Electric current flow through human skin at power frequency voltages

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Carter, A. O., and Morley R. (1969). *Brit. J. industr. Med.*, **26**, 217-223. **Electric current flow through human skin at power frequency voltages.** Alternating power voltages were applied to small pieces of living skin. Current and voltage were recorded continuously using voltages from 25 V to 250 V. At the lower voltages the skin appeared unaffected, but rapid destruction occurred at the higher voltages. It is concluded that skin impedance, whilst being extremely variable on account of many physical factors, is dependent on voltage and time of application in the range where dangerous electric shock occurs to human beings at power frequencies.

Much work has been done on the electrical properties of skin, both animal and human, over many years. Intact skin has generally been used, and the currents were in the milli- and micro-ampere range to avoid damage. In cases of significant electric shock, there is progressive damage to the skin with dramatic alterations in its electrical properties. Information on this is necessary to the understanding of the physiology and pathology of electric shock. This work is an attempt to obtain such information. Owing to the difficulties of extrapolation from animal skin, it was essential to use human skin.

Previous work

Earlier work was often of little value in our investigations, as all the conditions were not defined. Crile, Hosmer, and Rowland (1922) gave the conductivities of mashed tissues (not skin) in mhos (reciprocal ohms) without defining the voltage applied. Running through the earlier work is the idea that skin should have a computable resistance and impedance, if only such variables as temperature, salinity, blood flow, frequency, wave-form, and the value of the effective voltage could be defined and

controlled. Horton and Van Ravenswaay (1935) measured the electrical impedance of the body, including skin, at frequencies of 50 Hz to 10 kHz, using a bridge method. A total of approximately 50 cm² of upper arm skin was used but neither the current nor the voltage used was stated. Gougerot and Chanteur (1951), realizing that skin resistance could change rapidly with the voltage and the time of application, among other factors, used human volunteers. The maximum voltage used was 20 V at frequencies from $\frac{1}{4}$ to 50 Hz and with terminals 4.6×6.2 cm. gave impedance values between 13,000 and 40,000 ohms with a current of less than 1 mA.

Work on isolated frog and human skin by Conrad, Haggard, and Teare (1936) showed that human skin possessed both resistance and capacitance. The first and second fingers of one hand of a volunteer were immersed in salt solution. Rectangular current pulses were used and a minimum current of 0.2 mA for 6 milliseconds was needed to produce a sensation. An equivalent circuit was simulated by 19,500 ohms in parallel with a capacitance of 0.05 μ F. Barnett (1938) measured the electrical phase angle of normal skin from 2 kHz to 50 kHz. A bridge method was used but, as no mention is made of the voltage or current, the report is valueless for our purpose.

Barnett (1940) measured the seasonal variation in epidermal impedance in living psychiatric subjects. He gave values varying between 140 and 250 ohms for annular electrodes of 6 cm². at 11.1 kHz but did not state the current or the voltage. The variations in electrical phase angle of the skin were between 1° and 4°. Kouwenhoven (1949), in a paper on body resistance, put the resistance through dry epidermis at a maximum figure of 100,000 'ohms per sq. cm.' (Ω cm.²). The value, under wet conditions, can fall a hundredfold. No voltage, current or frequency is stated. Burns (1950) used $\frac{3}{4}$ in. (19 mm.) diameter surface electrodes on the pretibial area, 1 in. (25.4 mm.) apart, with volunteers. The skin in all cases was shaved and dried. It was then used as such, or sanded, or electrode paste was applied. For frequencies between 10 and 10⁴ Hz, the impedance varied between 10⁶ and 10² ohms. No current or voltage was stated. He represented the skin impedance by an equivalent circuit shown in Figure 1A. The effect of sweat on skin impedance was discussed by Kuno (1956), who considered that the sweat glands were areas of weakness in the skin impedance. Davis and Kennard (1962) said that, with direct current, skin obeyed the ohmic law up to 10⁻⁷ A/cm². at a temperature of 22–25°C. and a relative humidity of 40–45%. The resistance of the skin of the forearm varied between 6 and 2×10^5 ohms/cm². when the charge passed varied between 1.4 and 0.8×10^{-3} coulombs/cm². They also demonstrated that, even at these minute currents, the resistance of the skin altered with time and took some time to return to its original value. Elaborate work on the current-voltage relationship in human skin was done by Stephens (1963). The model which he suggested is shown in Fig. 1B with a non-linear resistance whose non-linearity exhibits no time lag. He used currents

