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Effects of current on human beings and livestock – Part 1: General aspects

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EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 1: General aspects

FOREWORD

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International Standard IEC 60479-1 has been prepared by IEC technical committee 64: Electrical installations and protection against electric shock.

This first edition cancels and replaces IEC TS 60479-1:2005, Amendment 1:2016 and IEC TR 60479-3:1998. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TS 60479-1 and IEC TR 60479-3:

- The contents of IEC TR 60479-3 relating to aspects unique to the effects of current passing through the bodies of livestock have been incorporated into a new Annex H (normative).

It has the status of a basic safety publication in accordance with IEC Guide 104.

The text of this International Standard is based on the following documents:

CDV	Report on voting
64/2275/CDV	64/2343/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60479 series, published under the general title *Effects of current on human beings and livestock*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

In order to avoid errors in the interpretation of this document, it should be emphasized that the data given herein is mainly based on experiments with animals as well as on information available from clinical observations. Only a few experiments with shock currents of short duration have been carried out on living human beings.

On the evidence available, mostly from animal research, the values are so conservative that this document applies to persons of normal physiological conditions including children, irrespective of age and weight.

There are, however, other aspects which should be taken into account, such as probability of faults, probability of contact with live or faulty parts, ratio between touch voltage and fault voltage, experience gained, technical feasibilities, and economics. These parameters should be considered carefully when establishing safety requirements, for example, operating characteristics of protective devices for electrical installations.

The form of the document, as has been adopted, summarizes results so far achieved which are being used by technical committee 64 as a basis for establishing requirements for protection against shock. These results are considered important enough to justify an IEC publication which may serve as a guide to other IEC committees and countries having need of such information.

This document applies to the threshold of ventricular fibrillation which is the main cause of deaths by electric current. The analysis of 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.

This document contains information about body impedance and body current thresholds for various physiological effects. This information can be combined to derive estimates of AC and DC touch voltage thresholds for certain body current pathways, contact moisture conditions, and skin contact areas.

This document refers specifically to the effects of electric current. When an assessment of the harmful effects of any event on human beings and livestock is being made, other non-electric phenomena, including falls, heat, fire, or others should be taken into account. These matters are beyond the scope of this document, but may be extremely serious in their own right.

Further experimental data are under consideration, such as recent ongoing experimental work on "current induced heart fibrillation by excitation with discrete Fourier spectra" which is intended to contribute to frequency factor data.

The characteristics of the impedance of the body of livestock and the effects of sinusoidal alternating currents are described in Annex H.

EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 1: General aspects

1 Scope

This part of IEC 60479 provides basic guidance on the effects of shock current on human beings and livestock.

For a given current path through the human body, the danger to persons depends mainly on the magnitude and duration of the current flow. However, the time/current zones specified in the following clauses are, in many cases, not directly applicable in practice for designing measures of protection against electrical shock. The necessary criterion is the admissible limit of touch voltage (i.e. the product of the current through the body called touch current and the body impedance) as a function of time. The relationship between current and voltage is not linear because the impedance of the human body varies with the touch voltage, and data on this relationship is therefore required. The different parts of the human body (such as the skin, blood, muscles, other tissues and joints) present to the electric current a certain impedance composed of resistive and capacitive components.

The values of body impedance depend on a number of factors and, in particular, on current path, on touch voltage, duration of current flow, frequency, degree of moisture of the skin, surface area of contact, pressure exerted and temperature.

The impedance values indicated in this document result from a close examination of the experimental results available from measurements carried out principally on corpses and on some living persons.

Knowledge of the effects of alternating current is primarily based on the findings related to the effects of current at frequencies of 50 Hz or 60 Hz which are the most common in electrical installations. The values given are, however, deemed applicable over the frequency range from 15 Hz to 100 Hz, threshold values at the limits of this range being higher than those at 50 Hz or 60 Hz. Principally the risk of ventricular fibrillation is considered to be the main mechanism of death of fatal electrical accidents.

Accidents with direct current are much less frequent than would be expected from the number of DC applications, and fatal electrical accidents occur only under very unfavourable conditions, for example, in mines. This is partly due to the fact that with direct current, the let-go of parts gripped is less difficult and that for shock durations longer than the period of the cardiac cycle, the threshold of ventricular fibrillation is considerably higher than for alternating current.

This basic safety publication is primarily intended for use by technical committees in the preparation of standards in accordance with the principles laid down in IEC Guide 104 and ISO/IEC Guide 51. It is not intended for use by manufacturers or certification bodies.

One of the responsibilities of a technical committee is, wherever applicable, to make use of basic safety publications in the preparation of its publications. The requirements, test methods or test conditions of this basic safety publication will not apply unless specifically referred to or included in the relevant publications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC Guide 104:2010, *The preparation of safety publications and the use of basic safety publications and group safety publications*

ISO/IEC Guide 51:2014, *Safety aspects – Guidelines for their inclusion in standards*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 General definitions

3.1.1
longitudinal current
current flowing lengthwise through the trunk of the human body such as from hand to feet

3.1.2
transverse current
current flowing across the trunk of the human body such as from hand to hand

3.1.3
internal impedance of the human body
Z_i
impedance between two electrodes in contact with two parts of the human body, neglecting skin impedances

Note 1 to entry: For the body of livestock, the impedance of the hooves, if any, are also neglected.

3.1.4
impedance of the skin
Z_S
impedance between an electrode on the skin and the conductive tissues underneath

3.1.5
total impedance of the human body
Z_T
vectorial sum of the internal impedance and the impedances of the skin

Note 1 to entry: For the body of livestock, Z_T is the vectorial sum of the internal impedance and the impedances of the hide, skin and hooves, if any (see Figure H.1).

SEE: Figure 1.

3.1.6
impedance of the hide and skin
Z_P
impedance between an electrode on the hide and/or skin and the conductive tissues underneath

3.1.7
impedance of the hoof
Z_h
impedance between an electrode under the hoof and the conductive tissues above it

3.1.8
initial resistance of the human body
R_0
resistance limiting the peak value of the current at the moment when the touch voltage occurs

Note 1 to entry: For the body of livestock the resistance of the hide, if any, is neglected, but the resistance of the hooves, if any, are included.

3.1.9
dry condition
condition of the skin of a surface area of contact with regard to humidity of a living person being at rest under normal indoor environmental conditions

3.1.10
water-wet condition
condition of the skin of a surface area of contact being exposed for 1 min to water of public water supplies (average resistivity ρ = 3 500 Ωcm, pH = 7 to 9)

3.1.11
saltwater-wet condition
condition of the skin of a surface area of contact being exposed for 1 min to a 3 % solution of NaCl in water (average resistivity ρ = 30 Ωcm, pH = 7 to 9)

Note 1 to entry: It is assumed that saltwater-wet condition simulates the condition of the skin of a sweating person or a person after immersion in seawater. Further investigations are necessary.

3.1.12
deviation factor
F_D
total body impedance Z_T for a given percentile rank of a population divided by the total body impedance Z_T for a percentile rank of 50 % of a population at a given touch voltage

$$F_D\left(X\%,\ U_T\right) = \frac{Z_T\left(X\%,\ U_T\right)}{Z_T\left(50\%,\ U_T\right)}$$

3.2 Effects of sinusoidal alternating current in the range 15 Hz to 100 Hz

3.2.1
threshold of perception
minimum value of touch current which causes any sensation for the person through which it is flowing

3.2.2
threshold of reaction
minimum value of touch current which causes involuntary muscular contraction

3.2.3
threshold of let-go
maximum value of touch current at which a person holding electrodes can let go of the electrodes

3.2.4
threshold of immobilization
minimum value of current through the body of the influenced human being or livestock (or part of the human body or livestock) which causes such muscular reaction that the person or livestock cannot move voluntarily, as long as the current flows

3.2.5
threshold of ventricular fibrillation
minimum value of touch current through the body of the human being or livestock which causes ventricular fibrillation

3.2.6
heart-current factor
F
factor which relates the electric field strength (current density) in the heart for a given current path to the electric field strength (current density) in the heart for a touch current of equal magnitude flowing from left hand to feet

Note 1 to entry: In the heart, the current density is proportional to the electric field strength.

3.2.7
vulnerable period
comparatively small part of the cardiac cycle during which the heart fibres are in an inhomogeneous state of excitability and ventricular fibrillation occurs if they are excited by an electric current of sufficient magnitude

Note 1 to entry: The vulnerable period corresponds to the first part of the T-wave in the electrocardiogram which is approximately 10 % of the cardiac cycle (see Figures 17 and 18).

3.3 Effects of direct current

3.3.1
total body resistance
R_T
sum of the internal resistance of the human body and the resistances of the skin

3.3.2
DC/AC equivalence factor
k
ratio of direct current to its equivalent RMS value of alternating current having the same probability of inducing ventricular fibrillation

Note 1 to entry: As an example for shock durations longer than the period of one cardiac cycle and 50 % probability for ventricular fibrillation, the equivalence factor for 10 s is approximately:

$$k = \frac{I_{\text{DC-fibrillation}}}{I_{\text{AC-fibrillation (RMS)}}} = \frac{300\ \text{mA}}{80\ \text{mA}} = 3{,}75 \text{ (see Figures 20 and 22).}$$

3.3.3
upward current
direct touch current through the human body for which the feet represent the positive polarity

3.3.4
downward current
direct touch current through the human body for which the feet represent the negative polarity

4 Electrical impedance of the human body and livestock

4.1 General

The values of body impedance depend on a number of factors and, in particular, on current path, on touch voltage, duration of current flow, frequency, degree of moisture of the skin, surface area of contact, pressure exerted and temperature.

A schematic diagram for the impedance of the human body is shown in Figure 1.

NOTE A modelling circuit for the human body is given in Annex G.

4.2 Internal impedance of the human body (Z_i)

The internal impedance of the human body can be considered as mostly resistive. Its value depends primarily on the current path and, to a lesser extent, on the surface area of contact.

NOTE 1 Measurements indicate that a small capacitive component exists (dashed lines in Figure 1).

Figure 2 shows the internal impedance of the human body for its different parts expressed as percentages of that related to the path hand to foot.

For current paths hand to hand or hand to feet, the impedances are mainly located in the limbs (arms and legs). If the impedance of the trunk of the body is neglected, a simplified circuit diagram can be established which is shown in Figure 3.

NOTE 2 In order to simplify the circuit diagram, it is assumed that the impedance of arms and legs have the same values.

4.3 Impedance of the skin (Z_S)

The impedance of the skin can be considered as a network of resistances and capacitances. Its structure is made up of a semi-insulating layer and small conductive elements (pores). The skin impedance falls when the current is increased. Sometimes current marks are observed (see 4.7).

The value of the impedance of the skin depends on voltage, frequency, duration of the current flow, surface area of contact, pressure of contact, the degree of moisture of the skin, temperature and type of skin.

For lower touch voltages the value of the impedance of the skin varies widely, even for one person, with surface area of contact and condition (dry, wet, perspiration), temperature, rapid respiration, etc. For higher touch voltages the skin impedance decreases considerably and becomes negligible when the skin breaks down.

As regards the influence of frequency, the impedance of the skin decreases when the frequency increases.

4.4 Total impedance of the human body (Z_T)

The total impedance of the human body consists of resistive and capacitive components.

For lower touch voltages, there are considerable variations in the impedance of the skin Z_S and the total impedance of the human body Z_T similarly varies widely. For higher touch voltages, the total impedance depends less and less on the impedance of the skin and its value approaches that of the internal impedance Z_i. See Figures 4 to 9.

As regards the influence of frequency, taking into account the frequency dependence of the skin impedance, the total impedance of the human body is higher for direct current and decreases when the frequency increases.

4.5 Factors affecting initial resistance of the human body (R_0)

At the moment when the touch voltage occurs, capacitances in the human body are not charged. Therefore skin impedances Z_{S1} and Z_{S2} are negligible and the initial resistance R_0 is approximately equal to the internal impedance of the human body Z_i (see Figure 1). The initial resistance R_0 depends mainly on the current path and to a lesser extent on the surface area of contact.

The initial resistance R_0 limits the current peaks of short impulses (e.g. shocks from electric fence controllers).

4.6 Values of the total impedance of the human body (Z_T)

4.6.1 Total body impedance dependence for large, medium and small surface areas of contact

The dependence of the total body impedance Z_T for the 50th percentile of a population of living human beings for large, medium and small surface areas of contact (order of magnitude 10 000 mm^2, 1 000 mm^2 and 100 mm^2 respectively) in dry, water-wet and saltwater-wet conditions at touch voltages U_T = 25 V AC to 200 V AC is shown in Figures 7, 8 and 9.

4.6.2 Sinusoidal alternating current 50/60 Hz for large surface areas of contact

The values of the total body impedances in Tables 1, 2 and 3 are valid for living human beings and a current path hand to hand for large surface areas of contact (order of magnitude 10 000 mm^2) in dry (Table 1), water-wet (Table 2) and saltwater-wet (Table 3) conditions.

The range of the total body impedances for touch voltages up to 700 V for large surface areas of contact in dry, water-wet and saltwater-wet conditions for a percentile rank of 50 % of the population is presented in Figure 4.

The values for Tables 1, 2 and 3 represent the best knowledge on the total body impedances Z_T for living adults. On the knowledge at present available, the total body impedance Z_T for children is expected to be somewhat higher but of the same order of magnitude.

Table 1 – Total body impedances Z_T for a current path hand to hand AC 50/60 Hz, for large surface areas of contact in dry conditions

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	1 750	3 250	6 100
50	1 375	2 500	4 600
75	1 125	2 000	3 600
100	990	1 725	3 125
125	900	1 550	2 675
150	850	1 400	2 350
175	825	1 325	2 175
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 For living persons the values of Z_T correspond to a duration of current flow of about 0,1 s. For longer durations Z_T values can decrease (about 10 % to 20 %) and after complete rupture of the skin Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it can be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 25 Ω.

Table 2 – Total body impedances Z_T for a current path hand to hand AC 50/60 Hz, for large surface areas of contact in water-wet conditions

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	1 175	2 175	4 100
50	1 100	2 000	3 675
75	1 025	1 825	3 275
100	975	1 675	2 950
125	900	1 550	2 675
150	850	1 400	2 350
175	825	1 325	2 175
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 For living persons the values of Z_T correspond to a duration of current flow of about 0,1 s. For longer durations Z_T values can decrease (about 10 % to 20 %) and after complete rupture of the skin Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it can be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 25 Ω.

Table 3 – Total body impedances Z_T for a current path hand to hand AC 50/60 Hz, for large surface areas of contact in saltwater-wet conditions

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	960	1 300	1 755
50	940	1 275	1 720
75	920	1 250	1 685
100	880	1 225	1 655
125	850	1 200	1 620
150	830	1 180	1 590
175	810	1 155	1 560
200	790	1 135	1 530
225	770	1 115	1 505
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 Due to low skin impedances in this case it can be assumed that Z_T depends little on the duration of current flow; Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it can be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 5 Ω.

The values indicated in Tables 1 to 3 have been derived from measurements carried out on corpses and on living persons (adults, males and females) as described in Annex A.

At voltages higher than approximately 125 V for water-wet conditions and 400 V for saltwater-wet conditions the values for the total body impedance are the same as for dry conditions (see Figure 4).

4.6.3 Sinusoidal alternating current 50/60 Hz for medium and small surface areas of contact

The value of the internal body impedances Z_i and of the initial body resistance R_0 (see 4.6) depend only to a small extent on the surface areas of contact.

