east-west directions (Na = Nb = N). For rectangular grids with Na ≠ Nb, the following rules apply:

When calculating V_m (mesh voltage), $N = \sqrt{Na \times Nb}$;

V_s (step voltage), N = Max (Na, Nb)

CRITERIA FOR DETERMINING ALLOWABLE STEP AND TOUCH VOLTAGES

Body Current Formula $(I_B)^2 t = K$ (7)

Dalziel's constant shock energy formula (7) was used in the previous editions. In assessing the merit of continuing to use this formula, the following facts have been taken into consideration:

1. In the 1961 edition, constant K equal to 0.0272 J had been considered valid for 99.5% of men weighing approximately 155 pounds (70.3 kg), resulting in the allowable value of a one-second current of 165 mA.

2. In the 1976 edition, the value of K was lowered to 0.0135 J, reflecting the more recent research by Dalziel and Lee (1969) and the recommendation to use a 50 kg weight as typical of a mixed population of men and women, leading to the allowable value of a one-second current of 116 mA.

3. Although some researchers question the validity of a correlation between the maximum tolerable value of the fibrillation threshold for humans and the weight of experimental animals, or interpret it differently (Jacimovic, 1974; Osypka, 1966), there is virtual agreement that for very short durations, for instance 0.06 seconds (3.5 cycles), practically no one will have fibrillation if the current through the body is less than 500 mA. Also, based on the more recent studies by Geddes and Baker (1971) and by Biegelmeier (1979), it appears reasonable to assume that for short durations below 0.5 second, a higher fibrillation threshold exists than that derived by Dalziel.

4. In using Dalziel's formula as a safety criterion, the Guide neglects the low probability of coincidence of all unfavorable conditions required to develop the shock situation, as it has been done in other standards.

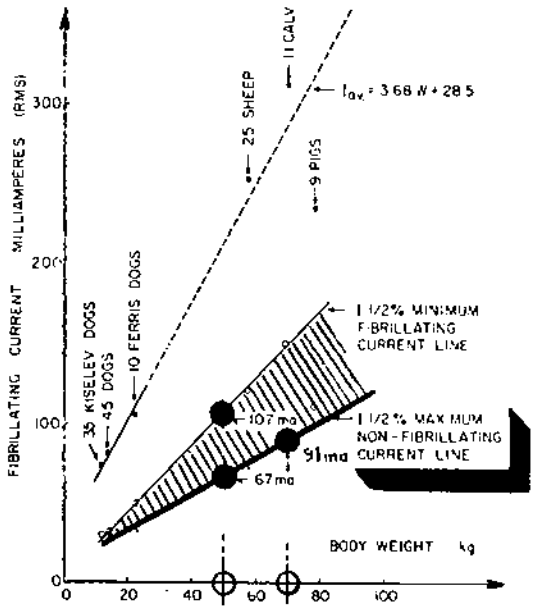
Based on this analysis, it has been decided to retain formula (7) in the following two alternatives:

a) Mixed population criterion per point 2, for K = 0.0135 J, Eq. (7a).

b) Adult population criterion, based on the average weight of 70 kg and, in difference to the 1961 formula, for K = 0.0246 J, resulting in a tolerable one-second current of 157 mA. The use of this latter option has been restricted to places which are not accessible to the public and which are attended by trained and mature workmen, such as in switchyards protected by fences, etc. As indicated in Fig. 4, this maximum non-fibrillating current of 157 mA at 70 kg base, is still below the threshold of fibrillation of 185 mA at 50 kg: Eq. (7b).

$$I_{B(50\ kg)} = 0.116/\sqrt{t} \quad \text{amperes ; seconds} \qquad (7a)$$

$$I_{B(70\ kg)} = 0.157/\sqrt{t} \quad \text{amperes ; seconds} \qquad (7b)$$



Effective rms values:

a. Non-fibrillating maximum of 116 mA, at 50 to 60 Hz / $\sqrt{3}$ = 67.0 mA

b. Non-fibrillating maximum of 157 mA, at 50 to 60 Hz / $\sqrt{3}$ = 90.7 mA

c. Fibrillation threshold to a, 185 mA at 50 to 60 Hz / $\sqrt{3}$ = 107 mA

Fig.4. Filbrillating and non-fibrillating currents vs. body weight for various animals, based on a 3-second shock, adapted from Dalziel and Lee (1968-69).

Resistance of Human Body

The 1983 revision re-affirms the assumption of a 1000 ohm body resistance, used in the previous editions, without change. Thus, for alternating current at 50-60 Hz normal power frequency, the human body can be represented by a non-inductive resistance. The resistance is between extremities, and is defined as follows:

1) Hand and shoe contact resistances are assumed as equal to zero.

2) A value of 1000 ohms represents the resistance of a human body from a hand-to-both feet and also from hand-to-hand, or from one foot to the other foot.

Accidental Circuit Equivalents

Great care has been given to ascertain the effect of a foot resistance, on the total effective resistance R_a of the accident circuit. Defining the equivalent circuit resistance for the step potential circuit as

$$R_{a_s} = 1000 + 2(R_F - R_{MF}) = 1000 + R_{2Fs} \qquad (8)$$

and

the equivalent circuit resistance for the touch potential circuit, as

$$R_{a_t} = 1000 + \tfrac{1}{2}(R_F + R_{MF}) = 1000 + R_{2Fp} \qquad (9)$$

where

R_F is the self resistance of each foot to remote earth, in ohms

R_{MF} is the mutual resistance between the feet, in ohms

R_{2Fs} is the resistance of two feet in series

R_{2Fp} is the resistance of two feet in parallel

it has been verified that for the choice of an 0.08 m (3 inch) radius for the disc representing a human foot, the simple equations for the series and parallel resistance of two feet as shown below, include only slight approximation.

$$R_{2Fs} \approx 6\rho_o \tag{10}$$

$$R_{2Fp} \approx 1.5\ \rho_o \tag{11}$$

Equation for Step and Touch Voltage Limits

Assuming the resistance of a human body from a hand-to-both-feet and also from hand-to-hand, or from one-foot-to-the-other-foot, equals 1000 ohms, the old equations (3) and (4) of Std. 80-1976 have been modified by inserting a derating factor C(p,po,h), in order to account for the limited thickness of a protective layer of crushed stone or similar material, ofen used in substations. Also a graph of C-curves has been included, allowing the determination of the effective resistivity value of the protective layer, as a function of its thickness and of the ratio of its nominal resistivity and the resistivity of underlying soil, Figure 7.

The modified equations are:

$$V_{ss} = [1000 + R_{2Fs}C(\rho,\rho_o,h')]\ I_B / t^{\frac{1}{2}} \tag{12}$$

$$V_{ts} = [1000 + R_{2Fp}C(\rho,\rho_o,h')]\ I_B / t^{\frac{1}{2}} \tag{13}$$

where, in addition to the already defined symbols,

h' is thickness of surface layer of resistivity po, in m,

R_F is resistance of a human foot, assumed to be 3 po, in ohms,

C is derating factor which is less than one for po > p, and equal to one for p = po (no protective layer used).

Metallic - Touch Potentials in GIS

A certain paradox, inherent in the GIS design, occurs the moment one tries to find the best concept for a safe GIS grounding. Simply put, contrary to the usual wisdom that a generously sized ground connection equals a good grounding practice, or the greater in numbers, the better grounding, one also has to consider what is to happen to the circulating currents generated in the GIS enclosures during a fault. The problem is not only where these currents will go but, more importantly, where one wants them to go, and still more of a concern, where the GIS manufacturer prefers the circulation to occur.

Although the technical specifics of that problem are beyond the scope of this publication, and most of the problem is usually resolved in a cooperation with the GIS manufacturer, it still is worthwhile to illustrate the type of questions which this new Guide 80 will help to answer.

1. If the circulating currents divide and flow via all available metallic paths, what ratio is to be expected between the currents circulating within the GIS assembly and those closing via a ground connection?

2. How much current circulating via a ground connection loop is too much?

3. Shouldn't the GIS be designed to be safe if eventually no circulating current would close via ground connections (at least for an external fault, as shown in Fig. 5 below)?

4. And, just how much of a grounding is needed for the best balance between operational and safety-related requirements?

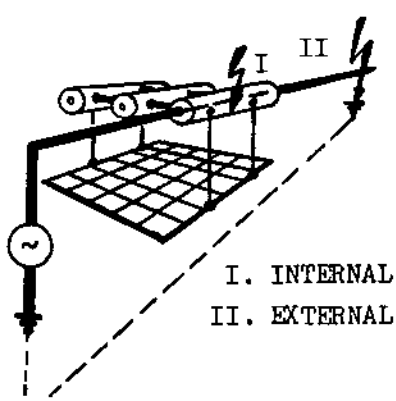


Fig. 5 Types of bus fault in GIS.

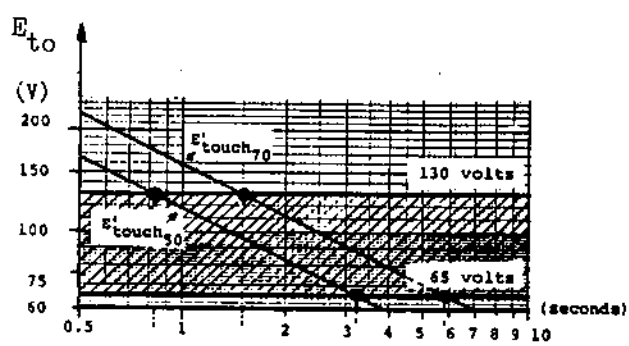


Fig. 6 Tolerable enclosure voltages for touch.

Presently, there are no clear-cut answers and solutions to the above. Most manufacturers consider the enclosures properly designed and adequately grounded if the potential difference Eto in Fig. 6, between individual enclosures and with respect to the voltage level of other grounded structures, does not exceed 65 - 130 volts during a fault. In terms of the proposed criteria,

this voltage range corresponds to the fault times from 0.8 to 3.2 seconds if a 50 kg criterion is used, and to the fault times from 1.46 to 5.8 seconds for the assumption of a 70 kg body, respectively. This relationship is, however, better perceived in the graphical form of Fig. 6, which also helps one to grasp the related problem of sufficient safety margins. The corresponding equations for a metal-to-metal contact either from hand-to-hand or from hand-to-feet, are:

$$V_{t_o}(50\ kg) = 116 / t^{\frac{1}{2}}, \quad \text{or} \quad V_{t_o}(70\ kg) = 157 / t^{\frac{1}{2}} \qquad (14), (15)$$

Closing Remarks

It might be argued that given the slight alternations made in the applicability criteria of Dalziel's formula and the re-affirmation of a 1000 ohm body resistance value, are not conservative enough. However, the following facts need also be taken into account:

1. The accidental circuit formula is more conservative than before, due to the introduction of derating factor C in calculating the resistance of a human foot.

2. The 8 cm disc radius of a foot equivalent is itself convervative as it corresponds more to a male adult weighing at least 70 kg than to the "mixed gender" individual of 50 kg.

3. The derating C-curves are also conservatively biased because the presence of a grounding grid is neglected. As shown in Sverak (1983), for a typical grid buried in depth h below the earth surface, which itself is covered by a protective layer of crushed stone h' thick, the calculated derated value of the surface resistivity is also a function of parameter $H = h + h'$, which tends to upgrade it back to its original value, equation (16).

$$\rho_o^* = C\rho_o(1 + 1.3a/H) \; ; \quad \begin{matrix} a = 0.08\ m \\ H = h + h' \end{matrix} \qquad (16)$$

Therefore, it is felt that while the accomplishments of 1983 edition are primarily in the area of engineering calculations where the revisions have been needed most, the overall impact of all proposed safety measures is reasonably balanced.