up to 1 mA (area of electrodes 7 cm².) with voltages up to 5 V. Rectangular current pulses, a.c. and d.c., and also combinations of these were used. He gave figures for skin resistance of the order of 1–13 k Ω for 7 cm². (i.e., 7–98 k Ω cm².) but these values are not relevant to the problem of electric shock in man. Puccini (1964) discussed the structural particularity of the electric path through human skin at voltages up to 5,000 V. He illustrated the histological changes that occur in human skin rather than its electrical properties.

A more detailed summary of previous work, including some of the above, was given by Tregear (1966).

Much work on the impedance of cadavers was performed by Freiburger (1934). As it is now known that skin lives for anything up to 24 hours after the death of the individual, and Freiburger was working near enough to death to obtain marked muscular contractions, it can be accepted that he was working with living skin. Though working with an intact cadaver, his work demonstrated that a marked rise in current occurs with skin damage. Freiburger's work seems practically unknown, being rarely mentioned in the literature.

Experimental work

Preparation of the skin

The skin from amputated limbs was available. Immediately after removal in the operating theatre, the limb was taken to the mortuary and a piece of healthy skin was removed from either the lower thigh or the middle of the lower leg, depending on the site of amputation. A ribbon, some $8 \times 1\frac{1}{2}$ in. (20×4 cm.), was removed and taken to the electrical apparatus, where any fat or subcutaneous tissue still remaining was scraped from the internal surface. A cleavage plane exists between the dermis and the subcutaneous tissue and only dermis and epidermis were used.

The time between amputation and taking the electrical measurements was a minimum of half an hour to a maximum of three hours.

The skin was at ambient room temperature (20–22°C.).

Electrical apparatus

The equipment is shown in Fig. 2, which is self-explanatory.

Electrode system One electrode consisted of a heavy brass plate, 3.6 in. (9.2 cm.) in diameter and 0.25 in. (0.6 cm.) thick. In the central area 1 mm. diameter holes at 5 mm. spacing had been drilled through. The skin specimen, approximately 1 in. square (6.25 cm².), was placed over these holes, the internal side downwards. The brass disc was placed in an enamel tray in which a tissue culture fluid was placed.¹ The fluid was isotonic

¹'Welcome' tissue culture medium 199 (Morton, Morgan & Parker). Single strength containing penicillin, 200 units/ml., streptomycin, 100 μ g./ml., and sodium bicarbonate, 1.1 g./litre.

FIG. 1. Electrical equivalent circuits for skin: (A) according to Burns (1950); (B) according to Stephens (1963).

FIG. 2. Electrical circuit diagrams: V1 – calibration voltmeter; A1 – calibration ammeter; V2, V3 – graphic recorders and cathode ray oscilloscope (voltage); A2, A3, and A4 – graphic recorders and cathode ray oscilloscope (current); S – specimen between electrodes.

with the skin, helped to keep it alive, and improved the electrical contact with the internal surface. It also supplied fluid to the skin, as was well demonstrated when currents were passed and blister formation occurred. The fluid in the tray was not deep enough to reach the upper surface of the brass plate but passed up to the skin through the holes by capillary action. The upper surface of the skin was dried before being mounted. The upper electrode consisted of a brass cylinder, 0.6 in. (1.5 cm.) in diameter and of the same height. It was mounted on a Perspex rod of the same diameter and 9.25 in. (23.1 cm.) long. The circular contact area of the electrode was 0.36 sq. in. (1.77 sq. cm.). This electrode was held on the skin manually.