However, when the surface area of contact is very small, in the order of a few square millimetres, the values are increased.

After the skin has broken down (for touch voltages over approximately 100 V and after longer durations of current flow), the total body impedance Z_T approaches values of the internal body impedance Z_i and depends only to a small extent on the surface area of contact and its condition of dampness.

The measurements of the dependence of the total body impedance Z_T on the surface area of contact for AC 50 Hz in dry, water-wet and saltwater-wet conditions which have been carried out on living persons at touch voltages of U_T = 25 V to 200 V are described in Annex A.

NOTE No data on Z_T for surface areas in water-wet and saltwater-wet conditions of persons or corpses is available for touch voltages above 200 V.

The dependence of the total body impedance Z_T for a current path hand to hand on the surface area of contact (from 1 mm^2 up to approximately 8 000 mm^2) in dry conditions for a touch voltage range of 25 V to 200 V, AC 50 Hz, measured on one person is shown in Figure 5. For touch voltages below 100 V and small surface areas of contact in the order of a few mm^2, deviations in the measurements can easily reach about +50 % of the average, depending on temperature, pressure, location within the palm of the hand, etc.

The dependence of the total body impedance Z_T between the tips of the right forefinger and the left forefinger (surface area of contact approximately 250 mm^2) on the touch voltage for AC 50/60 Hz for a voltage range from 25 V to 200 V is shown in Figure 6.

From Figure 6 one can calculate that the partial impedance of one forefinger at a touch voltage of 200 V is in the order of 1 000 Ω.

The measurements of the total body impedance Z_T shown in Figures 5 and 6 have been carried out on one living person only.

For a percentile rank of 5 %, 50 % and 95 % of a population of living human beings on the knowledge at present available, the following presentation is given for the total body impedance Z_T for large, medium and small surface areas of contact (order of magnitude 10 000 mm^2, 1 000 mm^2 and 100 mm^2 respectively) in dry, water-wet and saltwater-wet conditions:

- for large surface areas of contact, the values have been presented in Tables 1, 2 and 3 for dry, water-wet and saltwater-wet conditions for touch voltages U_T = 25 V to 1 000 V, AC 50/60 Hz;
- for medium surface areas of contact, the values are presented in Tables 4, 5 and 6 for dry, water-wet and saltwater-wet conditions for touch voltages U_T = 25 V to 200 V AC 50/60 Hz;
- for small surface areas of contact, the values are presented in Tables 7, 8 and 9 for dry, water-wet and saltwater-wet conditions for touch voltages U_T = 25 V to 200 V AC 50/60 Hz.

Table 4 – Total body impedances Z_T for a current path hand to hand for medium surface areas of contact in dry conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 25 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	11 125	20 600	38 725
50	7 150	13 000	23 925
75	4 625	8 200	14 750
100	3 000	5 200	9 150
125	2 350	4 000	6 875
150	1 800	3 000	5 050
175	1 550	2 500	4 125
200	1 375	2 200	3 525

Table 5 – Total body impedances Z_T for a current path hand to hand for medium surface areas of contact in water-wet conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 25 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	5 050	9 350	17 575
50	4 100	7 450	13 700
75	3 400	6 000	10 800
100	2 800	4 850	8 525
125	2 350	4 000	6 875
150	1 800	3 000	5 050
175	1 550	2 500	4 125
200	1 375	2 200	3 525

Table 6 – Total body impedances Z_T for a current path hand to hand for medium surface areas of contact in saltwater-wet conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 5 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	1 795	2 425	3 275
50	1 765	2 390	3 225
75	1 740	2 350	3 175
100	1 715	2 315	3 125
125	1 685	2 280	3 075
150	1 660	2 245	3 030
175	1 525	2 210	2 985
200	1 350	2 175	2 935

Table 7 – Total body impedances Z_T for a current path hand to hand for small surface areas of contact in dry conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 25 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	91 250	169 000	317 725
50	74 800	136 000	250 250
75	42 550	74 000	133 200
100	23 000	40 000	70 400
125	12 875	22 000	37 850
150	7 200	12 000	20 225
175	4 000	6 500	10 725
200	3 500	5 400	8 650

Table 8 – Total body impedances Z_T for a current path hand to hand for small surface areas of contact in water-wet conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 25 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	39 700	73 500	138 175
50	29 800	54 200	99 725
75	22 600	40 000	72 000
100	17 250	30 000	52 800
125	12 875	22 000	37 850
150	7 200	12 000	20 225
175	4 000	6 500	10 725
200	3 500	5 400	8 650

Table 9 – Total body impedances Z_T for a current path hand to hand for small surface areas of contact in saltwater-wet conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 5 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	5 400	7 300	9 855
50	5 105	6 900	9 315
75	4 845	6 550	8 840
100	4 590	6 200	8 370
125	4 330	5 850	7 900
150	4 000	5 550	7 490
175	3 700	5 250	7 085
200	3 400	5 000	6 750

4.6.4 Sinusoidal alternating current with frequencies up to 20 kHz and above

The values of the total body impedance for 50/60 Hz decrease at higher frequencies due to the influence of the capacitances of the skin and approach, for frequencies above 5 kHz, the internal body impedance Z_i.

The measurements of the total body impedance with frequencies up to 20 kHz at touch voltages of 10 V and 25 V are described in Annex B.

Figure 10 shows the frequency dependence of the total body impedance Z_T for a current path hand to hand and large surface areas of contact for a touch voltage of 10 V and frequencies from 25 Hz to 20 kHz.

Figure 11 shows the frequency dependence of the total body impedance Z_T for a current path hand to hand and large surface areas of contact for a touch voltage of 25 V and frequencies from 25 Hz to 2 kHz. From the results, curves have been derived giving the dependence of the total body impedance Z_T of a population for the 50th percentile rank for touch voltages from 10 V to 1 000 V and a frequency range from 50 Hz to 150 kHz for a current path hand to hand or hand to foot for large surface areas of contact in dry conditions. The curves are shown in Figure 12.

NOTE No measurements have been carried out in water-wet and saltwater-wet conditions.

4.6.5 Direct current

The total body resistance R_T for direct current is higher than the total body impedance Z_T for alternating current for touch voltages up to approximately 200 V due to the blocking effect of the capacitances of the human skin.

The measurements of the total body impedance which have been carried out with direct current for large surface areas of contact in dry conditions are described in Annex C.

NOTE No measurements have been carried out in water-wet and saltwater-wet conditions.

The values for the total body resistance R_T for direct current determined in the way described in Annex C are presented in Table 10 (see Figure 13, continuous lines).

For large surface areas of contact in water-wet and saltwater-wet conditions the total body resistance R_T may be determined with sufficient accuracy from Tables 2 and 3, while neglecting small differences of Z_T between alternating current and direct current which may exist in the voltage range below 100 V. For all other cases, the tables for alternating current can be used for a conservative estimate.

Table 10 – Total body resistances R_T for a current path hand to hand, direct current, for large surface areas of contact in dry conditions

Touch voltage V	Values for the total body resistance R_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	2 100	3 875	7 275
50	1 600	2 900	5 325
75	1 275	2 275	4 100
100	1 100	1 900	3 350
125	975	1 675	2 875
150	875	1 475	2 475
175	825	1 350	2 225
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value	575	775	1 050

NOTE 1 Some measurements indicate that the total body resistance R_T for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 For living persons, the values of R_T correspond to a duration of current flow of about 0,1 s. For longer durations R_T values can decrease (about 10 % to 20 %) and after complete rupture of the skin R_T approaches the initial body resistance R_0.

NOTE 3 Values of R_T are rounded to 25 Ω.

4.7 Value of the initial resistance of the human body (R_0)

The value of the initial resistance of the human body R_0 for a current path hand to hand or hand to foot and large surface areas of contact can be taken as equal to 500 Ω for a percentile rank of 5 % for alternating current and for direct current. The values for 50 % and 95 % of the population can be taken as equal to 750 Ω and 1 000 Ω respectively (similar to Table 1). The values depend only little on the surface areas of contact and on conditions of the skin.

NOTE The values for initial resistance R_0 are somewhat lower than the asymptotic values for the total body impedance Z_T for AC 50/60 Hz and the total body resistance R_T for direct current, because when contact is made the capacitances of the skin and the internal capacitance of the body are uncharged.

4.8 Characteristics of the impedance of the body of livestock

The characteristics of the impedance of the body of livestock are described in Annex H.

5 Effects of sinusoidal alternating current in the range of 15 Hz to 150 Hz

5.1 General

Clause 5 describes the effects of sinusoidal alternating current passing through the human body within the frequency range 15 Hz to 150 Hz.

NOTE The threshold of fibrillation for a given waveform can be obtained from Annex F.

The effects of sinusoidal alternating current passing through the body of livestock are described in Annex H.

NOTE Unless otherwise specified, the current values defined hereinafter are RMS values.

Examples of touch currents and their effects are shown in Figure 16.

5.2 Threshold of perception

The threshold depends on several parameters, such as the area of the body in contact with an electrode (contact area), the conditions of contact (dry, wet, pressure, temperature), and also on the physiological characteristics of the individual.

5.3 Threshold of reaction

The threshold depends on several parameters, such as the area of the body in contact with an electrode (contact area), the conditions of contact (dry, wet, pressure, temperature), and also on the physiological characteristics of the individual.

A value of 0,5 mA independent of time, is assumed in this document for the threshold of reaction when touching a conductive surface.

5.4 Immobilization

Immobilization in this document means the effect of electric current such that the body of the influenced human being (or part of the body) cannot move voluntarily.

The effect on muscles may result from current flowing through the affected muscles or through associated nerves or the associated part of the brain.

The values of current which cause immobilization depend on the volume of the muscles affected, the type of nerve and the parts of the brain affected by the current.

5.5 Threshold of let-go

The threshold of let-go depends on several parameters, such as the contact area, the shape and size of the electrodes and also on the physiological characteristics of the individual.

A value of about 10 mA is assumed for adult males in this document.

In this document a value of about 5 mA covers the entire population (for additional information, see Figure 23).

5.6 Threshold of ventricular fibrillation

The threshold of ventricular fibrillation depends on physiological parameters (anatomy of the body, state of cardiac function, etc.) as well as on electrical parameters (duration and pathway of current flow, current characteristic, etc.). A description of heart activity is given in Figures 17 and 18 and Annex E.

With sinusoidal alternating current (50 Hz or 60 Hz), there is a considerable decrease in the threshold of fibrillation if the current flow is prolonged beyond one cardiac cycle. This effect results from the increase in inhomogeneity of the excitatory state of the heart due to the current induced extra-systoles.

For shock durations below 0,1 s, fibrillation may occur for current magnitudes above 500 mA, and is likely to occur for current magnitudes in the order of several amperes, only if the shock falls within the vulnerable period. For shocks of such intensities and durations longer than one cardiac cycle, reversible cardiac arrest may be caused.

For durations of current flow longer than one heart period, Figure 19 shows a comparison between the thresholds of ventricular fibrillation from animal experiments and for human beings calculated from statistics of electrical accidents.

In adapting the results from animal experiments to human beings, an empirical curve c_1 (see Figure 20) was conventionally established for a current path left hand to both feet, below which fibrillation is unlikely to occur. The high level for short durations of exposure between 10 ms and 100 ms was chosen as a descending line from 500 mA to 400 mA. On the basis of information on electrical accidents, the lower level for durations longer than 1 s was chosen as a descending line from 50 mA at 1 s to 40 mA for durations longer than 3 s. Both levels were connected by smooth curves.

By statistical evaluation of animal experiments, curve c_2 and curve c_3 (see Figure 20) have been established defining a probability of fibrillation of about 5 % and 50 % respectively. Curves c_1, c_2 and c_3 apply for current path left hand to both feet.

5.7 Other effects related to electric shocks

Other electrical effects such as muscular contractions, rise in blood pressure, disturbances of formation and conduction of cardiac impulses (including atrial fibrillation and transient rhythm disturbances) may occur. Such effects are not generally lethal.

With currents of several amperes lasting more than seconds, deep-seated burns, and other internal injuries, may occur. Surface burns may also be seen.

High voltage accidents may not result in ventricular fibrillation, instead giving other forms of cardiac arrest. This is shown in accident statistics and confirmed by animal experiments. However there is at present insufficient data to differentiate the likelihood of these conditions.

Ventricular fibrillation is fatal because it denies blood flow which transports required oxygen. Electrical accidents that do not involve ventricular fibrillation can also be fatal. Other effects may affect respiration and might prevent the person from shouting for help. These related mechanisms include functional disturbance of respiratory control, paralysis of respiratory muscles, damage to the neural activation pathways for these muscles, and damage to the respiratory control mechanism within the brainstem. These effects, if permanent, lead inevitably to death. If a person is to recover from a reversible respiratory effect, prompt artificial respiration is mandatory. Nonetheless, the person may still die. If current flows through critical parts such as the spinal cord or the respiratory control centre, death can occur. These effects are under consideration and thresholds are not yet defined.

High transmembrane electric fields can damage cells, especially long slender cells, such as skeletal muscle cells. This is not a thermal effect. This has been observed for example with high-magnitude, short-duration body currents (such as from momentary contact with high-voltage power distribution lines). A high electric field across cell membranes can induce the formation of pores in the membranes. The effect is called electroporation. The pores may be stable and ultimately seal over, or may enlarge, become unstable, and subsequently cause rupture of the cell membranes. Tissue then becomes irreversibly damaged. Necrosis of the tissue can occur, often requiring amputation of injured limbs. Electroporation is not limited to any particular current magnitude or to any particular current pathway or duration of flow.

Related non-electrical injuries, such as traumatic injury, should be considered.

5.8 Effects of current on the skin

Figure 14 shows the dependence of changes of the human skin on current density, i_T (mA/mm^2) and duration of current flow.

As a guideline the following values can be given:

- Below 10 mA/mm^2, in general no changes to the skin are observed. For longer durations of current flow (several seconds) the skin below the electrode may be of greyish-white colour with a coarse surface (zone 0).
- Between 10 mA/mm^2 and 20 mA/mm^2, a reddening of the skin occurs with a wave like swelling of whitish colour along the edges of the electrode (zone 1).
- Between 20 mA/mm^2 and 50 mA/mm^2, a brownish colour develops below the electrode extending into the skin. For longer durations of current flow (several tens of seconds) full current marks (blisters) are to be observed around the electrode (zone 2).
- Above 50 mA/mm^2, carbonization of the skin can occur (zone 3).
- With large contact areas, current densities may be low enough not to cause any alterations of the skin in spite of fatal current magnitudes.

5.9 Description of time/current zones (see Figure 20)

The time/current zones and the current boundaries for the different physiological effects of the pathway hand to feet are given in Table 11.

Table 11 – Time/current zones for AC 15 Hz to 100 Hz for hand to feet pathway – Summary of zones of Figure 20

Zones	Boundaries	Physiological effects
AC-1	Up to 0,5 mA curve a	Perception possible but usually no 'startled' reaction.
AC-2	0,5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects.
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected.
AC-4 [a]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	c_1-c_2	AC-4.1 Probability of ventricular fibrillation increasing up to about 5 %.
	c_2-c_3	AC-4.2 Probability of ventricular fibrillation up to about 50 %.
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation above 50 %.

[a] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, Figure 20 relates to the effects of current which flows in the path left hand to feet. For other current paths, the heart current factor has to be considered.