It is the opinion of this writer and many members of the working group, that the subject of major improvements in the area of a tolerable body current will be timely for the next revision. Perhaps, it will be also possible to develop a viable probabilistic approach and re-define the present predominantly deterministic safety criteria, the same time too.

* * *

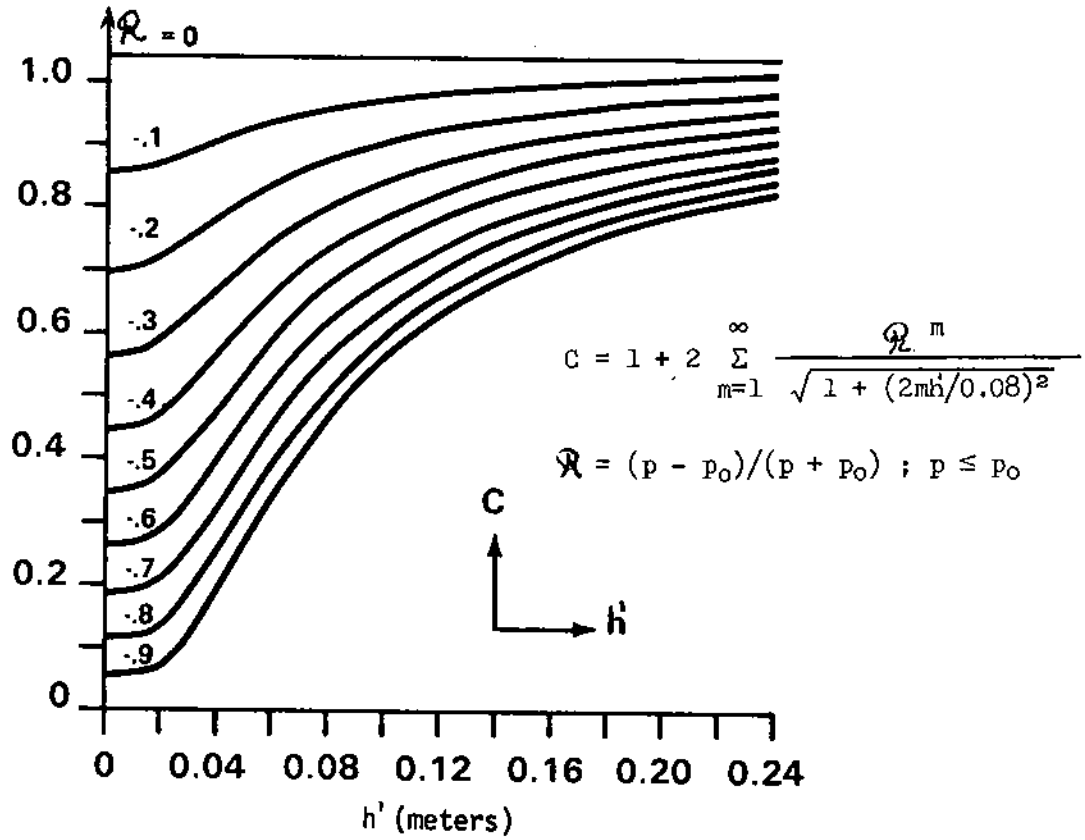


Fig. 7. Reduction Factor C as a Function of Reflection Factor $\Re$ and Crushed Rock Layer Thickness h^1

CONCLUSIONS

A brief summary of the proposed changes for a 1983 revision of the IEEE Standard 80, has been presented. It is believed that after the due balloting process and the final review of the proposed material by the IEEE Standards Board, the industry will again have a valuable tool for safe engineering practices in grounding of both conventional and gas-insulated substations.

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DISCUSSION

KRENICKY: The new safety standards IEC and IEEE (Re HV Equipment) do not mention at all the "Transient Potential Rise" as described in some papers. The discusser carried out some practical tests and is convinced that TGPR must be proven by the fact that nobody was seriously injured due to TGPR. The adequate remarks should be included in IEC and IEEE Standards (for conventional and for GIS high-voltage equipment).

SVERAK: Although the subject of a transient potential rise has not been mentioned in this paper, the revised IEEE Std 80 will contain the following statement in Section 8 (footnote to point 8.5):

> "Transient ground potential rise (TGPR) resulting from insulation breakdown or disconnect switch operation in GIS is a potential problem area. The direct effect of TGPR on humans may not be fatal but its secondary effect on unsuspecting personnel should be of concern to the design engineer and the manufacturer/88,89/".

Since essentially the same question was answered during the presentation of a second IEEE Committee Report by WG 78.1, published in the IEEE Trans. Vol PAS-101, No. 10, in October 1982, please refer to the Closure part of this reference, pp 4022-23.

SAFETY CRITERIA - A BASIS FOR CHOOSING THE PARAMETERS OF GROUNDING ARRANGEMENTS OF 50 Hz INDUSTRIAL ELECTRICAL INSTALLATIONS

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Abstract: This paper contains the results of investigations concerning electrical safety related to the effects of industrial frequency currents passing through the human body.

Results of experimental research into ventricular fibrillation conducted on animals for 50 Hz currents of short duration (in the range of 0.1 to 3 s) are presented.

Recommendations concerning maximum permissible 50 Hz currents for humans are given, which are included in GOST 12.1.038-82 "Occupational Standards Safety System; Electric Safety; Maximum Permissible Levels of Touch Voltages and Currents."

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One of the more important and complex problems of safe electrical energy utilization in the various branches of industry is the elaboration of safety criteria and scientifically substantiated levels of permissible currents and voltages for human beings. All the main technical decisions in the domain of protective grounding are unambiguously determined by electrical safety criteria.

The initial electrical safety criteria on which the permissible current and voltage levels are founded should be regarded as a group of specific physiological responses of the organism to the application of an electric current. In 1963 A.P. Kiselev and R.N. Karyakin proposed classification criteria corresponding to three distinct qualities of the human organism's response: the threshold value of perceptible current (first criterion), the threshold value of let-go current (second criterion) and the threshold value of fibrillating current (third criterion). The practical application of these criteria has been found to be justified and adequate by the majority of specialists at home and abroad.

It is recommended to determine the perception and let-go currents for a probability of perception and let-go of 0.5%. For the third electrical safety criterion it is recommended to adopt a value of the current corresponding to a 0.14% probability of heart fibrillation (the "three sigma" rule). For technical and economical reasons and owing to the diversity in electrical energy utilization, the choice of criteria when designing or implementing safety measures should be differentiated.

The threshold value of perceptible currents (first criterion) is the basis for determining the value of a prolonged and unintentional current flow. The results of research in perceptible currents, carried out in the USSR and abroad, for a current path "hand-hand" or "hand-feet" suggest that a value of 1 mA may be adopted.

The threshold value of let-go current serves as a basis for determining the value of a comparatively prolonged (in the order of tens of seconds) current flow. For the second criterion a value of 6 mA for the maximum permissible current for a path "hand-hand" or "hand-feet" may be accepted.

The threshold value of fibrillating current is the basis for determining the permissible limit value of the current for accidental shocks of short duration under fault conditions.

Investigations in determining the threshold values of fibrillating currents having a duration of 0.2 to 3 s were carried out in the USSR on animals (dogs) by A. Kh. Karasaeva and S.P. Vlasov under the supervision of N.L. Gurvich and A.P. Kiselev in 1966-1967, and were continued in 1971-1975 by B.M. Yagudaev and S.P. Vlasov in the duration range of 0.01 to 1 s under the supervision of N.L. Gurvich with the participation of V. Ya. Tabak, M.S. Bogushevich, Yu. G. Sibarov and N.N. Skolotnev.

Mathematical treatment of experimental results has shown that the threshold values for durations in the range of 0.01 to 3 s follow the log-normal probability distribution. In the time interval of 0.01 to 0.08 s, the lethal current in the more vulnerable phase of the cardic cycle (the T-phase) is independent of duration. This has been electrophysiologically substantiated.

The following table gives the maximum permissible 50 Hz currents, which, depending on their duration, do not lead to heart fibrillation with a probability of 0.9986.

The table also indicates the mathematical expectation and the rms deviation of the permissible current's decimal logarithm. The experimental results are scaled for humans whose body weight is 50 kg.

Table

Current duration; s	0.01–0.08	0.1	0.2	0.3	0.4	0.5	0.6	1.0
Maximum permissible current; mA	650	500	250	165	125	100	85	50
Mathematical expectation of permissible current's decimal logarithm	3.498	3.413	2.918	2.672	2.556	2.492	2.410	2.197
rms deviation of maximum permissible current's decimal logarithm	0.201	0.192	0.100	0.205	0.099	0.088	0.138	0.119

The maximum permissible current values are entered in GOST 12.1.038-82 "Occupational Safety Standards System. Electric Safety. Maximum Permissible Levels of Touch Voltages and Currents".

The values of maximum permissible currents were obtained for the most unfavourable combination of conditions: contact with live parts of an electrical installation coinciding with the appearance of a dangerous voltage during a fault and T-phase of the cardic cycle.

The general level of electric safety provided by grounding arrangements of industrial electrical installations, designed using initial safety criteria, should take into account the probability of coincidence of groups of independent compensating factors which is defined by the particular conditions of service.

Since July 1982 GOST 12.1.030-81 "Occupational Safety Standards System. Electric Safety. Protective Earthing" is in force in the USSR, regulating the design of grounding arrangements on the basis of touch voltage criteria. These normalized touch voltages are given in GOST 12.1.038-82 "Occupational Safety Standards System; Electric Safety; Maximum Permissible Levels of Touch Voltages and Currents", which has been implemented since July 1983.

The design of protective grounding arrangements in industrial electrical installations in compliance with GOST 12.1.030-81 and GOST 12.1.038-82 allows the wide use of the steel and reinforced concrete framework of industrial buildings as protective conductors, and of the reinforced concrete foundations of these buildings as grounding arrangements of industrial electrical installations.

Chapter 6

Panel Meeting on Future Work Required for Utility Standards on Electric Shocks

PANEL MEETING ON FUTURE WORK REQUIRED FOR UTILITY STANDARDS ON ELECTRIC SHOCKS

BRIDGES: As has been the custom established by Dr. Geddes, I will ask each of the panel members to introduce themselves and their affiliation, starting with Stan.

Panel:

Chairman:	J.E. Bridges, Senior Scientific Advisor, IIT Research Institute, USA.
Stan Arnot	Ontario Hydro, Senior Design Engineer, Transmission Stations Design, (Electrical Arrangement of Transformer Stations) Canada.
Rod Baishiki	Senior Transmission Line Design Engineer, Pacific Gas and Electric Co., USA.
Lesley Geddes	Director of Biomedical Engineering Center, Purdue University, USA.
George Sverak	Gibbs and Hill, Consulting Engineer, Transmission and Transportation Division, Chairman, Working Group 78.1 IEEE substation committee, USA.
Werner Hauf	Institute of Electropathology, Frieburg, Germany
Oberheiden	German Electro-Technical Manufacturers Association, Secretary IEC/TC64, Germany.
Biegelmeier	Electrical Engineer, Vienna, Austria.
Michael Wills	Physician, Ontario Hydro, Canada.

BRIDGES: Thank you, I have organized the panel discussion to follow the topics as listed in Fig. 1. The first topic will be current and future, utility industry grounding practices, and likely shock conditions. These will be addressed by Mr. Arnot and Mr. Baishiki. Next, we'll have a discussion on biomedical shock safety criteria from the viewpoint of use in standards. The people who contribute to this subject will be Mr. Oberheiden and Dr. Sverak. I might note, after completion of each of these topic areas, we'll have time for questions and suggestions as to possible project areas. Basic physiological effects will be summarized by Dr. Hauf, to be followed by a discussion on body impedance effects, complex wave forms, time duration effects by Dr. Biegelmeier.