5.10 Application of heart-current factor (F)

The heart-current factor permits the calculation of currents I_h through paths other than left hand to feet which represent the same danger of ventricular fibrillation as that corresponding to I_{ref} left hand to feet shown in Figure 20:

$$I_h = \frac{I_{ref}}{F}$$

where

I_{ref} is the body current for the path left hand to feet given in Figure 20;

I_h is the body current for paths given in Table 12;

F is the heart-current factor given in Table 12.

The heart-current factor is to be considered as only a rough estimation of the relative danger of the various current paths with regard to ventricular fibrillation.

For different current paths, the following heart-current factors are given in Table 12.

Table 12 – Heart-current factor F for different current paths

Current path	Heart-current factor F
Left hand to left foot, right foot or to both feet	1,0
Both hands to both feet	1,0
Left hand to right hand	0,4
Right hand to left foot, right foot or to 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, right hand or to both hands	0,7
Left foot to right foot	0,04

EXAMPLE A current of 225 mA hand to hand has the same likelihood of producing ventricular fibrillation as a current of 90 mA left hand to both feet.

6 Effects of direct current

6.1 General

Clause 6 describes the effects of direct current passing through the human body.

NOTE 1 The term "direct current" means ripple-free direct current. However, as regards fibrillation effects, the data given in Clause 6 are considered to be conservative for direct currents having a sinusoidal ripple content of not more than 10 % RMS.

NOTE 2 The influence of ripple is dealt with in IEC 60479-2:—, Clause 5.

NOTE 3 For durations of current flow below 10 ms, see IEC 60479-2:—, Clause 6.

An example of a touch current and its effects are shown in Figure 21.

6.2 Threshold of perception and threshold of reaction

These thresholds depend on several parameters, such as the contact area, the conditions of contact (dryness, wetness, pressure, temperature), the duration of current flow and on the physiological characteristics of the individual. Unlike alternating current, only making and breaking of current is felt and no other sensation is noticed during the current flow at the level of the threshold of perception. Under conditions comparable to those applied in studies with alternating current, the threshold of reaction was found to be about 2 mA.

6.3 Threshold of immobilization and threshold of let-go

Unlike alternating current there is no definable threshold of immobilization or let-go for direct current. Only making and breaking of current lead to painful and cramp-like contractions of the muscles.

6.4 Threshold of ventricular fibrillation

As described for alternating current (see 5.5), the threshold of ventricular fibrillation induced by direct current depends on physiological as well as on electrical parameters (see also Annex E).

Information derived from electrical accidents seems to indicate that the danger of ventricular fibrillation generally exists for longitudinal currents. For transverse currents, experiments on animals have, however, shown that at higher current intensities ventricular fibrillation may also occur.

Experiments on animals as well as information derived from electrical accidents show that the threshold of fibrillation for a downward current is about twice as high as for an upward current.

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.

Curves derived from animal experiments have been constructed that apply to longitudinal, upward (feet positive) current. Curves c_2 and c_3 in Figure 22 show the calculated combinations of current magnitude and duration at which the probabilities of ventricular fibrillation of the animals are about 5 % and 50 % respectively when the current path is longitudinal through the body (i.e. left foreleg to both hind legs). Curve c_1 shows current and duration combinations below which the likelihood of ventricular fibrillation is estimated to be very low for the same longitudinal pathway of current through the body based on the animal studies. Later studies show that the ventricular fibrillation threshold for humans is higher than the current magnitude as compared to the animals for each duration. For example, the left hand to feet threshold current for a healthy human might be in the order of 200 mA for long durations of current. However, not all human hearts are healthy, and some maladies can affect the ventricular fibrillation threshold. Some people with unhealthy heart conditions have ventricular fibrillation thresholds below normal, but the amount of the reduction is not precisely known. Therefore, it is recommended that the c_1 line shown in Figure 22 that is based on animal studies, be used to describe the ventricular fibrillation threshold for humans as a conservative estimate. There are no known electrical accidents that show an electrocution below the c_1 curve. This indicates that the c_1 curve is probably conservative for all humans. For longitudinal downward current (feet negative), the curves have to be shifted to a higher current magnitude by a factor of approximately 2.

6.5 Other effects of current

Above approximately 100 mA, a sensation of warmth may be felt in the extremities during current flow. Within the contact area, painful sensations are felt.

Transverse currents up to 300 mA flowing through the human body for several minutes might, increasing with time and current, cause reversible cardiac dysrhythmias, current marks, burns, dizziness and sometimes unconsciousness. Above 300 mA, unconsciousness frequently occurs.

With currents of several amperes lasting longer than seconds, deep-seated burns or other injuries, and even death, are likely to occur.

Effects such as electroporation (see 5.6) can result from contact with DC circuits as well as AC circuits.

Related non-electrical injuries, such as traumatic injury, should be considered.

6.6 Description of time/current zones (see Figure 22)

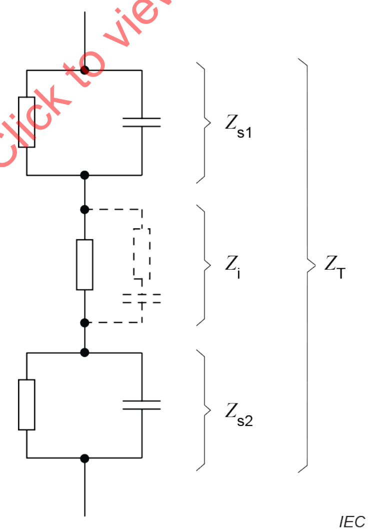
The time/current zones and the current boundaries for the different physiological effects of the pathway hand to feet are given in Table 13.

Table 13 – Time/current zones for direct current for hand to feet pathway – Summary of zones of Figure 22

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow.
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4 [a]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %.
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %.
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %.
[a] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, Figure 22 relates to the effects of current which flows in the path left hand to feet and for an upward current. For other current paths the heart current factor has to be considered.		

6.7 Heart factor

The heart factor F applies to direct current the same way it applies to alternating current (see 5.8).



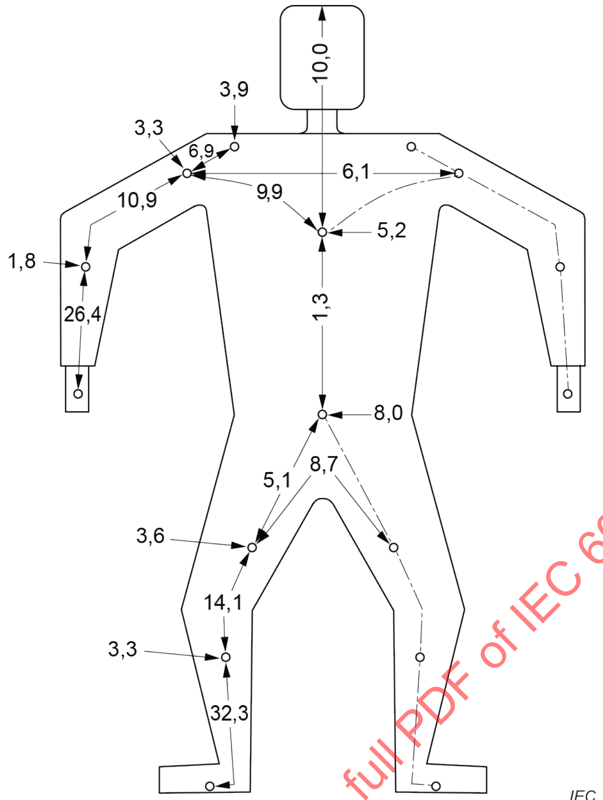
Key

Z_i internal impedance

Z_{s1}, Z_{s2} impedance of the skin

Z_T total impedance

Figure 1 – Impedances of the human body

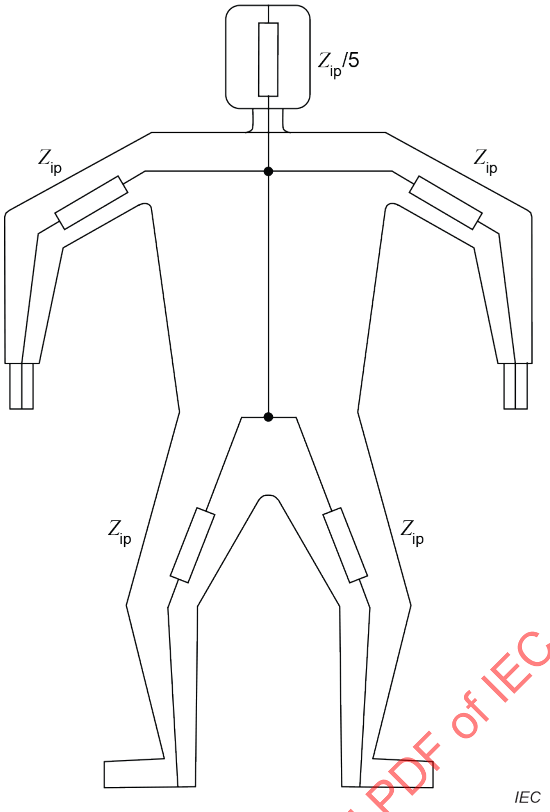


Key

The numbers indicate the percentage of the internal impedance of the human body for the part of the body concerned, in relation to the path hand to foot.

In order to calculate the total body impedance Z_T for a given current path, the internal partial impedances Z_{ip} for all parts of the body of the current path have to be added as well as the impedances of the skin of the surface areas of contact. The numbers outside the body show internal portions of the impedance to be added to the total, when the current enters at that point.

Figure 2 – Internal partial impedances Z_{ip} of the human body

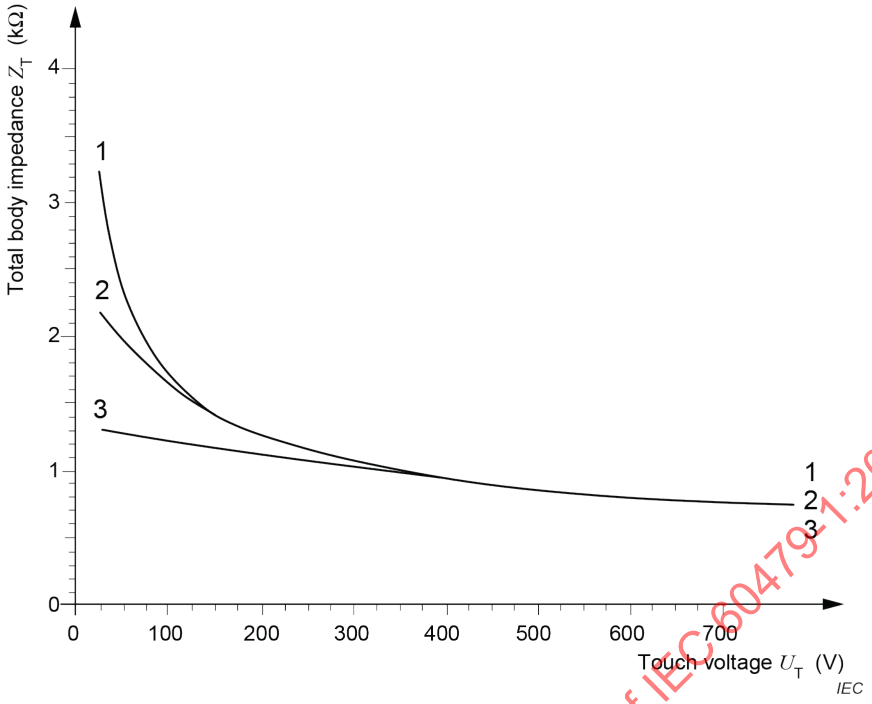


Key

Z_{ip} internal partial impedance of one extremity (arm or leg)

NOTE The internal impedance from one hand to both feet is approximately 75 %, the impedance from both hands to both feet 50 % and the impedance from both hands to the trunk of the body 25 % of the impedance hand to hand or hand to foot.

Figure 3 – Simplified schematic diagram for the internal impedances of the human body



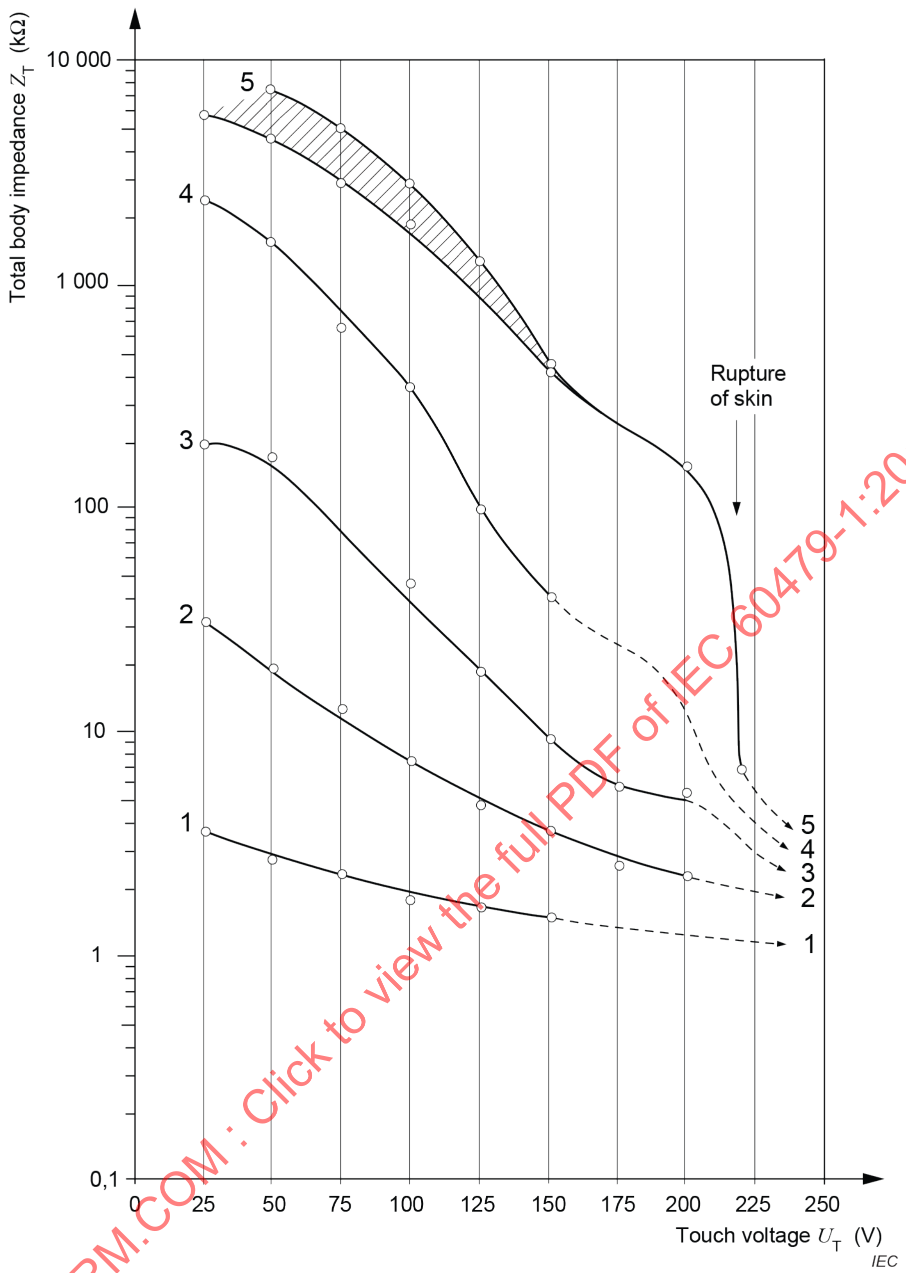
Key

1 dry conditions (Table 1)