UTILITY INDUSTRY GROUNDING PRACTICES

BIOMEDICAL SHOCK SAFETY CRITERIA FROM A STANDARDS VIEWPOINT

BASIC PHYSIOLOGICAL EFFECTS

BODY IMPEDANCE, COMPLEX WAVEFORMS

BODY-WEIGHT RELATIONSHIPS, STATE-OF-HEALTH

EPIDEMIOLOGICAL, NON-FIBRILLATION ASPECTS

SUMMARY

Figure 1 - Discussion Topics for Panel III

Dr. Geddes will discuss and summarize the body weight effects, and the impact of drugs and state-of-health. Dr. Wills will present some other viewpoints as to the non-fibrillation hazard areas that may exist for power lines; and he will discuss some of the epidemiological implications. Lastly, I will attempt to summarize the results of this conference. Please, note that after each main discussion topic the panel will be opened for questions, and if somebody wants to make a special contribution (like showing a few additional viewgraphs to fill in a particular topic area) it would be appropriate to do so at these intervals.

ARNOT: Figure 2 shows the grounding design of a transformer station which is typical for 1950's or earlier designs. Various structures in switchyards were connected together but not necessarily in a grid form, and I don't think that many calculations were done at that time. The fence of the transformer station was either connected to station grounding conductors or left floating with single ground rods installed on the fence line. The same station grounding system, recently rebuilt, is shown in Figure 3. I superimposed in this figure, in heavy dashed lines, the old grounding system as it was designed about 30 or 35 years ago. As you can see, the new design is a grid system. The values of the step and touch potentials were prime considerations in the design. Now, after hearing the contradicting information about body impedance, body weight scaling, etc., that has been presented to us in this room during this symposium, one may wonder how grounding designers will design, in the future, the right grounding system.

In Ontario Hydro, we recognize six basic circumstances which can contribute to the electrical shock and accidents. These six circumstances are shown in Figure 4. We think that if we can prevent occurrence of these, we will get safer installations. The value of body resistance, the use of body weight scaling relationships are of major importance to the designer of a power grounding system. Presently, we are using a value of one thousand ohms for body resistance, as recommended by IEEE standard 80. For the body weight scaling we use values of: 50 kg weight for a woman, 70 kg for a man, and 20 kg for a child. We calculate the parameters of grounding systems so that, if members of the public approach the station from the outside and touch the fence, they will not be in danger of an electric shock. We also take into account transmission towers located in places accessible to the general public, like parks, recreation areas, etc. New technology used by the power industry, specifically SF_6 insulated equipment allows the area occupied by stations to be drastically reduced. We have smaller and smaller stations, with higher and higher values of short-circuit current. As a result, ground potential rises are going up, the values of step and touch potentials are going up and designers are not left with much space to manoeuvre. If in addition, body resistance and body weight scaling values are lowered, designers will have to install

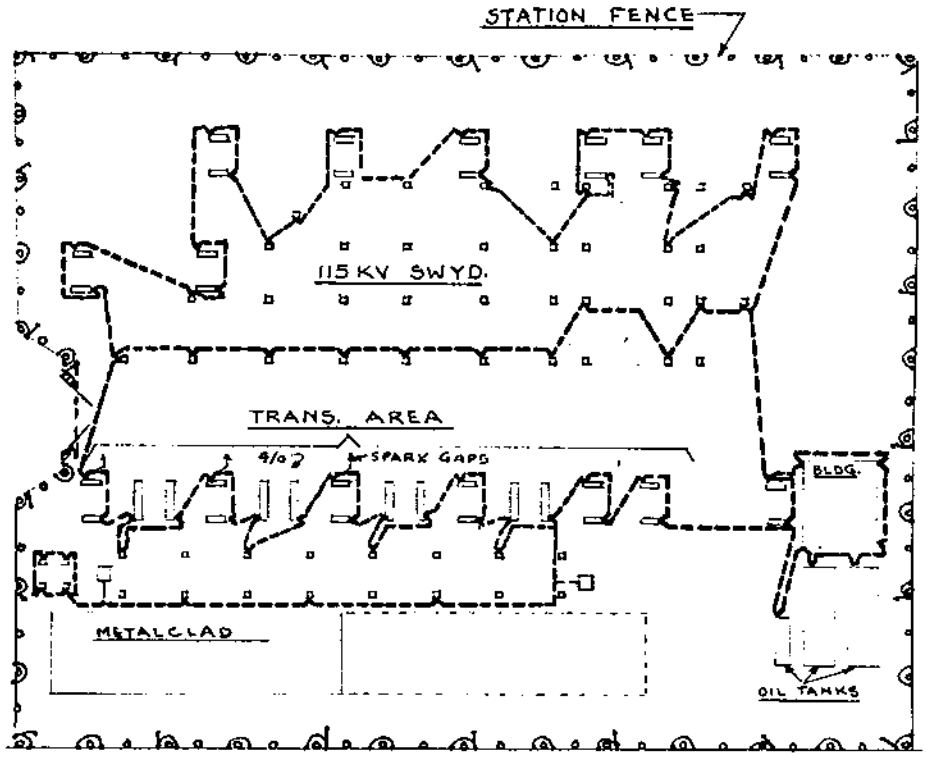

Figure 2

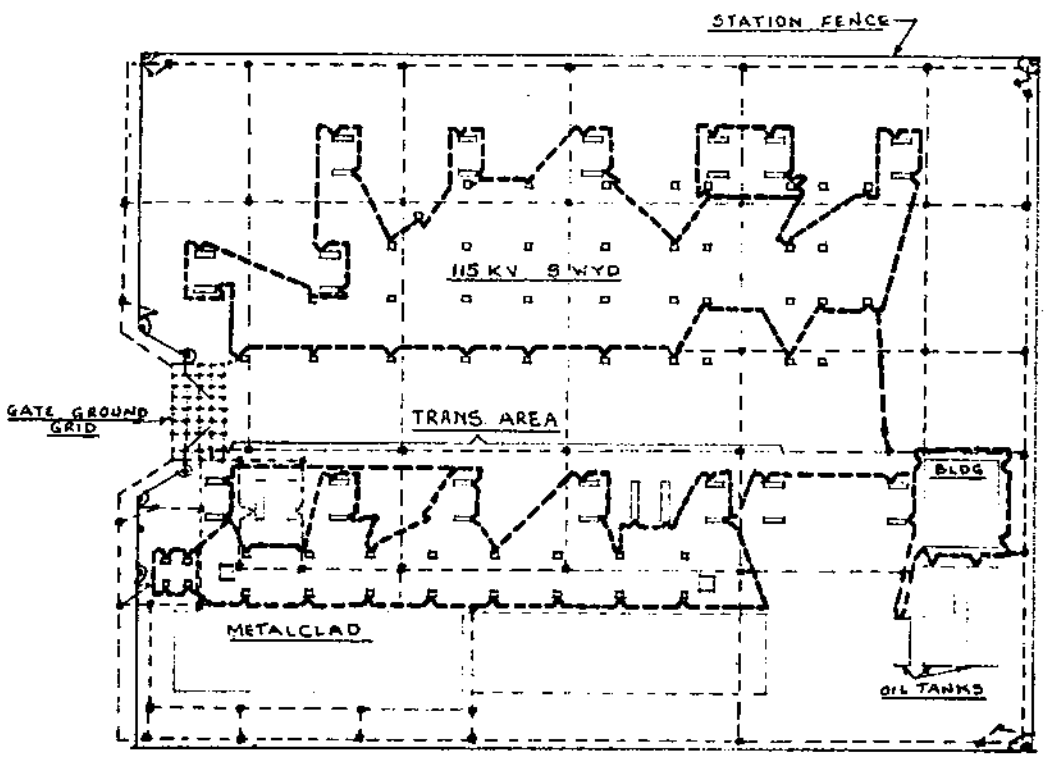

Figure 3

more dense ground grids which means more copper in the ground to smooth out the surface potential profile. I believe that this will cause the costs of grounding installation to rise. I realize that I've probably touched on quite a few problems which confront grounding designers in the power industry, and I hope that we might find some answers in the discussion which will follow.

1. High fault current to ground relative to size of ground system.

2. Soil resistivity high and current distribution unfavourable giving high voltage gradients at earth surface.

3. Presence of individual at such a point, at such a time, in such a position as to bridge two points of high potential difference.

4. Absence of sufficient contact or other series resistance to limit body current under above circumstances.

5. Duration of the fault and of body contact, and hence of current through the body, for a sufficient time to cause harm, at the given current intensity.

6. Coincidence of all the unfavourable factors above.

Figure 4

Circumstances Which Make Electric Shock Accidents Possible

BAISHIKI: I'll discuss the utility grounding practices from the maintenance point of view, based on PG and E's (Pacific Gas & Electric Co) practice (since the design part has just been covered). If a ground is to be installed, special testing procedures are always used to determine whether the line is deenergized. These procedures vary with voltage levels.

It should be noted that in California all maintenance is done with "hot stick" tools. In the case of 500 kV systems these tools approach the maximum practical length and it is possible that the future practices may utilize robots.

Most accidents in the utilities result from improper procedures. The factors contributing to these situations may include: disregarding the true values of danger after many years of non-eventful work, fatigue, long work hours with consequent loss of concentration, adverse weather conditions.

Examples of transmission line environments where accidents may occur are: (1) construction of transmission lines adjacent to existing transmission lines, (2) insulator changes on the lines, (3) snow conditions. Certain lines may have 15 to 20 feet of snow under them which presents a problem in reaching the ground (how do you ground with snow?), (4) granite, high resistivity soil (it is difficult to get a good ground), (5) tree trimming (a third party may be working the tools and dropping the limbs into the line) (6) construction equipment, such as cranes and booms; irrigation and gas pipes; construction and joint use right-of-ways; fences, and possible metallic objects in the right-of-way - all of these introduce additional factors making shock conditions involving grounding more likely.

In PG&E fences within the right-of-way are considered as design problem. A fence grounding standard exists which is based on electrostatic pickup as well as the magnetic induction. The recommended practice is to have one ground for electrostatic induction and then, if magnetic induction is present, the fence is sectionalized to be of certain maximum length depending upon the angle within the corridor. There is a lot of vineyards in California, and the vineyards are longer than fences. Since fences are mostly on public property, they are usually naturally segmented. But vineyards go on for thousands and thousands of feet. Therefore, more problems exist with vineyards than with fences.

All the grounding is taken care of in this way. But when we make a design, some assumptions have to be made. These include such questions as: what shoes, what kind of resistance values, what is the contact with the skin, and so on. In our practice, assumption similar to those of IEEE Standard 80 are made. The grounding design for fault conditions is more difficult and it even impossible everywhere. In these cases probabilistic design becomes a practical solution.

TAYLOR: The comment is on the problem of magnetic induction potential. When considering contacts with a low impedance source, there is a strong need for research not only in terms of body impedance but also in terms of the whole circuit impedance. I'm thinking mainly of the static condition, for instance, there may just exist a continuous magnetically induced voltage on the fence due to the load on the line nearby that someone can come by and contact. In this situation the duration of the contact may be very long.

SVERAK: If I recall correctly, about six years ago, Dr. Deno of General Electric Company conducted a study on electromagnetic and electrostatic effects. The study was published and it contains a wealth of information on the subject.

KRENICKY: Almost 20 years ago there began the era of gas-insulated switchgear installations (GIS), which have gained solid ground especially in the voltage range above 72.5 kV (today up to 800 kV), and which in some territories have even completely replaced conventional technology for new installations.

At the time the GIS technology was being introduced its high "almost absolute safety" was cited by manufacturers as well as the plant owners as the greatest achievement.