2 water-wet conditions (Table 2)

3 saltwater-wet conditions (Table 3)

Figure 4 – Total body impedance Z_T (50 %) for a current path hand to hand, for large surface areas of contact in dry, water-wet and saltwater-wet conditions for a percentile rank of 50 % of the population for touch voltages U_T = 25 V to 700 V, AC 50/60 Hz



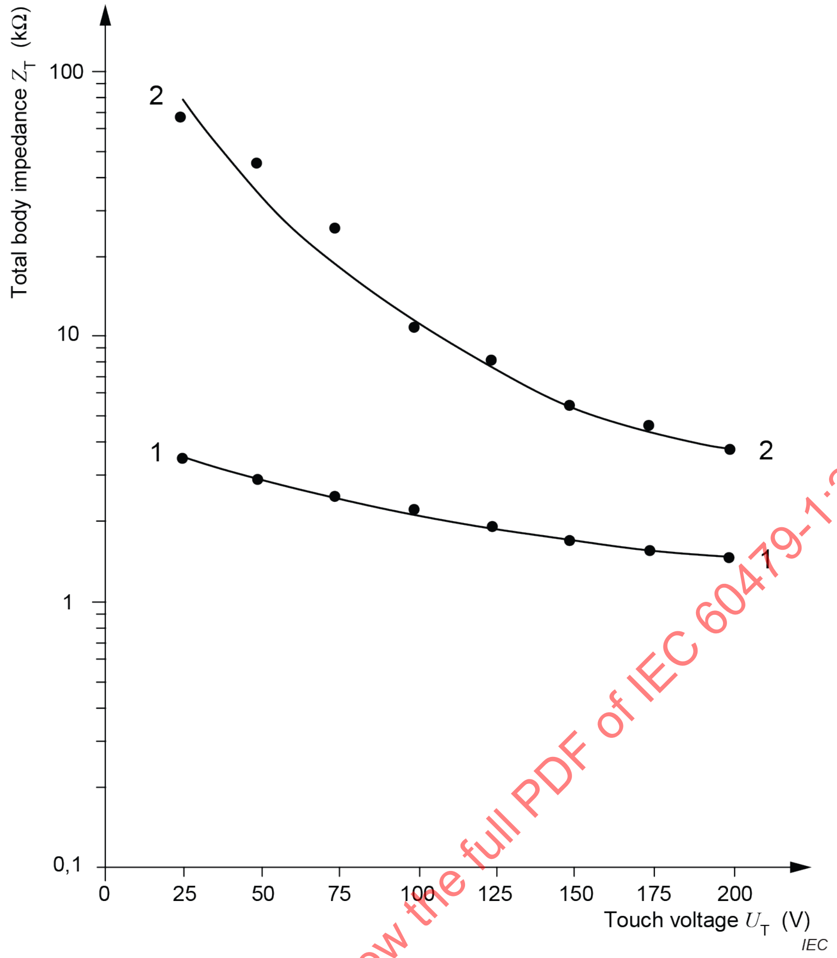
Key

1	Surface area of contact	8 200 mm^2
2	Surface area of contact	1 250 mm^2
3	Surface area of contact	100 mm^2
4	Surface area of contact	10 mm^2
5	Surface area of contact	1 mm^2

(Breakdown of the skin at 220 V)

NOTE For further details, see Annex D.

Figure 5 – Dependence of the total impedance Z_T of one living person on the surface area of contact in dry conditions and at touch voltage (50 Hz)

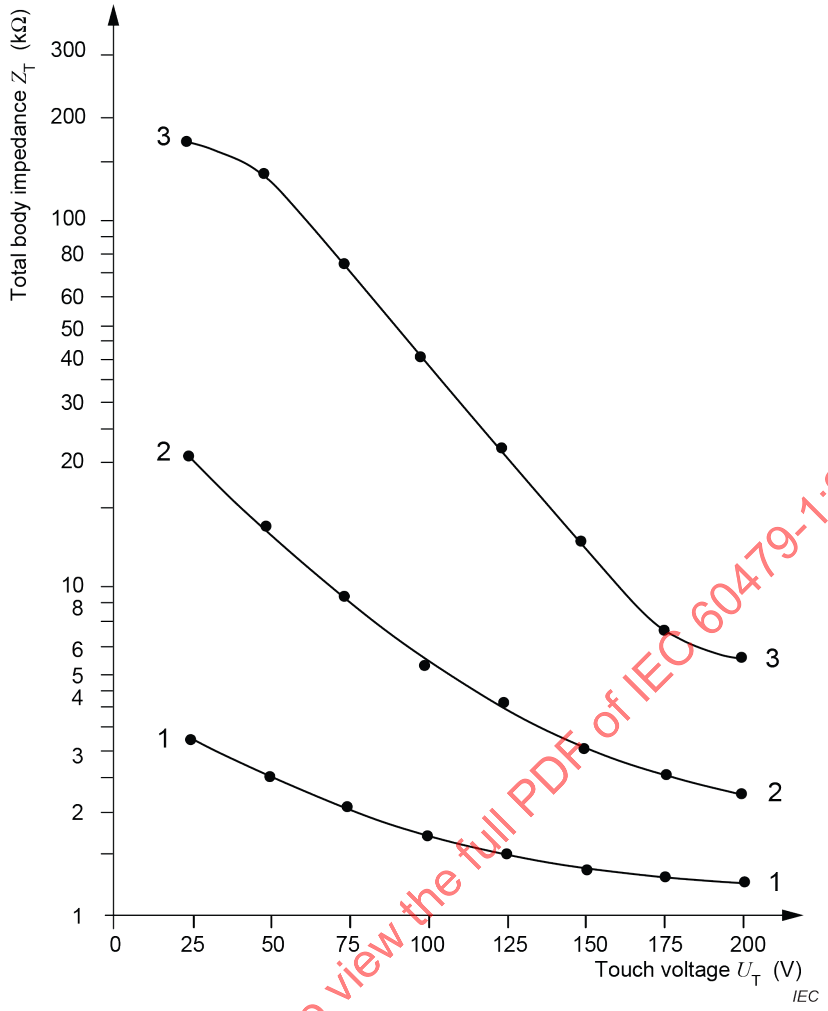


Key

1 large surface areas of contact (approximately 8 000 mm^2), current path hand to hand

2 surface areas of fingertips (approximately 250 mm^2), current path from the tips of the right to left forefinger

Figure 6 – Dependence of the total body impedance Z_T on the touch voltage U_T for a current path from the tips of the right to the left forefinger compared with large surface areas of contact from the right to the left hand in dry conditions measured on one living person, touch voltage range U_T = 25 V to 200 V, AC 50 Hz, duration of current flow max. 25 ms



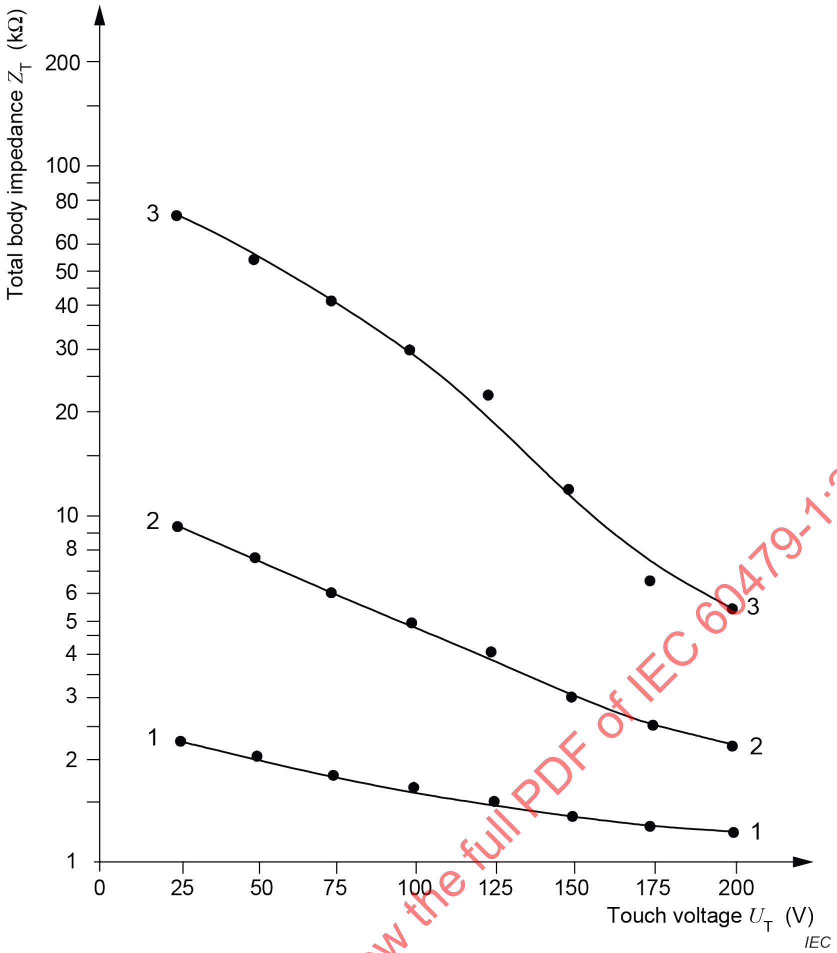
Key

1 large surface areas of contact, electrodes type A (order of magnitude 10 000 mm^2), according to Table 1

2 middle sized surface areas of contact, electrodes type B (order of magnitude 1 000 mm^2), according to Table 5

3 small surface areas of contact, electrodes type C (order of magnitude 100 mm^2), according to Table 8

Figure 7 – Dependence of the total body impedance Z_T for the 50th percentile rank of a population of living human beings for large, medium and small surface areas of contact (order of magnitude 10 000 mm^2, 1 000 mm^2 and 100 mm^2 respectively) in dry conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz



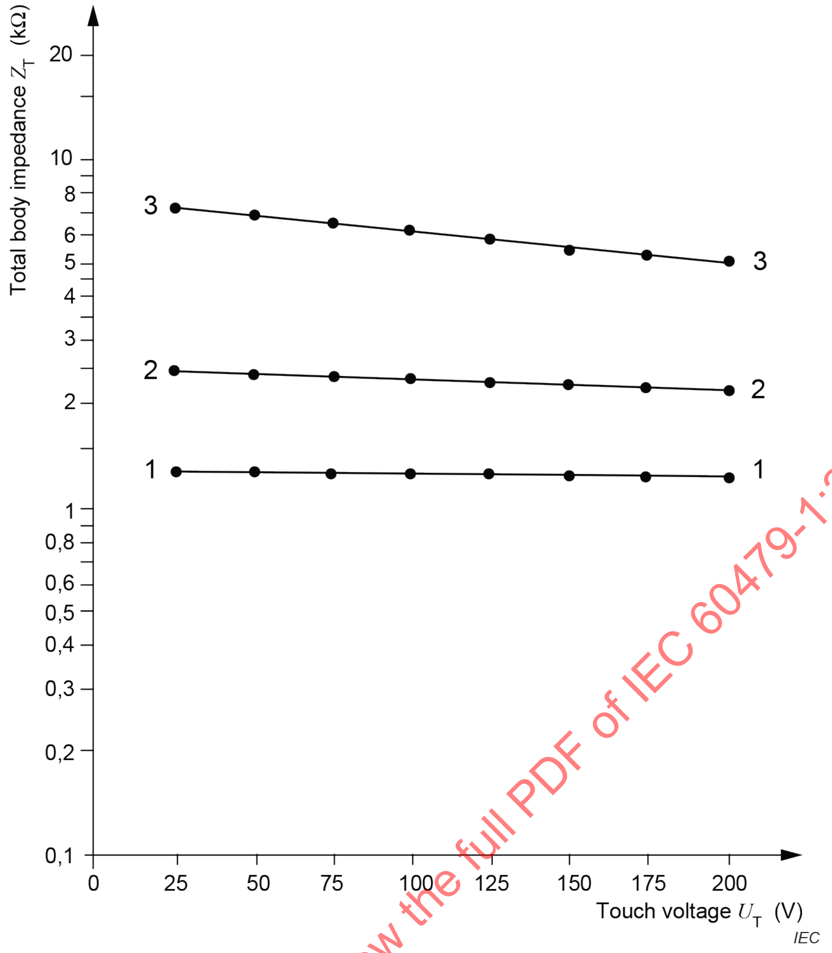
Key

1 large surface areas of contact, electrodes type A (order of magnitude 10 000 mm^2), according to Table 2

2 middle sized surface areas of contact, electrodes type B (order of magnitude 1 000 mm^2), according to Table 6

3 small surface areas of contact, electrodes type C (order of magnitude 100 mm^2), according to Table 9

Figure 8 – Dependence of the total body impedance Z_T for the 50th percentile rank of a population of living human beings for large, medium and small surface areas of contact (order of magnitude 10 000 mm^2, 1 000 mm^2 and 100 mm^2 respectively) in water-wet conditions at touch voltages U_T = 25 V to 200 V, AC 50/60 Hz



Key

1 large surface areas of contact, electrodes type A (order of magnitude 10 000 mm^2), according to Table 3

2 middle sized surface areas of contact, electrodes type B (order of magnitude 1 000 mm^2), according to Table 7

3 small surface areas of contact, electrodes type C (order of magnitude 100 mm^2), according to Table 10

Figure 9 – Dependence of the total body impedance Z_T for the 50th percentile rank of a population of living human beings for large, medium and small surface areas of contact (order of magnitude 10 000 mm^2, 1 000 mm^2 and 100 mm^2 respectively) in saltwater-wet conditions at touch voltages U_T = 25 V to 200 V, AC 50/60 Hz

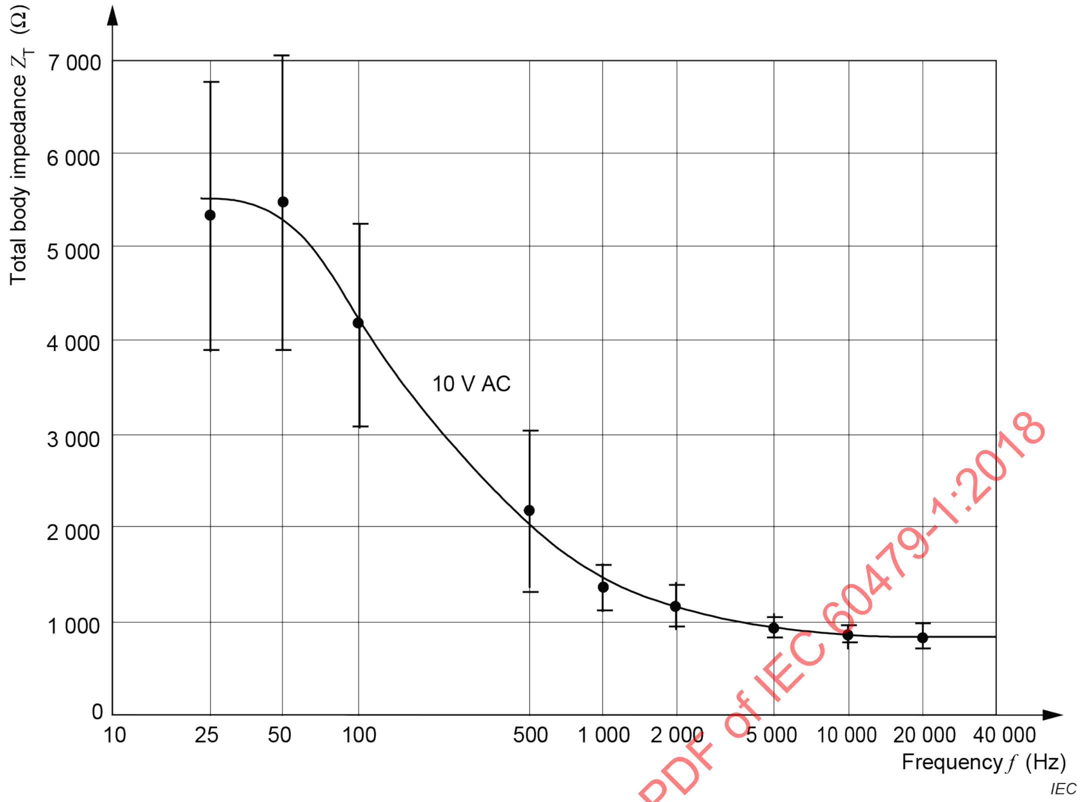


Figure 10 – Values for the total body impedance Z_T measured on 10 living human beings with a current path hand to hand and large surface areas of contact in dry conditions at a touch voltage of 10 V and frequencies from 25 Hz to 20 kHz

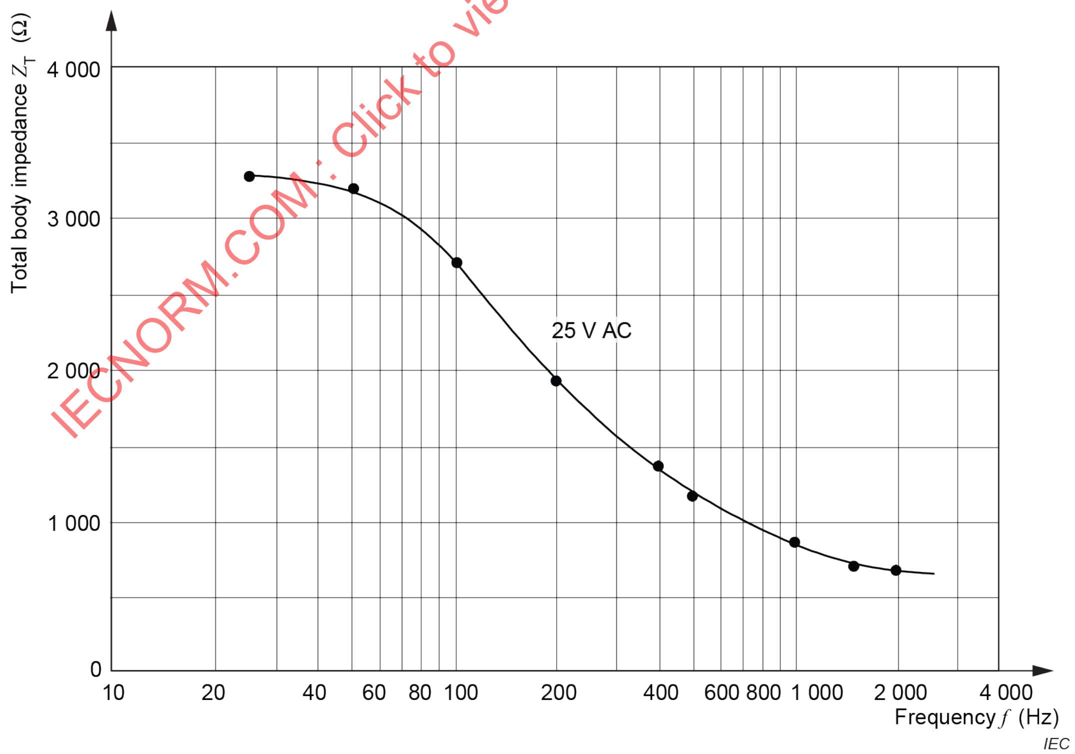


Figure 11 – Values for the total body impedance Z_T measured on one living human being with a current path hand to hand and large surface areas of contact in dry conditions at a touch voltage of 25 V and frequencies from 25 Hz to 2 kHz

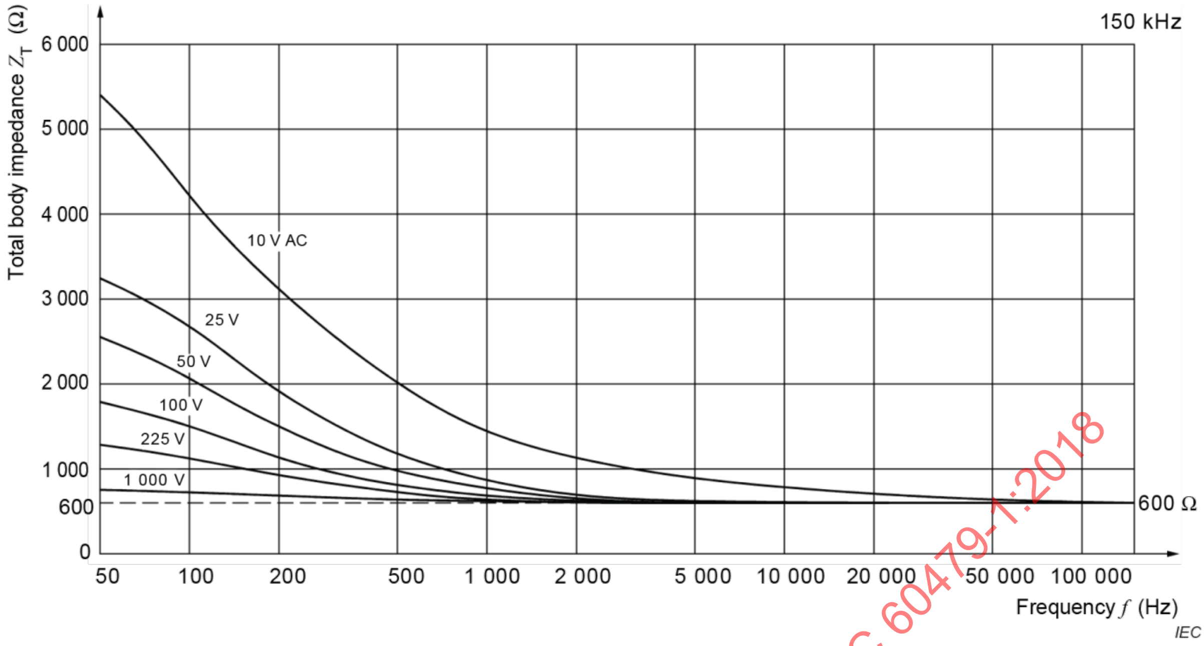
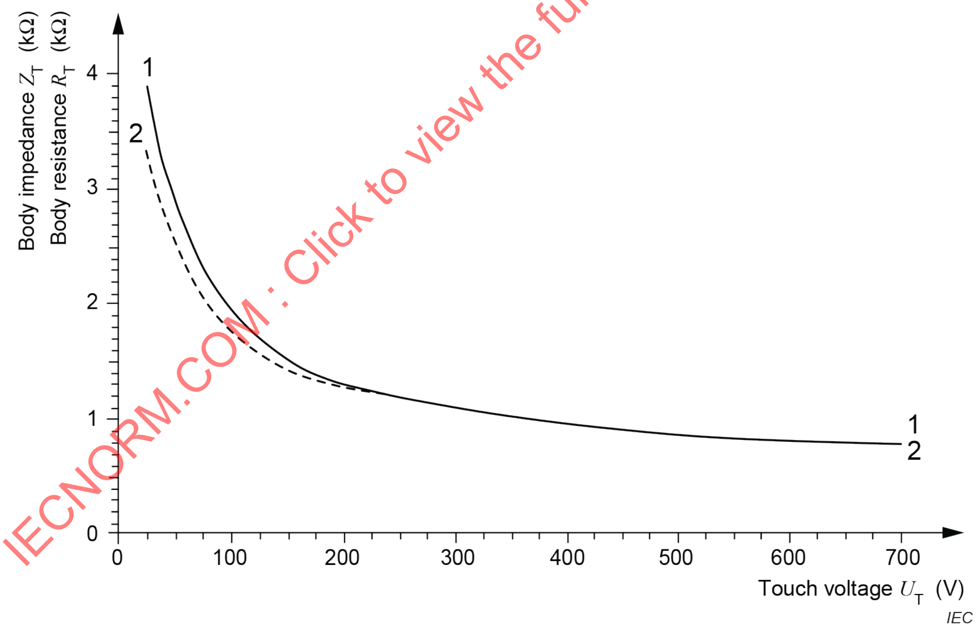


Figure 12 – Frequency dependence of the total body impedance Z_T of a population for a percentile rank of 50 % for touch voltages from 10 V to 1 000 V and a frequency range from 50 Hz to 150 kHz for a current path hand to hand or hand to foot, large surface areas of contact in dry conditions

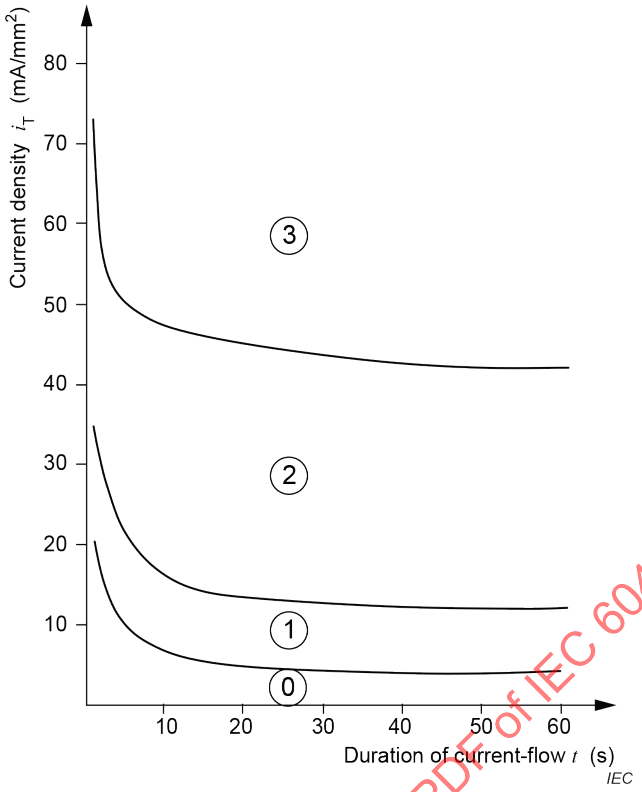


Key

1 body resistance R_T for DC

2 body impedance Z_T for AC 50 Hz

Figure 13 – Statistical value of total body impedances Z_T and body resistances R_T for a percentile rank of 50 % of a population of living human beings for the current path hand to hand, large surface areas of contact, dry conditions, for touch voltages up to 700 V, for AC 50/60 Hz and DC



Key

Zone 3 = carbonization of skin

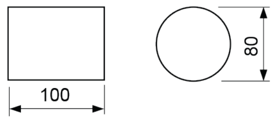
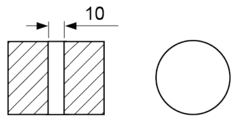
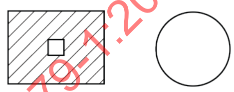
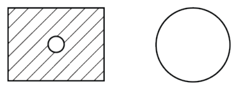
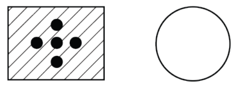
Zone 2 = current marks

Zone 1 = reddening of skin

Zone 0 = no effects

NOTE For a detailed description of zones, see 5.7.

Figure 14 – Dependence of the alteration of human skin condition on current density i_T and duration of current flow

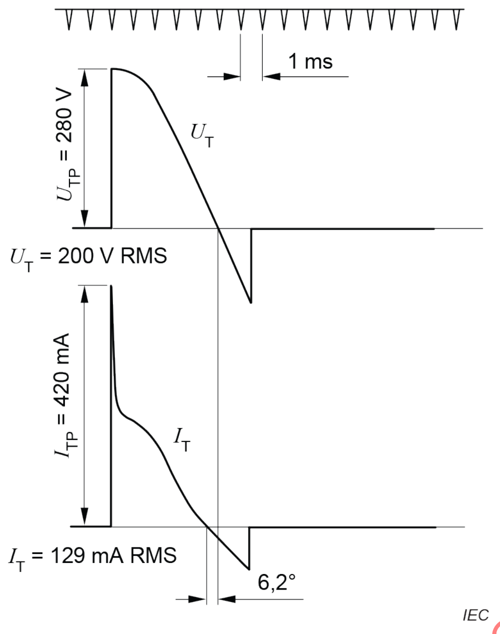
Electrodes type	**Shape of contact area**	**Contact area size effective (mm^2)** **Order of magnitude (mm^2)**	**Drawings** mm
A	Brass cylinder	Large 8 200 10 000	
B	Form of a ring by appropriate covering with insulating tape	Medium 1 250 1 000	
C	Square formed by appropriate covering with insulated tape	Small 100 100	
D	Cylinder of insulating material with circular electrode	10	
E	Cylinder of insulating material with circular electrodes [a, b]	1	

[a] For this type, four further circular electrodes of 1 mm^2 area were used situated crosswise at a distance of 30 mm from the electrode at the centre of the surface of the cylinder in order to measure the deviations for these points inside the palm of the hand.

[b] The results of the measurements with this type of electrodes showed little reproducibility.