Up to about 1980 the "absolute safety" was doubted by none. In practical application the expectations have been met entirely. To the best of our knowledge, at that time not a single serious electrical accident had been registered in GIS installations (which by the way is still the case today). Only extremely rare cases of certain sensations resulting from test flashovers have been heard of.

Thanks to the enthusiastic efforts of the Ontario Hydro research staff from 1980 to 1982 the mysterious sparking between various earthed GIS parts occasionally observed in certain GIS installations (during test flashovers and disconnect switch operations) was investigated. This enabled a clear physical description and measurement of the TGPR[1]). (The phenomenon was christened TGPR = Transient Ground Potential Rise.) In addition to the above it was also shown:

- How the sparking can be eliminated
- How the TGPR potential differences can be reduced.

[1] TGPR is the potential differences between various "earthed" installation parts. Typical values: f = a few MHz, rise time 5 to 20 ms, voltage: a few 10ths to 100 kV.

The findings were published in various articles, for which we express our thanks. However, in the same TGPR documents the question was raised several times:

- Can TGPR endanger persons?

- If yes, how great is the practical risk?

The formulation of these questions has disquieted many plant owners; it has even made them panic. In some cases the plant owners even went so far as to consider abandoning GIS in favour of conventional HV technology for "safety reasons".

In the following I would like to acquaint you with four practice-related tests. The tests were performed partly by the speaker himself.

TEST A

Touch tests in a 525 kV GIS installation

From the view of the present state of the art, with regard to TGPR this GIS didn't have the best construction.

During the disconnect switch operations the test subject deliberately touched various parts of the metal enclosure with the aim of finding the worst case situations occurring in practice.

A total of approximately 30 different tests were performed, and the conditions were often aggravated unrealistically. For example, the test person was standing on the bare ground or on the metal plate, in many cases barefoot or in wet socks.

The mathematically calculated highest contact voltages (unfortunately, the measurement did not function reliably) were above 100 kV. If it is assumed that during a disconnect switch operation only 10 to 20 prestrikes or restrikes with this value occurred, then according to the existing literature the energy absorbed by the test person was approximately 180 J.

The test subject was not able to ascertain any sensations during the numerous tests.

TEST B

The test subject coincidentally had the opportunity to perform the touch tests in the same installation during a test flashover of approximately 700 kV (test with oscillating pulse). The test was performed twice at a distance of approximately 10 m from the bushing. Here as well the test subject was not able to ascertain any sensations.

TEST C

At the University of Basel the speaker and other test persons (Prof Striebel) subjected themselves to an "impressive" experiment. The high-voltage source supplied by the University of Basel delivers approximately 200 kV and 750 kHz. (Further data such as impedance, current etc, are only now being determined.)

In the test the high-frequency current passed via approximately 10 cm arcing path through the body of the test subject in pulses for about 10 s. The test subjects felt a slight to medium "tingling" or burning in the hand holding the aluminum bar. In practice (in GIS) such inconvenient conditions can hardly occur.

TEST D

On September 17/18 1983 in a substation 550/230 kV in Los Angeles two gentlemen from DWP did some practical TGPR touch tests. They touched during disconnect switch operations the GIS enclosure close (ca. 1 m distance) to the sparking 230 kV bushing. No sensation could be achieved.

CONCLUSIONS

1. We do not want to overestimate the importance of the somewhat "primitive" TGPR tests. Otherwise, on the basis of practical tests performed and the previous very positive safety experience with GIS (up to now not a single serious accident, while with the conventional switchgear accidents are still occurring as before), we take it upon ourselves to claim that, in spite of the proven existence of TGPR (which by the way, exists not only in GIS), GIS is by far the safest HV technology. It can be said that the original expectations have been met completely.

2. The influences of TGPR on sophisticated electronics is not dealt with here.

3. The modern basic methods of preventing or suppressing TGPR are to be applied to the extent necessary and sensible.

4. The personnel is to be informed of TGPR phenomena and its relative degree of risk (if any) in a realistic manner. It is emphasized once again! Over-anxiousness and ignorance can also make genuine risk factors out of dangers which are objectively very low.

BRIDGES: Thank you very much for discussing some interesting demonstrations. I like the confidence of your findings; in other words, if you feel a certain threshold will not be a problem, then you demonstrate it yourself. I think this is most convincing.

KRENICKY: I would like once more and for the last time emphasize it: we are very thankful to the people from Ontario Hydro in spite of the fact that they caused some panic, because it is easy to criticize but it is not so easy to elaborate something and therefore once more thank you.

FORD: Anecdotal reports of this type are useful particularly if you understand the mechanisms behind what you're seeing. We're aware of instances, many instances where personnel have been in contact with GIS and we agree that as far as we know there have been no serious injuries. There's a range of reactions that have been measured from nothing as Mr. Krenicky has mentioned, through uncomfortable, through to, in one case, an instance where the person was in a optimally worse position where he described it as the strong shock, "a good belt". What we tried to do and I think what Prof. Geddes and I described, when we wrote our paper a couple of years ago on the subject, was to report what was known about the subject at that time. I don't think we said that it was dangerous, I think we said that it wasn't clear from the state of knowledge reported in the literature that it was not dangerous. There wasn't enough known about the subject to say one way or another. I think based on what we've heard today and up till now, (and I don't know if Prof. Geddes has changed his mind) what we need is more specific quantitative research on the topic before we can be convinced. Experiments as Mr. Krenicky has described are useful, but the sensation is very strongly configuration dependent, they must be documented in detail to ensure that the conditions are completely understood. I don't think that we should be alarmed about the situation, proper understanding of the problem and selective use of mitigation techniques has allowed utilities such as Ontario Hydro to live with this particu-

lar problem quite easily. I think that studying the physiological aspects would be an appropriate subject for R&D.

ARNOT: I would like to add to Dr. Ford's comments. We are quite concerned about the secondary effects of the transients. For example, a person standing on the ladder and suddenly seeing the discharge, might throw his hands out and fall off.

KRENICKY: That is correct. I would like to add that the risks should be compared. On one hand we have some relative risk decrease. On the other hand, there is a theoretical increase in the risk, and we start to panic. The risks in question should be investigated in relation to other risks which we confront daily.

BRIDGES: This certainly appears to be a very pertinent research area in terms of the very fast transients that the workers are exposed to.

GEDDES: I can only agree. No one knows whether these short duration transients can produce ventricular fibrillation. It is clear from what has been presented here that they can stimulate sensory receptors. Whether they can stimulate myocardium, whether they can stimulate myocardium in the vulnerable period to produce fibrillation no one knows. The shortest single pulse stimuli that have been shown to be capable of stimulating myocardium under controlled conditions, have been one microsecond long and these are an order of magnitude or more shorter than the pulses produced in GIS. So, I think this really calls attention to the need for a little research on this subject.

DAWALIBI: I would like to summarize my impression of the symposium as an electrical engineer. Before coming here I wasn't really so much sure about what physiological information study is available regarding human body resistances, and I was looking forward to find exactly what is available. Now, I'm really impressed with the information already available. But what is sad is that this information was available for sometime and nobody really has carried out a work similar to what Dalziel and his colleague have done twenty or thirty years ago. I can see much justification for further research in all areas including the short duration area. I can also see information useful which can be extracted from what is already available and I'm looking forward for something which would be similar to what Dalziel and his colleagues have already achieved twenty or thirty years ago.

SVERAK: I am pleased to be on the panel, because now I have an opportunity to respond, on behalf of IEEE Working Group 78.1, to a point raised so eloquently by Dr. Lee this morning: "Why are the engineers still using Dalziel's formula?"

In the late seventies, when the Working Group 78.1 had to decide whether the Dalziel's formula should or should not be reaffirmed in the 1984 edition of IEEE Standard 80, we of course did not have the S-curve of the recently amended IEC Report 479 - which Prof. Hauf has so kindly furnished me with a few weeks ago. However, we looked into the work of Prof. Biegelmeier and recognized the merit of his Z-curve and, in fact, acknowledged it in our document. But in view of the whole framework of safety criteria used in the standard, the Group felt that the correct decision was to retain the Dalziel's curve for another five years, until a thorough research in several areas of the relevant risk analysis is done, and a complete re-evaluation of the criteria is possible. The decision to retain 1000 ohms as the typical value of a body resistance between extremities, is also related to this standpoint.

Since these are the two specific items which are most likely to be directly compared (in terms of their recommended values) to similar values reported during this symposium, let's review the differences involved. Starting with the body current curve, consider Figure 5.

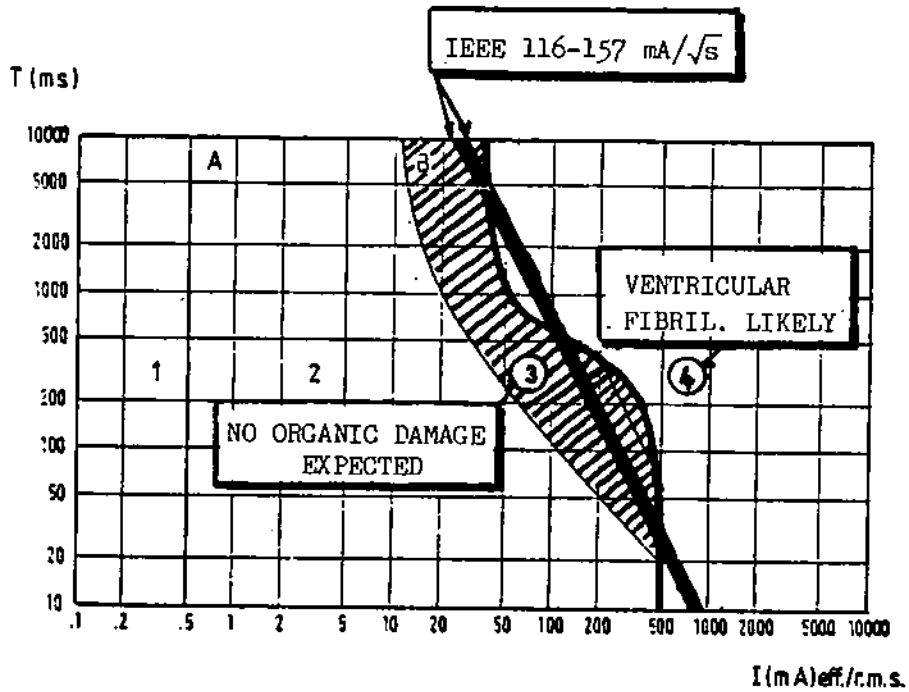

Figure 5

If one adds the mA (rms) equivalent of the IEEE 116 mA, and 157 mA curves to Figure 5 (borrowed from the IEC Report), the following observations can be made:

1. In the time segment between 0.025 and 0.5 seconds, within which a majority of fault-clearing times occurs, the IEEE curves are conservative.

2. From about the 0.5 second point, the IEEE curves show values exceeding those of the IEC curve, and diverge from it until the time of 0.7-0.8 seconds is reached. The curves meet again near a 5 second point. From there, the IEEE curves are conservative again.

3. For extremely short times below 0.025 seconds, that is for fault clearing operations within 1.5 cycle or less, the IEEE curves are somewhat less conservative than the IEC curve.

Concerning the role of body impedance in the safety criteria used, it was decided to retain the value of 1000 ohms as representative of the body impedance for both the hand-to-hand and hand-to-feet contact. The following assessment of this decision can be made:

4. Although the present research seems to converge to lower values than 1000 ohms (for instance, the diagram of internal body resistances of Smoot and Mogan yields 850 ohms between a hand and feet, and Biegelmeier reports the initial body resistance of 781 ohms, and the range of 530-1101 ohms for a group of 80 men and 20 women) the impact of these values is tempered by the fact that IEEE Standard assumes a zero value for the resistance of shoes. For substations, this is very conservative.