IEC

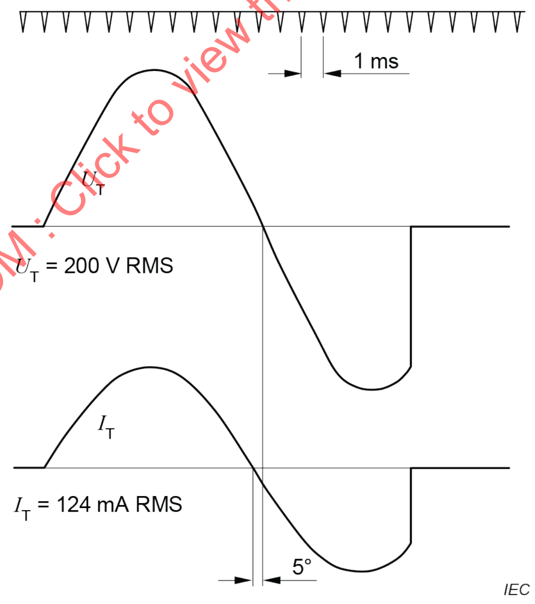
Figure 15 – Electrodes used for the measurement of the dependence of the impedance of the human body Z_T on the surface area of contact



Key

U_T = 200 V AC (RMS value), duration of current flow 6,5 ms, I_T (RMS) = 129 mA, peak value of touch current I_{TP} = 420 mA, total body impedance Z_T = 1 550 Ω, initial body resistance R_0 = 666 Ω, strong and painful sensation and involuntary muscular reaction in arms, shoulders and legs. Though the current path was hand to hand, the body was lifted up, which means that the muscles of the legs have been activated.

a) Contact made at the peak of touch voltage

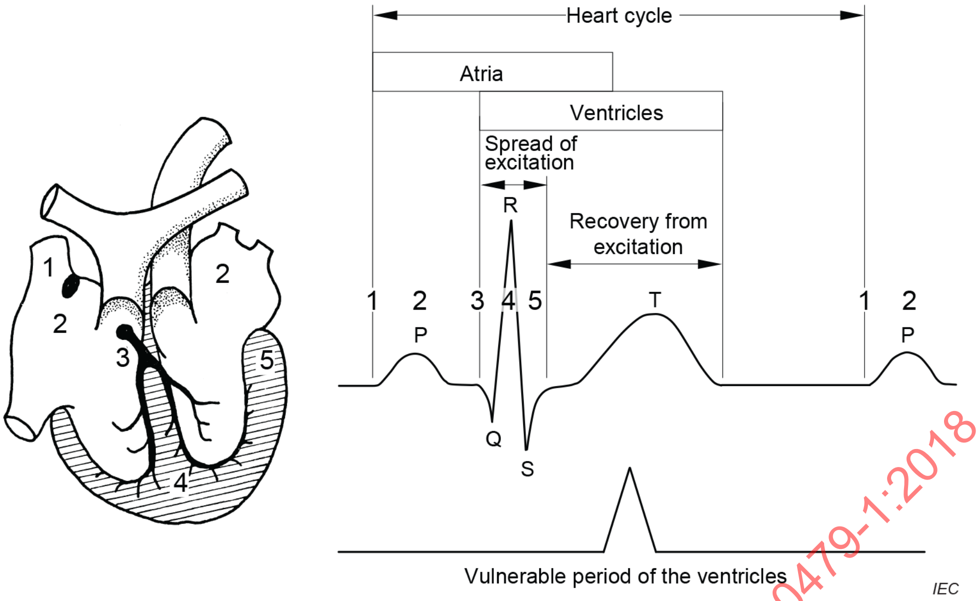


Key

U_T = 200 V AC (RMS value), duration of current flow 16,5 ms, I_T (RMS) = 124 mA, no spike in the current oscillogram, total body impedance Z_T = 1 613 Ω, physiological effects as mentioned under a).

b) contact made at zero crossing of touch voltage

Figure 16 – Oscillograms of touch voltages U_T and touch currents I_T for AC, current path hand to hand, large surface areas of contact in dry conditions taken from measurements



Key

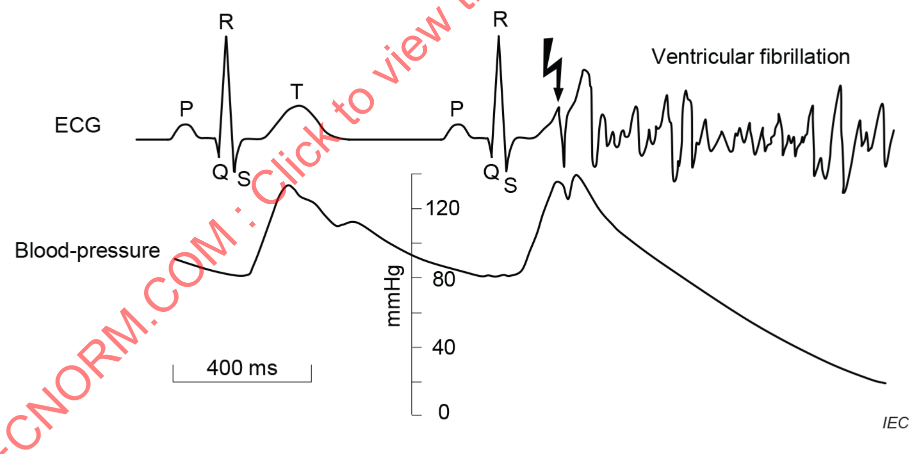
P interval of atrial depolarization

QRS interval of ventricular depolarization

T interval of ventricular repolarization

NOTE The numbers designate the subsequent stages of propagation of the excitation.

Figure 17 – Occurrence of the vulnerable period of ventricles during the cardiac cycle



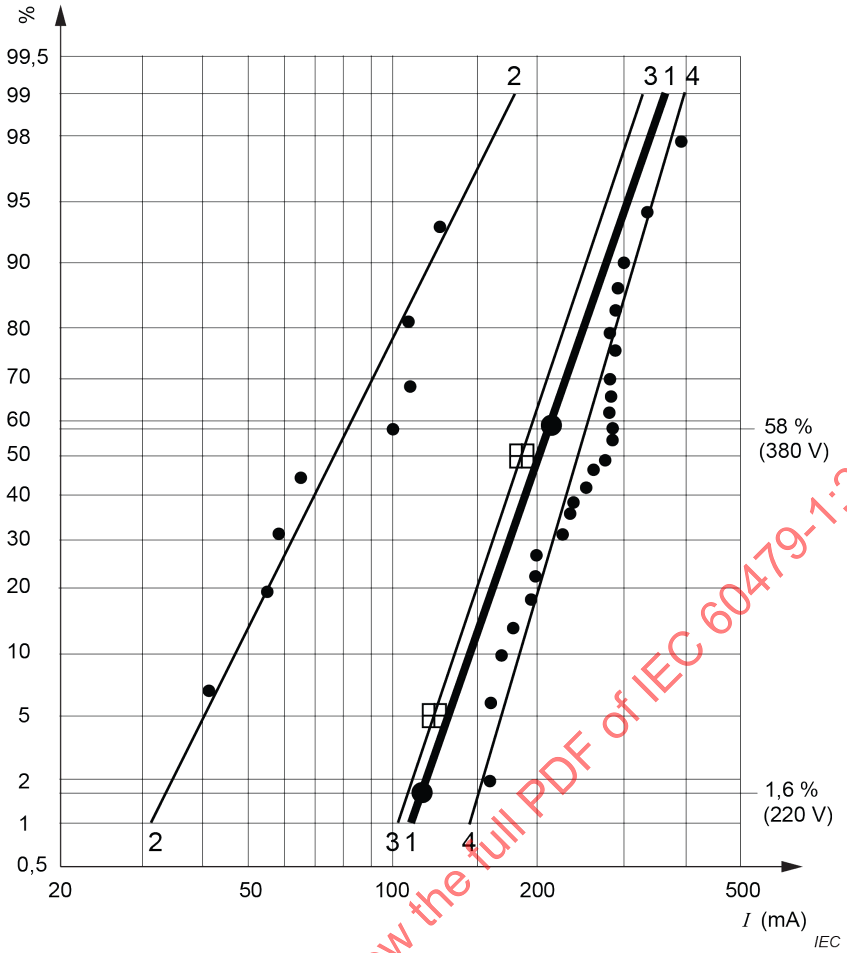
Key

P interval of atrial depolarization

QRS interval of ventricular depolarization

T interval of ventricular repolarization

Figure 18 – Triggering of ventricular fibrillation in the vulnerable period – Effects on electro-cardiogram (ECG) and blood pressure



Key

1 fibrillation data for persons calculated from statistics of accidents (U_T = 220 V, 1,6 %, U_T = 380 V, 58 %)

2 fibrillation data for dogs, duration of current flow 5 s

3 fibrillation data for pigs, duration of current flow t > 1,5 x heart-period

4 fibrillation data for sheep, duration of current flow 3 s

⊙ calculated values based on statistics of accidents (U_T = 220 V, 1.6 % and U_T = 380 V, 58 %, I_T = 110 mA and 220 mA respectively) [a]

⊞ statistical values of measurements with pigs (I (5 %) = 120 mA, I (50 %) = 180 mA)

[a] Values corrected with the heart-current factor F = 0,4.

Figure 19 – Fibrillation data for dogs, pigs and sheep from experiments and for persons calculated from statistics of electrical accidents with transversal direction of current flow hand to hand and touch voltages U_T = 220 V and 380 V AC with body impedances Z_T (5 %)

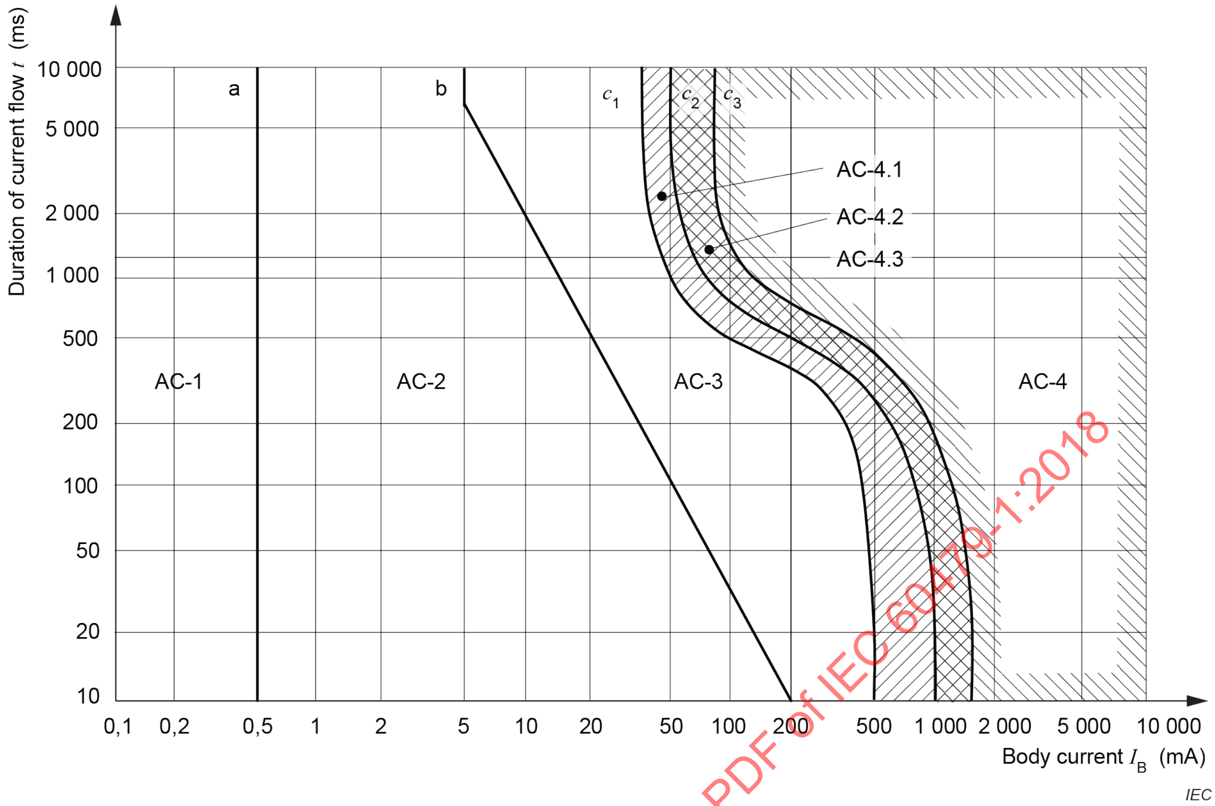
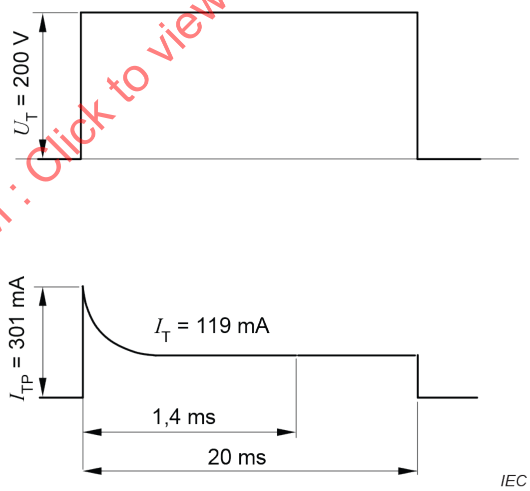


Figure 20 – Conventional time/current zones of effects of AC currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet (see Table 11)



Key

U_T = 200 V DC, duration of current flow 20 ms, touch current I_T = 119 mA, peak value of touch current I_{TP} = 301 mA, total body resistance R_T = 1 681 Ω, initial body resistance R_0 = 664 Ω, strong, burning sensation and involuntary jerk-like muscular reaction in arms and shoulders.

Figure 21 – Oscillogram of touch voltages U_T and touch current I_T for DC, current path hand to hand, large surface areas of contact in dry conditions

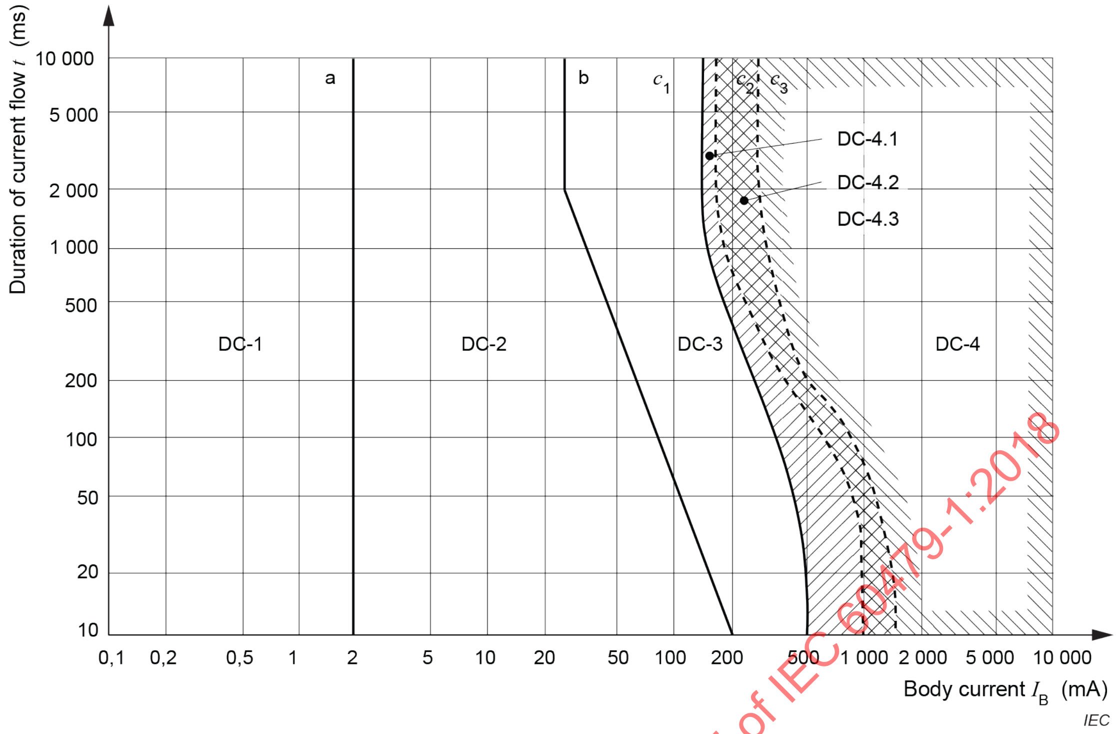


Figure 22 – Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path (see Table 13)

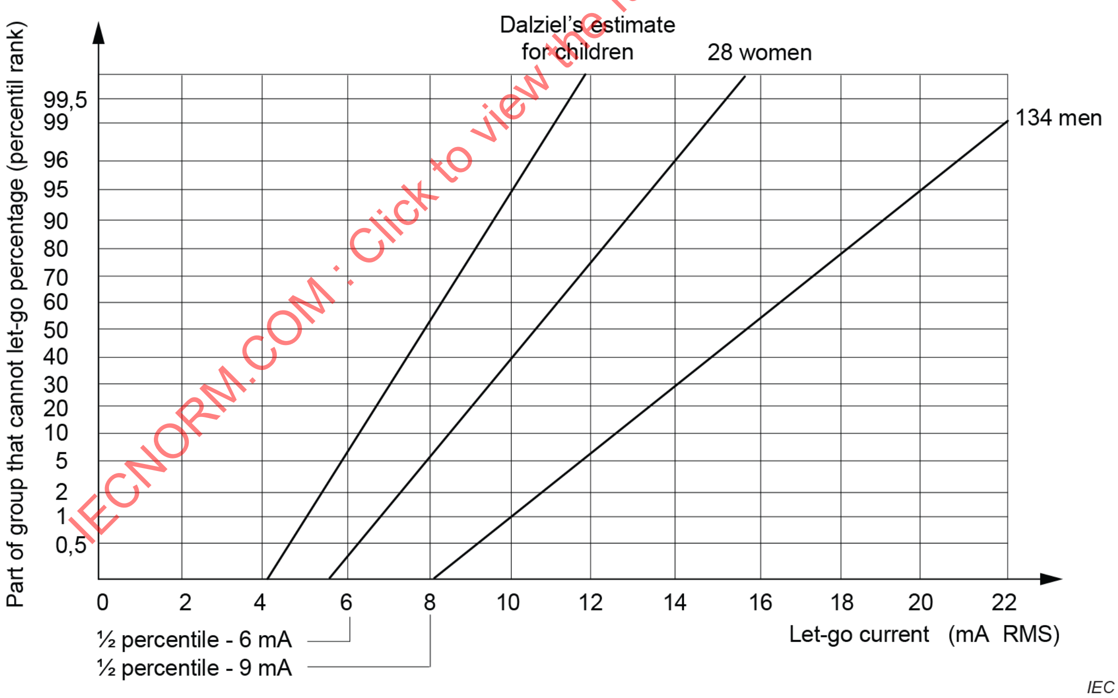


Figure 23 – Let-go currents for 60 Hz sinusoidal current

6.8 Effects of anodic versus cathodic DC currents

An electrode is an interface to another medium where charged particles are interchanged.

Charged particles are to be differentiated, an anion is a negatively charged particle and a cation is a positively charged particle.

An anode is an electrode which is at positive potential with respect to a lower potential reference, such as the positive terminal of a source. Anodic current is current that flows away from an anode.

A cathode is an electrode which is at negative potential with respect to a higher potential reference, such as the negative terminal of a source. Cathodic current is current that flows to a cathode.

To understand that current flow direction plays a role with DC pulses, first a simple explanatory model (Figure 24) is introduced.

The current in this context is conventional current as opposed to electron flow. Current is applied on a body part with an excitable structure (e.g. a nerve) inside via one small electrode 1 (called different electrode) and a large area electrode 2 (called indifferent electrode).

Current distribution is asymmetric with a large current density in area A and a low current density in area B. See Figure 24.

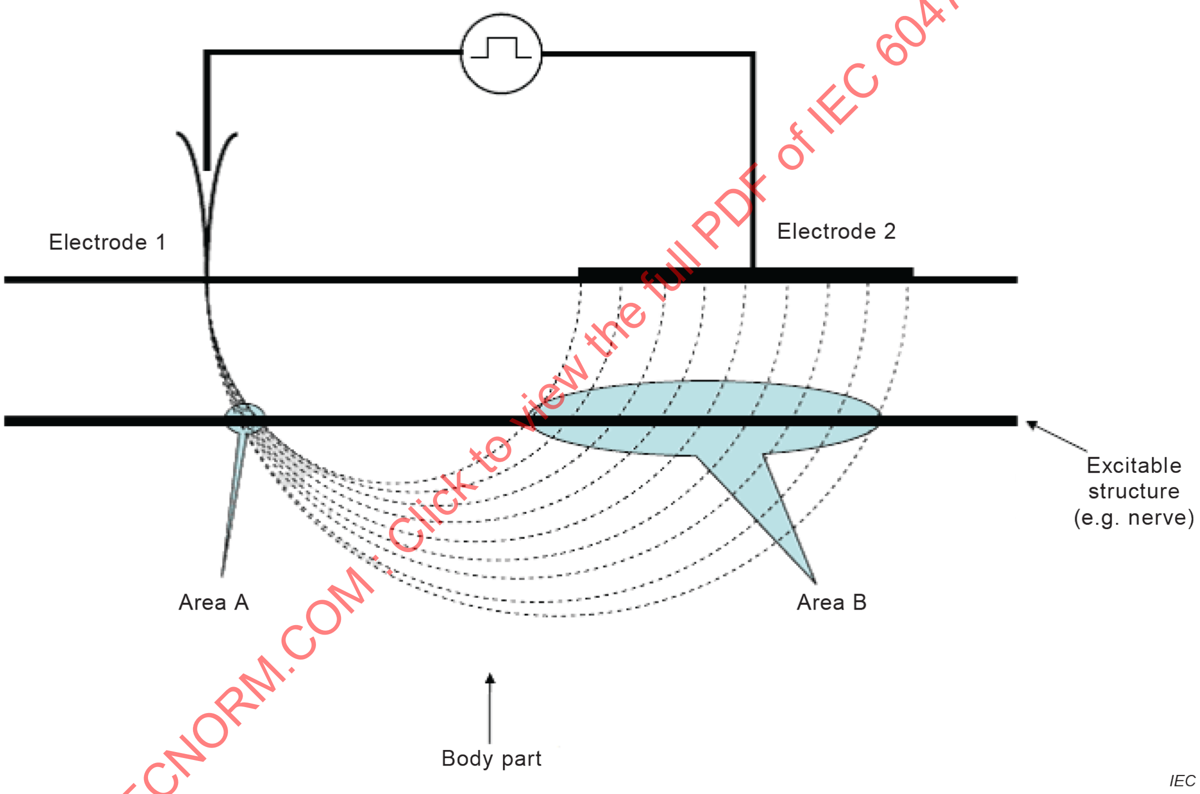


Figure 24 – Effects of anodic versus cathodic DC currents

Now various DC pulses show different behaviour. Responses of the excitable structure arises in the following order with respect to increasing excitation current depending on polarity and on either closing or opening the current flow of the circuit:

- cathodal make reaction (CMR);
- anodal make reaction (AMR);
- anodal break reaction (ABR);
- cathodal break reaction (CBR).

This is called the “law of polar excitation”.

This behaviour can be explained as follows.

The outside of the membrane of the excitable structure becomes more negative in area A when electrode 1 is the cathode. This results in that the membrane is depolarized because the internal potential of the cell is also negative: the cell fires, is excited from area A at closing of the current circuit, resulting in a CMR.

If the polarity is reversed (electrode 1 is now anode) then this same response is again arising from the cathode, but in this case it has its origin in area B with a lower current density, and is called an AMR because the reference is always the small different electrode. The threshold is higher than for a CMR. This sequence can be reversed (so called anodal dip) for short pulses of about 180 ms due to a transient Ca^{2+} ion current.

If the current is flowing after the closure and then opened, an opening response can occur.

The lower threshold for that kind of response occurs again from area A in the anodal case, the reason for the opening reaction is that the channels responsible are depolarized again because they were "clamped" before, during the persisted current flow, resulting in an ABR.

The CBR with the highest threshold of all has then its origin in area B.

In principle this behaviour of excitable cells to DC pulses always occurs if the current distribution is asymmetric and the effect is more or less prominent depending on the difference in size and current flow between the different and indifferent electrode. At least for pulses delivered within 1 cm of the cardiac surface, cathodal DC pulse trains are slightly safer as they require 25 % more current to induce ventricular fibrillation than anodal pulse trains [32][1].

Also, in principle, this behaviour is present for different types of cells, not only for nerve cells but equally for heart cells. The effect of the polarity is valid for perception and as well as for fibrillation (see Figure 25).

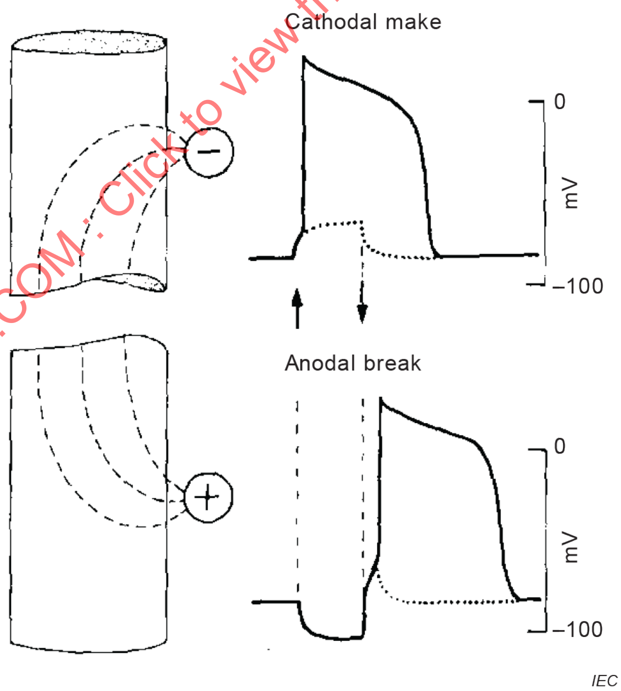


Figure 25 – Pulsed DC stimulation of single heart cells

The two types of pulsed DC stimulation appear due to changes in membrane potential during cathodic make and during cathodic break. Action potentials are elicited when the membrane potential attains the threshold.

1 Figures in square brackets refer to the bibliography.

Annex A
(normative)

Measurements of the total body impedances Z_T made on living human beings and on corpses and statistical analysis of the results

In order to obtain realistic values for total body impedances Z_T of living human beings, the following procedure was applied:

1) The measurements made on living human beings used a current path hand to hand with electrodes shown in Figure 15.
2) Measurement of the total body impedance have been made on 100 living persons at 25 V AC 50 Hz with large surface areas of contact (electrodes type A in Figure 15) in dry conditions. The measurements were made 0,1 s after applying the voltage. The values for total body impedances for a percentile rank of 5 %, 50 % and 95 % were determined with the results shown in Table A.1.

Table A.1 – Total body impedances Z_T, electrodes type A for dry conditions and deviation factors F_D (5 % and 95 %)

Condition	Total body impedances Z_T (Ω) / deviation factors F_D		
	5 %	50 %	95 %
Dry	1 750 / 0,54	3 250	6 100 / 1,88

3) Measurement of the total body impedance have been made on 10 living persons with medium and small surface areas of contact (electrodes type B and C in Figure 15) in dry, water-wet and saltwater-wet conditions, duration of current flow max. 25 ms. The results are shown in Tables A.2 and A.3.
   a) Electrodes type B (order of magnitude 1 000 mm^2)

Table A.2 – Total body impedances Z_T, electrodes type B for dry, water-wet and saltwater-wet conditions and deviation factors F_D (5 % and 95 %)

Condition	Total body impedances Z_T (Ω) / deviation factors F_D		
	5 %	50 %	95 %
Dry	12 900 / 0,63	20 600	32 800 / 1,59
Water-wet	5 500 / 0,59	9 350	15 900 / 1,70
Saltwater-wet	1 850 / 0,76	2 425	3 175 / 1,31

   b) Electrodes type C (order of magnitude 100 mm^2)

Table A.3 – Total body impedances Z_T for dry, water-wet and saltwater-wet conditions and deviation factors F_D (5 % and 95 %)

Condition	Total body impedances Z_T (Ω) / deviation factors F_D		
	5 %	50 %	95 %
Dry	80 400 / 0,48	169 000	355 500 / 2,10
Water-wet	39 700 / 0,54	73 400	135 600 / 1,85
Saltwater-wet	5 400 / 0,74	7 300	9 875 / 1,35

In a first approximation for the calculation of Z_T (5 % and 95 %) from the values of Z_T (50 %) for dry and water-wet conditions at U_T = 25 V, the deviation factors

$$F_D\ (5\ \%) = 0{,}54 \text{ and } F_D\ (95\ \%) = 1{,}88$$

and for saltwater-wet condition

$$F_D\ (5\ \%) = 0{,}74 \text{ and } F_D\ (95\ \%) = 1{,}35$$

were chosen. They are assumed to be independent of the surface area of contact.

4) The total body impedance Z_T of one living person was measured under the conditions of item 1), 2) and 3) above with touch voltages up to 150 V and, in addition, with shock durations up to 0,03 s for touch voltages up to 200 V.

   The following conditions for the current path and durations of current flow have been used:

   Test series A: Effective contact area 8 250 mm^2, electrodes grasped with both hands, duration of current flow 0,1 s (Figure 15, electrodes type A).

   Test series B: Effective contact area 1 250 mm^2, electrodes grasped with both hands, duration of current flow several seconds up to 75 V and 0,1 s above 75 V (Figure 15, electrodes type B).

   Test series C: Effective contact area 100 mm^2, electrodes pressed against the middle of the palms, duration of current flow several seconds up to 75 V and 0,1 s above 75 V (Figure 15, electrodes type C).

   Test series D: Effective contact area 10 mm^2, electrodes pressed against the middle of the palms, duration of current flow several seconds up to 100 V and 0,1 s up to 0,3 s above 100 V (Figure 15, electrodes type D).

   Test series E: Effective contact area 1 mm^2, electrodes pressed against the middle of the palms, duration of current flow several seconds up to 150 V and 0,1 s up to 0,2 s above 150 V (at 220 V breakdown of the skin was observed) (Figure 15, electrodes type E).

5) The total body impedance was measured for a touch voltage range of 25 V to 200 V, AC 50 Hz between the tips of the right and left forefingers (surface area of contact approximately 250 mm^2). The measurements were made 20 ms after applying the voltage. The voltage was applied at zero crossing of the touch voltage.

   The results are shown in Figure 6.

6) Measurements were made by Freiberger [1] on a large number of corpses for current paths hand to hand and hand to foot with large electrodes (approximately 9 000 mm^2) for touch voltages of 25 V to 5 000 V in dry conditions. The values for the total body impedances for a percentile rank of 5 %, 50 % and 95 % were determined.

   The measurements were made 3 s after applying the voltage.

7) The total body impedances for large surface areas of contact measured on corpses (item 6) above) which for touch voltages up to 220 V showed excessively high skin impedances were modified by adjusting the curves to the values measured on living persons.

   For this adjustment, the change of body impedances caused by the change of temperature of corpses to 37 °C of living persons was taken into account by a temperature reduction factor F_T = 0,7.

8) For medium and small surface areas of contact the total body impedances Z_T (50 %) for a 50 % percentile rank of a population of living human beings could be established with the values found by the measurements described under items 1) to 4) for dry, water-wet and saltwater-wet conditions for touch voltages U_T = 25 V to 200 V.

9) For large, medium and small surface areas of contact in dry, water-wet and saltwater-wet conditions all values for 5 % and 95 % percentile rank of a population of living human beings could be calculated by applying the deviation factors F_D (5 %) and F_D (95 %) to the values of Z_T (50 %).

These deviation factors were calculated for touch voltages up to 400 V from the values F_D (5 %) = 0,54 and F_D (95 %) = 1,88 at U_T = 25 V for dry and water-wet conditions changing with the impedance of the skin up to 400 V to the values F_D (5 %) = 0,74 and F_D (95 %) = 1,35 for saltwater-wet conditions due to the fact that for saltwater-wet conditions the impedance of the skin is assumed as negligible. These values of F_D are shown in Table A.4.

Table A.4 – Deviation factors F_D (5 %) and F_D (95 %) for dry and water-wet conditions in the touch voltage range U_T = 25 V up to 400 V for large, medium and small surface areas of contact

U_T V	25	50	75	100	125	150	175	200	300	400
F_D (5 %)	0,54	0,55	0,565	0,575	0,585	0,6	0,615	0,625	0,68	0,74
F_D (95 %)	1,88	1,84	1,8	1,76	1,72	1,685	1,65	1,6	1,48	1,35

For saltwater-wet conditions the deviation factors are independent of the touch voltage, F_D (5 %) = 0,74 and F_D (95 %) = 1,35.