5. Considering that a majority of substations can be classified as an environment with controlled access, it also is worth mentioning that the Standard retains a 16 cm diameter for the metallic disc representing a bare human foot. This

value was originally related only to a male adult weighing 70 kg, assumed in the 1961 edition.

6. In safety equations for the step and touch voltage limit, the resistance of a human body is combined with the resistance of feet to ground. In substations, as opposed to other places, usually the latter value is a dominant factor, due to the use of crushed stone or similar highly resistive materials within the substation area. Hence, in this context, it is rather significant that the proposed revision introduces a derating factor for the ground resistance of a human foot, as a function of the thickness of the upper layer.

7. Finally, according to the IEC report, a 1.25 times higher current can be allowed for the path from a right hand to both feet, and a 2.5 times higher current for the hand-to-hand path compared to the left hand-to-feet path. These factors further reduce the probability of a sufficiently adverse combination of circumstances necessary for a severe accident.

In sum, the undeniably probabilistic nature of accidental events can be seen as blurring the impact of above mentioned differences, while the reaffirmation of conservative criteria based on the simultaneous occurrence of worst conditions, makes the Standard safety biased.

VAINBERG: I would like to comment on the discussion by Dr. Sverak. The deterministic and probabilistic approaches to grounding and the safety associated with it should not be confused. Up to now, the approach used in the grounding design has been deterministic. Therefore, it is not appropriate to talk about fuzziness in parameters affecting the deterministic design. Without a proper probabilistic assessment, it is impossible to say that a change in parameters, for example, in the body impedance from 1000 ohms to 500 ohms is not going to have any effect. In our studies [2] on risks associated with transmission line grounding hazards, we found out that this risk was very close to a generally acceptable value of 10^{-6}. If a 500 ohm value was used for the body impedance, the risk would have become unacceptably high, which means a utility may have to spend a lot of funds to eliminate the risk. In addition, I would like to point out that in order to carry out a proper probabilistic design, one has to have an accurate knowledge of the body parameters. My impression, from this conference, is that we lack a lot of basic knowledge on fibrillation thresholds and other effects of electrical shocks such as burns, asphyxia, etc. More research should be devoted to these aspects.

SVERAK: I think that we are in no serious disagreement about most of these subjects. What I have suggested is that the seemingly deterministic approach of IEEE Standard 80 involves a number of assumptions which contain an element of probabilistic judgement. Aside from using a body current curve indicating the 99.5 per cent safe threshold of non-fibrillating currents, there are at least seven circumstantial conditions which must develop simultaneously: a fault current and time of exposure must reach the maximum deign values, a hand contact must be perfect, a person must be present in the worst location with respect to the grid geometry and be barefoot, etc. In reality, the impact of the individual probabilities involved is such, that unlike for the open spaces under transmission lines, their neglected influence is dominant. In substations, where the use of a protective layer of crushed stones is nearly a rule, the impact of using a 500 ohm body resistance would most likely be about a 15 per cent change in the mean value of the human impedance to ground, i.e., hardly a prominent risk factor. But, a recognition of the low probability that a person is barefoot, is likely to be far more significant for fenced switchyards than for open spaces.

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[2] M.A. El-Kady and M. Vainberg, "Risk Assessment of Grounding Hazards due to Step and Touch Potentials Near Transmission Line Structures", IEEE Trans. Power Apparatus and Systems, Vol. PAS-102, 1983, pp 3080-3087.

In summary, the overall concept of safety criteria of IEEE Std. 80 cannot be viewed as completely deterministic. Implicitly, these are criteria of a multi-conditioned shock-exposure event, for which the allowed value of a body current for a predetermined time parameter, or the given body resistance, represent just two of many factors. However, more research is needed. The effect of multiple reclosures is one of the problem areas deserving further attention.

OBERHEIDEN: Mr. Chairman you have heard this afternoon from Prof. Hauf about the revision of the forthcoming IEC publication 479 on the effects of current passing through the human body and it may be interesting for the audience to learn what the present state of work on the six parts of this publication is. Part one of this forthcoming publication has been adopted by the national committees of the IEC. However, at the working group 4 meeting just a few days ago in Toronto we have decided to make small amendments. This makes it necessary to submit these amendments for a new vote to national committees, but this vote will introduce a rather short delay, so that, by the middle of next year that publication will be available. The next part of the publication, part 2, is titled: "Effects of Alternating Current with Frequencies above 100 Hz". We dealt with first draft for this part at our meeting in Toronto and we noticed that there is very few data available on this subject. We are nevertheless circulating a first draft to national committees in the hope that we will have some response and obtain more facts. So, if any member of the audience can contribute to this area, please pass it over to your national committee of the IEC. The third part, effects of direct current, is actually at the voting stage and we will know the result of the voting by the end of October this year. The fourth part, effects of special waveforms of current, deals with alternating current superimposed with dc and with rectified alternating current. This part is submitted to national committees for comments, and not for voting yet. Another step will be necessary to adjust it and then to submit it to the voting. The fifth part, effects of unidirectional single impulse currents of short duration, had been submitted for comments and the comments were available at our Toronto meeting; we have considered these comments and have made proposals on how to deal with various comments. The committee TC64 will at their next meeting in May, 1984 decide on how to handle these various comments and then the next draft will be submitted for voting. And, finally, part six, impedance of the human body, is also at the voting stage now and we will know the results of the vote by the end of October this year.

We have all heard great many data on physiological effects of the electric current on the human body in these three days. As a simple electrical engineer, I must say that sometimes one feels confused about the amount of data which are presented in very different forms in many various ways. It has been the intention of the IEC to have all available data analyzed and presented in a form which is suitable for the use by electrical engineers. So, this is the intention of publication 479. However, this is yet an intermediate step because it is not the intention that publication 479 be used by every designer of electrical equipment or every designer of electrical installations. There are the competent technical committees of the IEC which shall make use of publication 479 and make the appropriate rules for their field of application. So they have to take into account not only the facts that are presented in publication 479 but also other aspects for instance, probability of faults, probability of contact with live or faulty parts, technical feasibility in the various fields of application and last, but not least, economic aspects. Furthermore, it is important to us that the rules of the IEC which are addressed to electrical engineers all over the world, be clear and simple. I would remind you of a paper, of a curve that had been presented by Mr. Remond this afternoon showing the disconnecting times versus touch voltage. This is a presentation as we have it actually in one of our publications for electrical low-voltage installation. It turned out that quite a number of national committees found that even this sort of presentation was too difficult and too complicated to be used by an ordinary engineer. We are now working on a concept

which we think is easier to apply, namely to define the fault clearing times with respect to the system voltage. So that for instance for 220 V system, we say in case of a fault, disconnection has to occur within 0.2 s, or for 110 V disconnection time could be 0.4 s. This idea is not really finalized yet, but we are working on this concept. We hope that in this way, we will come to a rather simple standard which nevertheless, takes into account the basic principle given in the publication 479. It shall not be and must not be in contradiction to what is given in the publication 479. So this is how we expect to implement the facts of the publication 479. I would also like to add a last word, Mr. Chairman, on the necessity of having uniform standards within the IEC and, hopefully, in the long run within the world. At the moment the safety rules are rather different in the various fields of electrotechnology. For instance, the heavy current field that is the power electronics, the control electronics, information technology - they all have their different rules which are not coordinated. This is a result of an historical development. It is our aim in the IEC to come to solutions where, for these different fields of technology, we have a coherent set of requirements with regards to safety. In particular, the advisory committee on safety in the IEC-ACOS - is pushing along these lines and we hope to come to such results in the next few years, so that afterwards national committees can take over.

DAWALIBI: I must say that I wasn't really aware of your work and it seems really interesting. Is this publication 479 available?

OBERHEIDEN: At the moment the 1974 edition of the publication 479 is available. But as you have just heard, it is under revision.

DAWALIBI: Is the mandate of your committee to provide rules for power networks as well as low voltage network? Is that going to cover substation, transmission lines, as well as domestic appliances and so on? Or are you going to be specific about the power installation?

OBERHEIDEN: When I give you the answer I must make a distinction between IEC and what the working group 4 of TC64 does. Namely, the publication 479 is generally valid. There is no restriction at all. With regards to installation routes for high voltage networks, at the moment nothing is done in the IEC; TC64 theoretically does not confine itself to low voltage but in practice we are working only in the low voltage fields. That means up to 1000 V ac and up to 1500 V dc.

DAWALIBI: When do you expect to have the revised Publication 479 available?

OBERHEIDEN: Well, this publication 479 will appear stepwise, and the first publication will appear next year. I would say half of the publication will be available by the end of the next year.

HAUF: I will address some actual problems that are of interest for physicians in occupational health specialty and also in forensic work. The effects of low frequency electric currents are usually functional and grounding injuries are very rare. But, electric burns should also be taken into account, as a special consideration. The effects increase, as current magnitude increases and occur only during passage of the current. Any later effects can not be usually related to an electric shock. There is no accumulation, and no increase in sensitivity from shock to shock. All that happens are physiological effects. Heart infarction as a consequence of an electric shock is not very likely, as well as changes in the EEG. The basic effects we have to consider for establishing safety requirements are: perception current, let-go current, currents for muscle contractions, as well as muscular contractions with fractures of bones as consequences, fractures of vertebrae, muscular and tendonal tears, disturbances of formations and conduction of impulse in the heart including fibrillation and transient cardiac arrest.

Ventricular fibrillation is considered the main cause of death from an electrical shock. Death can occur as a result of cardiac arrest, but we have no idea how many deaths are caused by direct cardiac arrest, or by ventricular fibrillation. We also state that in cases of electrical shocks, people are not at once dead, but only appear dead. They die as a consequence of asphyxia. Usually in these cases you cannot find organic damages and the reasons are functional changes. It is also very important to know how any health changes should be related to an electric shock.

KURN: You may remember that this morning I was mentioning that in the experiments that we carried out using dogs, the weight of the dog seemed to have very little effect on the shock sensitivity and very little effect on the resistance of the animal at all. This raised some questions and I tried to get some ideas. One I came up with, I offer for your consideration; it is quite an interesting idea. If you take a conducting sheet of material, usually a carbon fibre, it is fixed in the smallest dimension. Then define the resistance of this material in ohms per cm square, and, if all the dimensions are changed linearly, you end up with the same resistance. Let us take a sheet, one cm square and roll it into a tube. We haven't changed any of the data at all; it is still ohms per cm square but it is now the surface of a cylinder. I'm not suggesting that you can represent an animal with a single cylinder, but I suggest that you might represent it as a whole jumble of pipes. If we now take the case of an insulating framework, which most of us know as the skeleton, surrounded by a load of plumbing, and a few wires, we might end up with something that represents an animal body. And from that if you think about it you change all the dimensions equally, you change nothing, the current distribution stays the same through the whole animal. It's quite an interesting concept, maybe a little simplified but it is worth considering. And we thought this might be the explanation for the results that we were getting for these particular animals. If you change the shape then you get a very different answer.

Recently we were doing work under water. During this work we discovered that the person at greatest risk is not the diver, but the swimmer, the man on the surface. There are more people swimming than there are diving. We also have a child risk here. Youngsters swim in pools and just this morning I visualized the youngster swimming in the pool and answering a telephone which is at the pool's edge. A gentleman from Bell Telephone was saying they hadn't had an accident. I don't know what voltage Bell Telephone use on their wire, but the British Post Office uses 50 V. We made some calculations based on curves that were known a long time ago (I don't relate these at all to any of the IEC figures that have been quoted so far today). If we take now a wet person, who's likely to have a 1000 ohms impedance, probably less for the child at the pool's edge), we do have a situation here where even with 10 V, 10 milliamperes is going to pass through a body and that doesn't look too healthy for 10 s. So then, this is an area that perhaps we ought to do a little more work at. We were interested in the effects of short shock this morning. I was particularly interested in the 5 millisecond duration, in the odd sensitivity that existed there. We are now in a world where semiconductors are getting into the supply in increasing quantities, and next we may be putting a TV at the pool's edge. I don't think it would create a problem normally. But, let us consider that there is a fault on it and it has gotten wet. After all, it is likely to fall in the pool, isn't it? Now, we may have a very distorted waveform coming out of that device that might even be a train of 5 millisecond pulses repeated at 60 times a second. If we take that condition, we do have a risk. At 60 times a second, quite a few of those pulses have got to fall in the vulnerable period. Is there a protection device that will look after it? I think this is something we're going to have to develop before it becomes a hazard. That's the point I want to make. For once can we get the protection set up before the incidence occurs?

BAISHIKI: In California there's a restriction on where you can have the receptacle near a swimming pool, and it can't be too close to the pool. It is also required that a GFI (ground fault interrupter) is installed on a receptacle near the pool.

BRIDGES: This discussion provides a good introduction to Dr. Biegelmeier's summary on the state of the art in the body impedance and suggestions for future research.

BIEGELMEIER: First of all I would like to underline the words of Mr. Oberheiden, who called for very simple wiring rules. Our contractors are simple people, they want to have simple rules that they can understand. So I think that the aim of TC64 should be to give simple wiring rules to people who are making the installations. We have to provide the scientific background for these rules, but we should try to encourage technical committees to use this scientific background in a simple way. Now, as far as I can tell, what we have seen in these three days, is the following: First, there's the problem of body weight scaling for fibrillating thresholds. You have heard my opinion. I still believe that when we derive thresholds from dogs which weigh from 8 to 16 kilograms, which is the weight of a child from one to three years with a heart rate of 180 beats per minute, we are on a very safe side. It doesn't make any sense to me to calculate from the dog weight to 50 or 70 kilogram adults and then calculate back to a child of 8 kilogram, because then, suddenly, you find different values. This is a serious problem. Dr. Green compared the dog's heart with a man's heart. When he made experiments with his heart patients, he found that the heart of a man is less sensitive than the heart of a dog as far as electrostimulating is concerned. So, if we apply the data that we know from these experiments to human beings, we are on the safe side, and this is what working group 4 has done in the draft now. The values given in the tables are applied to human beings independent of age and weight. There's also the question of health. It is known that if you inject chemicals into the heart, and Dr. Green also has done this, the fibrillating threshold doesn't change much. The second point is that Dr. Green's comparison was done on heart patients, which were just before heart operations. They were certainly sick people as far as the heart is concerned. So, on the whole, I think that the working group 4 has been very careful and very conservative in deriving these values for fibrillation thresholds for ac 50/60 Hertz. As far as body impedance is concerned, we have very good data now in part 6. We have derived probability values for 5%, for 50%, and even for 95% body impedances and now we have added on Monday for the ac fibrillating thresholds also the 5%, 50% and 90% values. So the technical committees can choose which values they think are appropriate. Even the 5% threshold gives conservative limits and it might, for instance, be applied by people considering safety problems in high voltage plants where the probability of fault is very small. Certainly in domestic installations we shall use the safety curve at 550 milliamperes. So there is a large field of experience we can get hold of and we should try to apply this experience to the wiring rules in a most simple way.

I also have two other suggestions. When using publication 479 for protection purposes in low voltage installations we should carefully distinguish between protection against indirect and direct contacts. For indirect contacts, when an insulation fault causes the current flow through the protective wire, we should accept simple values as mentioned by Mr. Oberheiden: 50 V conventional voltage limits for 0.8 seconds duration as proposed now, and maybe twice as much, 100 V for 0.4 seconds. There will be very reasonable values for TM systems or even for TE systems. In contrast, an additional protection against direct contact is needed and we are using high density ground fault interrupters. The tripping characteristics of these ground fault interrupters should be discussed seriously. My feeling is, that when used to protect single circuits with socket outlets, ground fault interrupter should have a sensitivity of approximately 10 milliamps

at the beginning of the tripping; we could also have a tripping in 0.5 seconds for 30 milliamps and 0.2 seconds for 60 milliamps. But, the value of 100 mA which I have experienced myself should not be allowed for more than 20 milliseconds. This is in accordance with the Underwriters Lab's proposal, because then the muscular reaction is fairly strong and a problem is not that of lethal electrocution, but that of a muscular shock.

BRIDGES: Thank you very much. This allows me a chance to say something about IEEE 80. From Dr. Sverak you heard that they were using the body weight scaling factor to consider the possibility of children coming in contact with metal near the rights-of-way. You also heard from Mr. Mogan and Mr. Smoot that they have examined the information also available to you and come to the same conclusion as Dalziel, that there is a body weight scaling phenomenon. And at this point I'd like to have Mr. Geddes comment on that.

GEDDES: I only have my own data and, therefore, I'm biased. I think that when talking about a body weight factor you're really talking about a very variable thing, as Dr. Biegelmeier pointed out. Our studies were done over a range of species and I make no apologies for that. We were interested in the fibrillating threshold for shocks of 5 seconds duration applied to each of the animals and we went up in weight scales. The curves shown this morning have to be used probabilistically. If the line with a 50% probability is examined, you notice a scatter of data. There are animals that require considerably less current than the average, and animals that require considerably more. So we have the variability among the animals which tend to make the weight characteristics less clear in a single species. This same argument has been brought up with ventricular defibrillation. There are those who say children are like a species of dogs and others say adults are like big animals and that there is a dose for defibrillation of the adult and there's a smaller dose for children. That is merely just another way of describing that there is some function of body weight. It may not be a strong one. The point I'd like to make is that if you're going to look at an electrocution equation, it should consider and contain a constant or a factor that is geometry. That is the direction in which the current is applied. It should contain a factor that has to do with the duration of current flow. That is another important factor. It should also contain a body weight. In that connection, one has to be extremely careful when applying bursts of 50 or 60 hertz that are about equal to or shorter than the duration of the cardiac cycle (0.25 or 0.3 seconds in man). If the burst is short with respect to the cardiac cycle and there is no heart beat, that will merely illicit a single heart beat. If the duration is of the order of 0.2 seconds and the shock is applied when there is no heart beat, the end of the shock could hit the vulnerable period and fibrillation could occur. I think the paper given from Dr. Green's laboratory shows that time of the beginning of the shock relative to the cardiac cycle and the burst duration are important considerations and research is needed on these particular points.

Now, while I have the stage, I would like to comment upon metabolic status affecting the threshold for ventricular fibrillation. I can say emphatically that it does. I must disagree with those who say it does not. There is lots and lots of evidence that point out to metabolic status altering the ventricular fibrillation threshold. In the early days of cardiac pacemaking, for example, when they did not have demand pacemakers, they would put in a pacemaker and the pacemaker would drive the heart and shortly thereafter AV conduction would return. At this point the ventricles would be stimulated by the normal impulse and by the pacemaker stimulus. It was the habit of cardiologists to find the pacing threshold at time of implant and double or triple it (because pacing threshold increases as a tissue capsule grows around the pacing electrode). If the patient got hypoxia, the threshold for fibrillation in the vulnerable period dropped and there is published literature on that. Secondly, drugs do alter the threshold for fibrillation, epinephrine being one of them; any drug that hypo-polarizes, knocks out some

of the membranes potential, makes the membrane very, very excitable and a single stimulus will produce fibrillation quite easily. Perhaps the most outstanding factor that sensitizes a myocardium to fibrillation is hypothermia. It is not uncommon to encounter ventricular fibrillation in drowning accidents in low temperature water. The last factor that alters myocardial irritability is ischemia; patchy ischemia, poor circulation in one area of the myocardium as opposed to another, as produced in a ligation or partial ligation of a coronary artery. Therefore, I don't think that we can say for sure that metabolic status is unimportant. All the evidence that I have seen indicates that metabolic status is an important factor in the susceptibility to ventricular fibrillation.

BRIDGES: Thank you Dr. Geddes, I might also remind the participants that the paper by Dr. Griffin supports Dr. Geddes' viewpoint.

WILLS: I'd like to present to you my point of view as a practicing occupational health physician who has no responsibilities for designing utilities and no responsibilities for standards. During the last three days I've seen people who, from my point of view, are using rather linear deterministic a priori reasoning starting with basic electrophysiology and progressing forward from there. I think I'd like to point out to you that there is another area of science which at least in North America has been not used at all in the whole area of the effects of electrical contacts. That is the area of epidemiology.

If you think of a basic disease model and electrical contacts - then accidents are disease. If we look at the electrical disease, it is really the interaction of an agent which is some form of electricity and a host in a particular environment. The last three days we've concentrated on the agent as a specific entity defined by waveform, quantity, frequency, time duration, etc. We've thought of the host as being everything from an isolated profused guinea pig heart to a hog, to a cadaver, and a particular environment which is usually a laboratory setting. What we haven't done really and what I think should be done is take a look at populations. In other words try and determine who is at risk, what is the environment that they're at risk in and what are the causes which are not necessarily ventricular fibrillation, or respiratory arrests, but causes in terms of say, ground fault areas, or poor systems design. By taking an epidemiological approach, it may well be that you can "short circuit" some of the work that has to be done at a basic fundamental level. I don't see in North America any well done epidemiologic studies that define who it is at risk in what environment and what the causes are. Only through doing this sort of work can you come up with priorities. Priorities in terms of prevention, because we're really interested in preventing the electrical disease. Earlier, Mr. Bridges said that fundamental to any improvement in electrical safety are the electrical shock biological safety criteria. Well, I would ask this question: can we quantify the magnitude of the problem in terms of the morbidity, mortality, or total human detriment secondary to inappropriate electrical shock safety criteria? I don't think that has been done from an epidemiologic point of view and I don't think that, from an epidemiologic point of view we've taken a look at what the fundamental problems are. And I'm taking a look at it from somebody downstream, not someone who is upstream, or who has the responsibility for developing safety criteria.

Lastly, there is another area that I think is crucial. This is not in the area of primary prevention; it's not even the area of secondary prevention, but it's tertiary prevention. And tertiary prevention is treating the effects. I point particularly to the devastating thermal burns that one sees in so many of these electrical contact accidents. Electrical contact burns, as Dr. Cabanes mentioned, are not like thermal burns. With current conduction, you get damage along the whole current pathway. The injuries are more like crush injuries; you get full thickness tissue destruction. The problem is how to treat these people. Usually, the surgeon nibbles away at the burned area over a number of days, taking a long

time, because he doesn't want to get rid of potentially viable tissue. This leaves the wound exposed at risk from sepsis, and at a risk of renal failure. So, it would be nice if, at an early stage, we could define what is going to be viable and what is not going to be viable, so that in fact, some surgery could be done early to minimize the amount of time spent in hospital, to minimize the person's risk of sepsis and renal failure and contracture; so that the victims could get on to early rehabilitation and perhaps even plastic surgery. Some of this work is being done as I know by the group in Montreal at the Royal Victoria Hospital, by Dr. Daniel and some of it, I understand, is being done by Dr. Sances. This I think is another very important area that has to be looked at. When someone dies of ventricular fibrillation or respiratory arrest secondary to electrical contact that is indeed unfortunate. But when people have severe burns, you really have to do something with the living person that you have left. Thank you.