By this method the total body impedances Z_T have been calculated for dry, water-wet and saltwater-wet conditions for large, medium and small surface areas of contact for the 5th, 50th and 95th percentile rank of a population of living human beings shown in Tables 1 to 3 and 4 to 9.

Annex B
(normative)

Influence of frequency on the total body impedance (Z_T)

In order to obtain realistic values for the influence of frequency on the total impedance Z_T of living human beings, the following procedure was applied:

1) Measurements were made on 10 living human beings at a touch voltage of 10 V for frequencies from 25 Hz to 20 kHz with a current path hand to hand with large cylinder electrodes (approximately 8 000 mm^2) in dry conditions.

   The values for the total body impedances for a percentile rank of 5 %, 50 % and 95 % were determined by statistical methods.

2) Due to strong muscular effects, measurements were made only on one living human being at a touch voltage of 25 V for frequencies from 25 Hz to 2 kHz under the conditions described in item 1) above.

   The measurements of item 1) and item 2) were made 0,05 s after applying the voltage.

   The results of these measurements are shown in Figures 10 and 11.

3) For a percentile rank of 50 %, Figure 10 for a touch voltage of 10 V, and the values of Table 1 for 50 Hz and touch voltages from 25 V to 1000 V were used for Figure 12. Figure 12 shows the dependence of the total body impedance on the frequency for a range from 50 Hz to 2 kHz for a percentile rank of 50 % of a population for touch voltages from 10 V to 1 000 V AC with a straight line between the asymptotic values of 750 Ω at 50 Hz and 600 Ω at 2 kHz.

4) Values for total body impedance above 2 000 Hz have been estimated by extrapolation from existing data and are shown in Figure 12.

The curves for touch voltages of 50 V to 1 000 V (dashed lines in Figure 12) have been drawn in analogy to the curves for 10 V and 25 V which are based on the measurements described under item 1) and 2), above.

Annex C
(normative)

Total body resistance (R_T) for direct current

In order to obtain realistic values for the total body resistance R_T of living human beings, the following procedure was applied:

1) Measurements were made on 50 living persons at a touch voltage of 25 V pure DC with a current path hand to hand with large cylinder electrodes (approximately 8 000 mm^2) in dry conditions.

   The values for the total body resistance R_T for a percentile rank of 5 %, 50 % and 95 % were determined by statistical methods.

2) The values for the total body impedances for AC 50 Hz, at touch voltages above 200 V according to Table 1 were used for the total body resistance R_T for direct current for touch voltages between 200 V and 1 000 V DC and the asymptotic values.

   The values of the total body resistance R_T for touch voltages between 25 V and 200 V have been derived from Figure 13 drawn similar as for AC 50 Hz.

   The values for the total body resistance R_T for direct current determined by the method described above are given in Table 10.

NOTE Above 200 V, the differences between the skin impedance for AC 50 Hz and the skin resistance for direct current are assumed to be negligible.

Annex D
(informative)

Examples of calculations of Z_T

Calculations of touch currents I_T are important to evaluate measures of protection against electric shock and for the investigation of electrical accidents.

The touch current I_T is calculated by:

$$I_T = \frac{U_T}{Z_T}$$

where

U_T is the touch voltage;

Z_T is the total impedance of the human body for given current path, surface area and condition of contact.

The following calculations are based on the relevant tables of this document and are carried out for the 50th percentile rank (50 % of the population). The 50th percentile rank was taken because its values are statistically most reliable.

The calculations are carried out for four examples:

1) Touch voltages 100 V and 200 V, dry surface areas of contact, current path hands to feet, surface areas of contact for hands medium (order of magnitude 1 000 mm², Table 4), for feet large (Table 1).
2) Touch voltages 100 V and 200 V, dry surface areas of contact, current path hand-hand, surface areas of contact small (order of magnitude 100 mm², Table 7).
3) Touch voltage 25 V, saltwater-wet surface areas of contact, current path both hands to the trunk of the body, surface areas of contact: large for hands (order of magnitude 10 000 mm², Table 3) and very large for the trunk of the body (skin impedance negligible). This current path simulates a person sitting on the ground and holding a faulty equipment of Class III (SELV) with both hands.

   In the calculations the values are rounded to 5 Ω.
4) At a touch voltage of at least 1 000 V, the area of contact, condition of contact and nature of voltage make no material difference to the body resistance values. The current path chosen simulates a person sitting on the ground touching a high voltage conductor with the head.

EXAMPLE 1

Touch voltages 100 V and 200 V, AC 50/60 Hz, current path hands to feet, dry conditions, surface areas of contact for hands medium, surface areas of feet large.

The following designations are used:

Z_{TA} (H-H) total body impedance, large surface areas of contact, hand to hand

Z_{TA} (H-F) total body impedance, large surface areas of contact, hand to foot

Z_{TA} (H-T) total body impedance, large surface areas of contact, hand to trunk

$$Z_{TA}\text{ (H-T)} = Z_{TA}\text{ (H-H)}/2$$

Z_{TA} (T-F) total body impedance, large surface areas of contact, trunk to foot

$$Z_{TA}\text{ (T-F)} = Z_{TA}\text{ (H-F)} - Z_{TA}\text{ (H-T)}$$

Z_{TB} (H-H) total body impedance, middle sized surface areas of contact, hand to hand

The Z_T values Z_{TA} (H-H) for large surface areas of contact are given in Table 1, the values for medium surface areas of contact Z_{TB} (H-H) are given in Table 4.

The calculation for the 50th percentile rank is then carried out as follows:

Z_{TA} (H-H) = 1 725 Ω (100 V) and 1 275 Ω (200 V), for the current path hand-foot with the factor 0,8.

NOTE Some measurements suggest a 10 % to 30 % reduction of the hand to hand body impedance in order to calculate the hand to foot body impedance. Taking an average of 20 % gives the factor 0,8.

Z_{TA} (H-F) = 1 380 Ω (100 V) and 1 020 Ω (200 V)

Z_{TA} (H-T) results in Z_{TA} (H-T) = Z_{TA} (H-H)/2

Z_{TA} (H-T) = 860 Ω (100 V) and 635 Ω (200 V)

hence with Z_{TA} (T-F) = Z_{TA} (H-F) – Z_{TA} (H-T),

Z_{TA} (T-F) = 520 Ω (100 V) and 385 Ω (200 V).

For medium surface areas of contact (approximately 1 000 mm^2), from Table 4:

Z_{TB} (H-H) = 5 200 Ω (100 V) and 2 200 Ω (200 V)

hence with Z_{TB} (H-T) = Z_{TB} (H-H)/2

Z_{TB} (H-T) = 2 600 Ω (100 V) and 1 100 Ω (200 V).

The total body impedance Z_T' = Z_{TA} (T-F) + Z_{TB} (H-T)

Z_T' = 3 120 Ω (100 V) and 1 485 Ω (200 V)

and with hands and feet in parallel Z_T = $Z_T'/2$

Z_T = 1 560 Ω (100 V) and 740 Ω (200 V)

leading to the touch currents I_T

I_T = 65 mA (100 V) and 270 mA (200 V).

A summary of the results of the calculations is given in Table D.1.

Table D.1 – 50th percentile values for the total body impedance for a current path hands-feet, medium surface area of contact for hands, large for feet, reduction factor 0,8, dry conditions, touch currents I_T and electrophysiological effects

Touch voltage V	Impedance hand-trunk Z_{TB} (H-T) Ω	Impedance trunk-foot Z_{TA} (T-F) Ω	Impedance hands-feet Z_T Ω	Touch Current I_T mA	Electro-physiological effects for a duration of current flow t = 10 ms to 30 ms
100	2 600	520	1 560	65	Short jerk-like sensation
200	1 100	385	740	270	Heavy electric shock, lifting of the body, cramp in the arms

Attention is drawn to the fact that at U_T = 200 V the touch current I_T is four times as high as for 100 V. If the duration of current flow is longer than approximately 0,2 s, ventricular fibrillation would occur with a high probability.

EXAMPLE 2

Touch voltages 100 V and 200 V, AC 50/60 Hz, current path hand to hand, dry conditions, surface areas of contact small (electrodes type C, Table 7).

The calculation is simple. The total body impedance for small surface areas of contact in dry conditions according to Table 7 is shown with Z_{TC} (H-H) = 40 kΩ for U_T = 100 V and 5,4 kΩ for U_T = 200 V.

This results in touch currents of I_T = 2,5 mA for U_T = 100 V and I_T = 37 mA for U_T = 200 V, the latter value still being under the threshold of ventricular fibrillation. For longer durations of current flow (some seconds) after the breakdown of skin impedances (Z_T approximately 1 000 Ω), I_T would certainly surpass 0,1 A causing a fatal electrical accident.

EXAMPLE 3

Touch voltage 25 V, AC 50/60 Hz, current path both hands in parallel to the trunk of the body, saltwater-wet conditions, surface areas of contact for hands large and for trunk of the body very large (skin impedance negligible). Here also the calculation is simple. The total body impedance Z_T (H-H) is given in Table 3 for the 50th percentile rank as 1 300 Ω.

Hence with Z_{TA} (H-T) = Z_{TA} (H-H)/2 = 650 Ω.

For hands in parallel to the trunk of the body

Z_T = Z_{TA} (H-T)/2 = 325 Ω

resulting in a touch current I_T = 77 mA.

In spite of the use of safety extra low voltage (SELV) a shock with strong involuntary muscular reactions far above the threshold of let-go occurs.

EXAMPLE 4

The asymptotic impedance values associated with a hand to hand path for voltages of 1 000 V and above at the 5 %, 50 % and 95 % population levels are respectively 575 Ω, 775 Ω and 1 050 Ω. At this voltage, the skin impedance is negligible. In order to use Figure 2 to calculate the value of Z_T, the hand to hand results requires a 10 % to 30 % reduction as shown by the Note 1 in the tables. Taking an average value of 20 %, this gives a hand to foot value of 460 Ω, 620 Ω, 840 Ω, respectively.

Applying the factors given in Figure 2, the calculation of the total body impedance Z_T of a person sitting on the ground touching a high voltage conductor with the head is straightforward:

at the 5 % value Z_T = 460 Ω × (0,10 + 0,013) = 52 Ω;

at the 50 % value Z_T = 70 Ω;

at the 95 % value Z_T = 95 Ω.

In this example, the resultant touch current is of the order of tens of amperes and will increase at higher voltages.

Annex E
(informative)

Theories of ventricular fibrillation

Ventricular fibrillation (VF) is a phenomenon which has been better known since the detection of electrical activity of the heart (ECG) [35]. The main mechanism of this abnormal, generally lethal activity of the heart ventricles was found when it was discovered that small volumed circulating exciting waves are responsible for minimal inefficient and only local blood pumping properties, in contrast to the straight, strong and efficient normal excitation and pumping process.

The reason for the unexpected possibility for the transition from normal operation to the initiation of VF lies in the natural inherent inhomogeneity within the electrical repolarization phase of the ventricles. This phase is called the "vulnerable" phase because of the fact that an electrical impulse or direct or alternating current from the outside can elicit VF during this period. VF can also be induced by rapid cardiac capture.

Experimental and theoretical research showed that the processes seem to be more complex than for circular excitation waves only. Also more sophisticated waveforms led to the conclusion that the initiation process of VF, as well as its persistence, has additional components compared to that of a simple re-entry of excitation [36]. These findings led to spiral waves breakup and to single and multiple wavelet hypothesis [37][38].

Moreover, the initiation of VF is increased by preceding ventricular extrasystole (VE) and the more frequently they arise the more dangerous they can be (see IEC 60479-2). The reason for this phenomenon is that every additional VE increases the inhomogeneity during the ventricular repolarization [40][42]. The inner layers of the ventricular wall have per se a longer repolarization time than the outer layers and this difference is increased by a more frequent VE which forms the substrate for fibrillation initiation. This is also true for direct current and explains why fibrillation due to direct current can take place [43].

Termination of VF is called ventricular defibrillation. Defibrillation is presently performed with a biphasic shock. There are three major theories of defibrillation:

- progressive depolarization [44];
- upper limit of vulnerability [45];
- virtual electrode induced re-excitation [46][47].

The role of the first phase is to charge the vast majority of the cardiac cell membranes with a large charge of 3 ms to 10 ms duration. The role of the second phase is to return the cell membrane voltage to zero [48].

Annex F
(informative)

Quantities of upper limit of vulnerability (ULV)and lower limit of vulnerability (LLV)

The heart's threshold of fibrillation for a given waveform is the minimum value of current to which it should be subjected to precipitate ventricular fibrillation. IEC 60479 (all parts) devotes itself to determining this threshold for different waveforms.

It is noted however that "defibrillation" is a therapeutic modality used to treat a heart in fibrillation. This process involves passing a large impulsive current through the fibrillating heart with the intention of halting fibrillation.

The design of a defibrillator is beyond the scope of this document, however the terms ULV and LLV are very commonly met in this context.

There is a band of currents which produce fibrillation in the myocardium if delivered in the vulnerable period (portions of the T-wave). Present literature suggests that strong short pulses delivered outside of the vulnerable period do not induce VF but only cause an extra cardiac contraction. Above this band of currents, the heart is reliably defibrillated by short (3 ms to 10 ms) impulse shocks delivered in the same location in the cardiac cycle. This level is the upper limit of vulnerability (ULV) of the myocardium. It has been shown in multiple studies to be a good predictor of the defibrillation threshold for the myocardium, this parameter being important, for example, in determining the setting for an implantable cardiac defibrillator (ICD) [49].

The lower limit of vulnerability (LLV) is the fibrillation threshold as determined in IEC 60479 (all parts).

Annex G
(informative)

Circuit simulation methods in electric shock evaluation

The use of modelling in evaluation of any situation is valuable since the modelling is substituted for direct measurement of the application of forces which may be harmful or deleterious to the body [50]. Direct electric shock experimentation, whether on humans or animals, has been severely restricted over the last few decades forcing consideration of modelling as a substitute. Such modelling has been used for years, most recently in the evaluation of touch currents according to the frequency filtered effect as are evaluated in many product standards.

An important contribution to experimental data is ongoing in governmental funded experiments with animals.

Based on direct measurements on the heart (and necessary translation to the human) new simulation boundaries will provide input conditions to the whole body situation (e.g. touch models hand to hand, hand to foot). New simulation models based on control circuits levels up the voltage which contacts the human until the given current density (or other appropriate parameters) is reached. This ongoing and recent experimental work is under consideration.

The process of determination of a dangerous current involves determination of the current in the body, including at the myocardium. This is hard to perform experimentally, however it can be modelled using circuit analysis methods which require describing the body and its operation as an equivalent electrical circuit. This discussion is to inform readers of the existence of these models and to provide a reference to further discussions on, and usages of, them.

The body model which is commonly used is shown in this document, consisting of resistance and capacitance representing the combined impedances of the skin. In series with these is a simple resistance representing the body internal resistance.

A voltage is applied between the terminals of the model and the resulting current in the internal body resistance can be considered to approximate the myocardial current.

So, as a first approximation, measuring this current for an applied voltage will model the body current. Further analysis can be accommodated by adding a circuit that mimics the body response further. For instance, several filter networks have been developed that provides correction for the frequency filter effects noted in IEC 60479-2.

Hart [33] proposes the following modelling network as a useful one for modelling the startle-reaction frequency effect from the 'a' curve in Figure 20 (see Figure G.1).