SHERMAN: I would like to suggest to the panel a slightly different point of view on the problem that has been discussed in the last three days, and that is the effect of the electrical shock. Talking at this moment as a physiologist, I get impressed by the huge amount of available information on what happens under different conditions to the current, to the fibrillation threshold, to the current pathway in the body and so on. One gets really impressed by the number of experiments done to avoid looking at an underlying problem. Experiments were done where the hands were wetted in water, where hands were wetted in 3% saline, where the electrodes were applied from one point to another and so on. But really, the only underlying mechanism that has been proposed and discussed for the transfer of the electrical current from the source to the body, has been a two-component model, an RC skin model and a simple R model for the body impedance. It is really surprising that there has not been more work on modelling or understanding better the characteristics of a human body from an electrical engineering point of view. Large amount of physiological data is available on the subject and is waiting for someone to incorporate it in a proper model. This is a rather superficial account of what happened in the three days. There certainly is some work done in the field but we still are very far from understanding what really skin is comprised of and how it behaves under the conditions of interest. And certainly a better understanding of even that one parameter, the skin properties, would significantly reduce the number of variables that researchers in the field have to deal with, and would greatly simplify I think the task of the people who are assembled here.

GEDDES: I'd like to respond to that. As a matter of fact that comment leads directly to the comment that I wanted to make. I'd like to point out that the body is not a volume conductor; it consists of distributed resistivity ranging from a 53 ohm-centimeters for plasma, 150 ohm-centimeters for blood, 2000 ohm-centimeters for lung, 15,000 ohm-centimeters for bone and 500 ohm-centimeters for muscle, (muscle has about 150 to about 750 Ω-cm resistivity, depending upon the direction of the current flow). However, one of the things that you should know is that tissue resistivity is current density dependent: it decreases as the current density is increased. It is also temperature dependent: it has a temperature resistivity coefficient of about -2% per degree C increase. So, if the current is flowing, as you increase the temperature the resistivity is decreased. Here is a nice non-linear property. During the past few days I have heard about many studies being made on body impedance in which electrodes have been put on tissue and I have not once heard any example of a potential electrode put on the skin beside the current carrying electrode. So, I'll have to conclude that the body impedance values include the electrode impedance. Electrode impedance is a non-linear circuit. It contains resistive and capacitive elements. It is also non-linear; the impedance goes down with increasing current density. There is a lot of electric chemistry involved. It is also highly dependent upon contact area. The current density distribution under an electrode is not uniform. If you take a circular disc electrode and put it on the skin, there'll be three times the current density under the perimeter as compared to the centre. When you're

talking about tissue sensation, this should be taken into account. So there is a fair body of literature on the non-linear properties of electrodes and tissue and we should look at it. I would like to see some of the studies that I heard today repeated with a potential electrode surrounding the current carrying electrode, or perhaps with a hole in the middle and the potential being measured in the middle, because then, I think, you could separate electrode phenomena from body phenomena.

BRIDGES: Dr. Sances presented yesterday the four electrode concept which measured the resistivity of the tissue while undergoing a 60 cycles current surge.

FORD: I would like to summarize the way I see the situation now in regard to the three main topics that seem to be in dispute. On the current-duration curve, IEC is proposing the Biegelmeier-Lee Z-curve; IEEE is using Dalziel. On body impedance IEC has got impedance as a function of voltage, IEEE has got a constant 1000 ohms. In body weight scaling, IEC says no, and IEEE says yes. Now, I've got three questions. The first one I guess is primarily addressed to Mr. Arnot and to Mr. Baishiki. Can utilities live with a difference in standards? Is there a need for uniform standards? The second question is: can uniformity of standards be achieved based on existing knowledge? And lastly, can the differences be attacked, if there is a lack of knowledge; that is, can the differences be attacked or are there ways to solve these problems? Are there aspects which are amenable to R&D which could solve these problems?

BAISHIKI: I think there is a need for a uniform standard.

ARNOT: If I may add to it, the IEEE standard 80 did serve us pretty good so far. And for 75 years Ontario Hydro did not have a fatality caused by the ground potential rise. But, I am afraid that we are running out of time. I think that we should try to converge the standards and I would like to appeal to standard bodies to try to get these standards together and hammer out something that can be used throughout the world. We didn't have the fatalities probably because all the six circumstances which I showed before, had not come to play simultaneously. But as I said before, the stations are getting smaller, the short circuit current is getting higher and probably, one day, we will get an accident that will be very hard to explain. On the other hand, we might satisfy our managers and bosses and think about the economy of the whole thing. If we go to the lower body impedance and other similar assumptions, it might require more materials to be used and so on. But again and again, I think it should be stressed that the uniform standards will be very desirable and welcome by the design engineers throughout the power industry.

NILES: This area was touched upon during the Underwriter Labs and the Consumer Product Safety presentation this morning and it dealt with retrofitting. One of the things that really wasn't said was whether or not they are going to include retrofitting on standards within appliances, etc. One of the things that we should talk about in the utility industry, which I know my company does not like to hear, is retrofitting. For example, designs on Ontario Hydro systems and our designs were not any better 30 years ago, but we have a lot of stations of that design and I'm sure you do too. Are we thinking about retrofitting those? Our answer basically is - no; we don't have to do that from a legal point of view, because, if the design standards at that time were adequate, then they should be adequate now. But this is a whole area of discussion that perhaps needs to be at least thought about. Maybe we should have a lawyer here.

OBERHEIDEN: Mr. Chairman, I would strongly support the idea of having uniform standards and I really don't see any need for having different standards. Different standards have developed in the course of the time, this being a purely historical development. I'm also quite sure that the existing different standards have been produced with the idea of coming to consensus. I'm quite sure that at

the origin of these different standards, different opinions existed and finally one came to a common result. In the same way, it should be possible to come to a uniform result worldwide.

HEROUX: I have a short comment on the subject of body weight scaling and fibrillation currents. A physician will usually dose drugs on the basis of body weight; so many milligrams per body weight. As Dr. Cabanes said a little earlier, one better way to do this is to use body surface as a variable. I think there is an even better way than body surface, and that is the weight to the power of 0.7. Although it might seem strange, a bigger person needs less of a drug for a given physiological effect. So the factor of 0.7 is uncomfortably close to 0.66, which is the value that one gets from considering the current density as the critical variable. Therefore, there is the possibility that the relationship between body weight, and body weight scaling is a purely physiological effect. That would mean that electricity is just like another drug. Then, the large scatter observed by Prof. Biegelmeier in various animals would seem to me to be more compatible with pharmacology than with electrical engineering.

GEDDES: The point you make is very, very well taken. If you plot the peak current versus body weight for defibrillation with say a damped sinusoid over a large range of species the exponent is $W^{0.7} - W^{0.8}$. So, yes it isn't linear with body weight. Heavy animals require slightly less than you'd expect on the basis of their weight when you scale from small animals. This was a surprise that came to us after we did experiments with enough animals over a large enough range.

R.J. TAYLOR: One important R&D need is 60 Hz body-circuit impedance measurements of barefeet children contacting ground under wet contact conditions. This total body-circuit impedance versus various soil types is needed to evaluate hazards to children contacting low impedance voltages such as magnetic induction to fence from power lines.

A.M. DOLAN: I have two points: We have been discussing for the past three days the electric shock problem. In reality there exists two problems: (1) Electrophysiological problem (Geddes, Antoni, Roy, Reilly) (2) Electromagnetic field problem (Bridges & others).

Electrophysiological studies will tell us what levels of electric field or current density will affect the heart, respiratory muscles, nerves in a particular way. Knowing that we can use electromagnetic field information to determine the conditions under which those particular levels will be delivered to the organs. Knowing those conditions designers can go to work.

More analysis of these individual parts of the whole problem needs to be done and I put in a plea for that basic work.

M. FORTIN: Basic research and engineering data presented here will surely be useful for us and for utility engineers dealing with electrocution and electrocution prevention. More work related to effects of electric shocks on respiratory muscle, nervous center, and skeleton muscles will also be of interest to us.

But my main concern as a utility safety engineer, arises from the consequences of electrical burns subsequent to medium to high voltage injury. For utility, and more specifically, for a distribution utility I represent here, these are the more common types of electrical accidents. Great efforts are made to avoid any electrocution by adequate tooling, training and work procedures, but a finite risk will always remain.

- At the present time, these electrical burns result in very severe amputations leading young men to become almost complete invalids. The effects of these injuries on personnel and family are extremely heavy and long lasting.

- My suggestion would then be to strongly support any research and clinical efforts aimed at: 1. A better knowledge of the physiology of damages to internal tissues; 2. A rapid diagnostic of these damages; 3. Preserving tissues, and arresting progressive damages, thus reducing, as much as possible, the extent of amputations.

BRIDGES: Thank you. As chairman of this panel, I have awakened in the middle of the night in cold sweat thinking that the panel discussion would fall flat and we would have a half hour of nothing to be said. The opposite has happened. I do think it is time for me to note some of the research areas and also give you a chance to add to these or perhaps comment on them.

Because Charles Dalziel is a great contributor to electrical safety, his prestige has carried and maintained his philosophy. This basically means that imbedded in many of our standards and publications, we have a body-weight scaling relationship. Whether this is correct or not, is not clear. The evidence is somewhat inconclusive for a variety of reasons which were said before. So clearly, we need to think about answering the basic question: do we use the same shock standards for children as for adults? This is what the real question is.

I also think that the body resistance for children remains an unanswered area. Some people say the resistance of the child will increase because they have smaller area; you heard Mr. Kurn saying that the child's resistance will be the same; we heard another argument by Dr. Griffin who said that the child has more water in the tissue implying a lower resistance. Perhaps then, the average resistivity of the child's tissues would be such that it would tend to compensate for the reduction in size. I think the body resistance of children is another research area.

There seems to be some disagreement as to the influence of drugs and the state of health of the subject on a fibrillation threshold. This perhaps could be resolved by a more careful review of the literature and results of other studies dealing with the subject area of cardiac pacemakers.

Another important point is the one raised by Dr. Lee regarding respiratory arrest. There is no post-mortem data for humans in this case, because it is particularly difficult to determine how that person died in retrospective studies. I think that is another area for research.

Another area is let-go effects for children. Especially, we need to look at the effects above 100 H_3 in terms of let-go and fibrillation.

Another topic that wasn't discussed but it seems to me quite apparent after listening to the papers by Prieto and Sances, is shocks with long durations. When a subject is in contact with a constant voltage line for more than 10 seconds the body resistance keeps progressively dropping. And where people have been exposed to shock for longer than 10 seconds, it could well be that the death is caused, in part, by the collapse of the body resistance due to thermal effects and other phenomena which can occur beyond 10 seconds. As is the case for very long-duration shocks, the physiological effects of very short duration shocks are also not well understood. While some valuable results for very short-duration have been presented here, further effects are needed, as evidenced in the discussions by Krenicky, Geddes, Ford and Arnot.

There are concerns by people who are making digital equipment or oscilloscope power supplies about the waveform effects of shocks with frequencies above 100 Hz. We've witnessed a great debate on whether one could use a linear model or a non-linear model. Clearly there is a need to find an improved way to understand this phenomena of how non-linear waveforms cause fibrillation or how they affect let go levels.

In the area of body impedance, the break-down or collapse of the skin impedance should be considered further. For example, under moderate voltage shock conditions, a small area contact is more likely to cause break-down of the resistance of the skin than a large area contact. Other phenomena have been offered, such as current channelling through certain weak points in the skin. This seems to be another area for research, as well as the effect of non-sinusoidal waveforms on the skin resistance.

We have discussed why we had the conference. One reason, we are having the conference is because we were not exchanging the information. For example a great deal of effort has gone into IEC work, and much of it is very useful information but not widely known in North America. Here, we've been critical of about 5% of the IEC information that's been developed, but it is clear that 95% of it is very useful. Allowing the North American utility engineers and biomedics to talk with the experts from Europe and vice versa should be very useful.

Hopefully we can set up some means where we can have a more continuous exchange of information. When I was looking into shock effects about 5 years ago, and attempted to make a literature search, Dr. Biegelmeier's name has only surfaced once as a result of the computer search. This should not be. We should implement the broadest exchange possible. It may be that when one studies the effect of thermal burns on animals (such as Dr. Sances has done) some of the data would be useful for fibrillation studies. Some of the instrumentation studies that both Dr. Sances and Dr. Heroux presented, will be of general value.

In terms of the specific problems associated with IEEE 80, the point was raised that for the step potential shock exposure condition not enough current gets to the heart to induce fibrillation before other effects occur. The heart factor in that particular situation should be quantitatively determined. Another step potential concern has to do with knock-down reflexes for a standing subject upon onset of a ground fault and subsequent possible re-exposure of the subject while in a prone position to high earth potentials, if the circuit breaker recloses before the fault is cleared.

I think another crucial issue for IEEE 80 (as mentioned before) is body-weight scaling. This is so embedded in North-American standards that the biggest impact of the IEC standards, if widely accepted, will be in the body-weight scaling area. If body-weight scaling requirements can be dropped based on solid scientific data, we may be able to save significant amounts of metal in grounding systems where public access is likely.

These are most of my comments on the research areas, perhaps I should throw this open for a few minutes for comments from others.

HEROUX: A few remarks with regard to future direction of research. First, since electrocution is a low probability event, there is, I feel a need to pool statistics worldwide and to improve the analysis of accidents. Secondly, utilities need to rationalize their risk assessment methods in order to simultaneously consider mild risk to large numbers of people, such as might be the case with leukemia, and large risk to small numbers of people, which would likely be electrocutions. Thirdly, Dr. Sherman made an interesting remark yesterday on the transition from step to touch potential in the case of reclosure. Such ergonomic type arguments

are not well enough known in my opinion. A good analysis of these elements could eventually allow utilities to save money. Fourth, in relation to changes of tissue resistivity and skin with current, I think this is one of a few questions that are simultaneously of interest to engineers, physiologists and clinicians. Thank you.

MARBLE: I have a question I'd like to put forth on behalf of some of my colleagues. It pertains to potential rise of the neutral in a distribution network. The question is, what standards do North American utilities have at present, if any, for allowable values of distribution system neutral potential rise under load for various classes of consumer loads; for example industrial, domestic, and dairy farms. The comment following the question is, such standards would certainly seem desirable from a safety viewpoint. It is recommended here that maximum tolerable neutral potentials should be established for the various different exposures likely to be encountered in practice and to suit the differing human and animal sensitivities to shock and electric currents.

BRIDGES: Does anybody want to comment on that? I believe the gentleman that is the researcher with the University of Minnesota had been working in a similar area; did you exchange your viewpoints with him?

MARBLE: Yes, we did discuss it a bit and he suggested the standards were practically non-existent.

BRIDGES: Well I think that represents an area for future work. Thank you very much.

DOLAN: I would not like to see Dr. Wills' comments dropped. He suggested the need for epidemiological studies. I think it is interesting that he coined the expression electrical disease. We have been talking about electrical accidents, but in fact they're probably not accidents at all. An accident implies some sort of randomness and electrical accidents are of course not random in place or in time or the persons that they occur to. In fact they exhibit a lot of the characteristics of infectious diseases. There is a source of infection - namely the power source; there is a vector, namely the line or the electrical instrument or whatever gives the shock. There is a susceptible host, namely man and there is pathology, which is a burn, respiratory arrest, circulatory arrest, or neurological damage. I think study of these diseases may well suggest different ways of preventing them. We have been very successful in preventing infectious diseases in different ways; we vaccinate against smallpox, we spray malaria mosquitos in this particular case, we eliminate the source in the case of typhoid fever by cleaning up the sewers and such. Each treatment is different. It may well be that the treatment for electrical burns is different than the treatment for neurologic damage or respiratory distress, so I would support the need for epidemiological study.

BRIDGES: We have thoroughly met the goals of our conference. The utility engineers from the North America exchanged information with shock experts from all around the world. And we clearly have established the state-of-the-art. We've identified some controversial issues but we were obviously here not to resolve such issues.

On behalf of the Conference Committee, I wish to thank all who have taken the time from busy schedules to prepare papers, or come all the way from Europe. I also acknowledge the sponsors of the conference, Canadian Electrical Association, Electric Power Research Institute and Ontario Hydro for their support.

I thank both the participants and sponsors for the opportunity for me to be the chairman. To me, this has been a very worthwhile conference and I hope that the results of this will bear fruit for the next 10 years. Thank you again.

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Neckarwerke AG, Germany

Mr. D.A. Watson
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Mr. G.S. Watt
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Dr. M.C. Wills
Ontario Hydro, Canada

Mr. R. Wilson
Ontario Hydro, Canada

Mr. W. Wisecup
The Aerospace Corporation, USA

Mr. G.L. Wortman
Ontario Hydro, Canada

Mr. J. Yurkin
Construction Safety
Association of Ontario, Canada

SYMPOSIUM ON ELECTRICAL SHOCK SAFETY CRITERIA

PROGRAM

Wednesday, September 7, 1983

Opening of Symposium:
Symposium Chairman: J.E. Bridges, IITRI, USA

Day I: Physiology of Electrical Shocks

Session I:

Chairman: Dr. R. Kavet, EPRI, USA

1.1 Nature of Physiological Effects of Electrical Currents - Dr. J. Cabanes, Electricité de France, France
1.2 The Electrophysiologic Basis for the Cardiac Ventricular Fibrillation Threshold and Factors that Affect It. - Dr. J.C. Griffin, Baylor College, USA
1.3 Pathophysiological Basis of Ventricular Fibrillation - Prof. H. Antoni, Institute of Physiology, Freiburg, Germany
1.4 The Conditions Necessary for the Electrical Induction of Ventricular Fibrillation - Prof. L.A. Geddes, Purdue University, USA

Session II:

Chairman: Dr. I. Sherman, Institute of Biomedical Engineering, Canada

2.1 Potential Distribution in the Vicinity of the Hearts of Primates Arising from 60 Hz Limb-to-Limb Currents - J.E. Bridges, IITRI, USA
2.2 Capacitive Discharge Studies -Dr. J. Myklebust,Dr. A. Sances, Jr., Dr. M. Chilbert, T. Prieto and T. Swiotek, Medical College of Wisconsin, USA
2.3 New Knowledge on Disturbances of Heart Rhythm Produced by Electric Currents of 50 Hz in Dogs and Humans and Shock Criteria for Durations Less than 10 ms - Dr. H.L. Green, Dr. J. Ross, Clinical Research Centre and Dr. R. Kurn, ERA, England

Session III:

Panel Meeting on Physiology of Electric Shocks

Chairman: Prof L.A. Geddes, Purdue University, USA
Vice-Chairman: Prof. H. Antoni, Institute of Physiology, Freiburg, Germany

Panel: J.E. Bridges, Dr. J. Cabanes, Dr. J.C. Griffin, A. Dolan, Prof. W.R. Lee, Dr. J. Myklebust

Topics

a. body weight scaling
b. electrocution equation
c. relative importance of physiological effects caused by electric currents, such as respiratory arrest, etc.
d. effect of age and health conditions on fibrillation thresholds.

Thursday, September 8, 1983

Day II - Body Impedance

Session IV: 8:30 - 12:00

Chairman: R. Del Bianco, CEA, Canada

4.1 New Knowledge on the Impedance of the Human Body - Prof. G. Biegelmeier, WG04, IEC/TC64, Austria
4.2 Body Impedance of Non-human Primates Under Constant Voltage Shock Conditions - J.E. Bridges
4.3 Analysis of Cross-body Impedance at Household Voltage Levels - T. Prieto, Dr. A. Sances, Jr., Dr. J. Myklebust, and Dr. M. Chilbert, Medical College of Wisconsin, USA
4.4 Experiments with Regard to Basic Safety Measures for Electrical Equipment and Installations - Prof. G. Biegelmeier, WG04, IEC/TC64, Austria
4.5 Dynamic Aspects of Body Impedance - R. Nute, Tetronix, USA

Section V:

Chairman: Dr. G.L. Ford, Ontario Hydro, Canada

5.1 A Five-Part Resistor-Capacitor Network for Measurement of Voltage and Current Levels Related to Electric Shocks and Burns - W. Hart, Fluke Co, USA
5.2 Resistivity Changes of Tissue - Dr. A. Sances, Jr., J. Szablya, Dr. J. Myklebust, J. Ackerman, T. Prieto, Dr. M. Chilbert, T. Swiontek, and C. Brown, Medical College of Wisconsin, USA.
5.3 An Equivalent Voltage for Sinusoidal and Non-sinusoidal Voltage Waveforms - R.C. Menendez, Bell Laboratories, USA
5.4 Intra-Body Current Probes, Dr. P. Heroux, IREQ, Canada

Session VI:

Panel Meeting on Body Impedance

Chairman: Prof. G. Biegelmeier, WG04, IEC/TC64, Austria
Vice-Chairman: J.P. Reilly

Panel: Prof. R. Hauf, P. Héroux, Prof. W.R. Lee, R.C. Menendez, Dr. A. Sances, Jr., A. Smoot, O.Z. Roy

Topics

a. applicability of animal experiments to human body modelling
b. current/voltage sources for body impedance measurements
c. effect of size, location and type of electrodes on measurements
d. body impedance as a function of current density and path.

Friday, September 9, 1983

Day III - Safety and Standards

Session VII:

Chairman: M. Vainberg, Ontario Hydro, Canada

7.1 Human Sensitivity to High Voltage Transient Currents - J.P. Reilly, J. Hopkins University, USA
7.2 Body Impedance for Currents of Short Duration - R. Taylor, J. Hopkins University, USA
7.3 The Effects of Short Duration Transients on Cardiac Rhythm - O.Z. Roy, A.J. Moztimer, B.J. Trollope, E.J. Villeneuve, National Research Council of Canada, Canada
7.4 Intricacies of Safety Criterion Around Power System Structures - R. Baishiki, Pacific Gas and Electric, USA; F. Dawalibi, Safe Engineering Services, Canada
7.5 Safety Criterion for Intended or Expected Non-Lethal Electrical Shocks - Dr. T. Bernstein, University of Wisconsin, USA
7.6 Methods of Calculating Electrical Body Impedance and Equipment for Measuring Leakage Currents - A.W. Smoot, Underwriters Laboratories, USA; N. Mogan, Consumer Product Safety Commission, USA

Session VIII:

Chairman: J.H. Dunlap, EPRI, USA

8.1 Requirements for Grounding Practices and Standards - The Revision of IEC Report 479 - Prof. R. Hauf, WG04, IEC/TC64, Germany
8.2 Highlights of the Proposed Revision of IEEE Standard 80 - Dr. J.G. Sverak, Gibbs and Hill Inc, USA
8.3 Electrical Safety Criteria - A Basis For Choosing the Parameters of Earthing Arrangements of 50 Hz Industrial Electrical Installations - Dr. Sc. R.N. Karyakin, VNII Projectelectromontazh; M.Sc. B.M. Yagudaev, A.A. Skochinsky, Mining Institute and M.Sc. S.P. Vlasov, Moscow Institute of Transport Engineering; USSR

Session IX:

Panel Meeting on Future Work Required
for Utility Standards on Electric Shocks

Chairman: J.E. Bridges, IITRI, USA
Vice-Chairman: Prof. R. Hauf, WG04, IEC/TC64, Germany

Panel: S. Arnot, Prof. G. Biegelmeier, R. Baishiki, Prof. L.A. Geddes, Dr. H.L. Green, Dr. J.G. Sverak, Dr. M.C. Wills

Topics
a. R&D needs
b. needs of standards on electrical shocks
c. uniformity of standards