Method

A sensibly constant voltage ($\pm 3\%$) was used in each experiment and the transformer in use was of sufficient rating to ensure this. The alternating voltage applied was derived from the 50 Hz mains supply and was of reasonably sinusoidal form. The voltage and current flowing through the skin were then recorded by either a pen recorder or a multi-channel ultraviolet light recorder. The voltage and the current wave-forms could be observed directly on the cathode ray oscilloscope. A new piece of skin was used for each experiment.

At each voltage two experiments were done. In the first, contact with the skin was established before the voltage was applied. In the second, contact with the skin was established after the voltage had been applied to the electrodes.

At low voltages, when the rise of current was slow, the experiment was terminated when any information obtained further would have been irrelevant as far as electric shock was concerned. At higher voltages, the current was stopped when the damage to the skin was so gross, as shown by smoke and sparks, that there was danger of a short circuit. A band pressure was maintained

on the upper terminal via the Perspex rod. Furthermore, it was possible to observe the effects on the skin in detail and to break the circuit when necessary.

The ultraviolet and pen recorders produced timing marks which could be checked against the supply frequency of 50 Hz. A calibration of the apparatus was carried out on each occasion. From the records it was possible to measure the current and voltage against time and to calculate the impedance.

Results

Graphs of current against time are shown in Figs 3 to 8 for 50 Hz applied voltages. The peak current is shown and represents the magnitude attained in each half cycle. A scale of root mean square (r.m.s.) current is also shown for comparison purposes, but, since this is derived by ratio from the peak values, it is only valid so long as the current is a sine-wave ($\text{r.m.s.} = \text{peak}/\sqrt{2}$). The 'specimen' voltage taken from the mains was of reasonable sinusoidal form throughout (less than 2% of 3rd and 5th harmonics) but the current showed signs of distortion on some of the tracings. Such a tracing is shown in Figure 9. A variable harmonic content such as this has not been considered further as it has not been shown to be of any importance in electric shock.

No difference could be detected between those graphs in which skin contact had been established before the voltage was applied and the graphs where it was established after the voltage had been applied to the electrodes (see caption to Figs 3 to 8).

In the first 25 cycles (0.5 sec.) shown, the current was increasing and distortion is shown clearly, but after three seconds the distortion has fallen to a low

For legends to Figs 3 to 8 see p. 221

value. A similar pattern occurred for voltages up to 125. Above that, there was gross current distortion and variation in magnitude accompanied by rapid physical destruction of the skin.

At 25 V, the growth of current and reduction of impedance were comparatively slow. Even after periods of contact of longer than one minute, no damage to the skin was visible.

At 30 V, damage occurred in some cases in the form of blisters which surrounded the upper electrode. The blister fluid, on account of its volume, must have come from the tissue culture fluid beneath.

At 50 V, blistering occurred more often. In this voltage region there was a distinct change in the

envelope of the current curve. The rapid rise in current was sometimes followed by a fall.

At 70 V, gross blistering occurred in seven seconds and the rise-and-fall shape was distinctive.

At 100 and 125 V, gross blistering was occurring in less than one second and the experiments had to be terminated due to the danger of a short circuit. The explosive nature of the experiment can be appreciated from the estimation that several hundred watts are being fed into a tissue volume of half a cubic centimetre.

At 200 and 250 V, there was gross sparking followed by a sheet of flame at the specimen. The rise of current was so rapid that there seemed no possi-

FIGS 3 to 8. Graphs of current against time for various applied voltages. (These curves show 'envelopes' of the 'peak' currents.) Figure 3 shows the first 10 seconds of the graphs shown for 90 seconds in Figure 4. Figure 5 shows the first 10 seconds of the graphs shown for 90 seconds in Figure 6. Identical graphs in Figs 3 and 4 and in Figs 5 and 6 have the same numbers. (Skin surface contact area = 1.77 cm.²) Contact established before voltage in curves 2, 5, 7, 8, 9, 12, 14, 16, 18, 19, 22, and 23. Contact established after voltage in curves 1, 3, 4, 6, 10, 11, 13, 15, 17, 20, 21, and 24.

bility of a controlled experiment. The current wave-form showed large departures from a sine-wave.

An experiment to demonstrate that the skin was alive during and at the end of the experiment is given as an appendix (p. 218).

Discussion

The electrical impedance of human skin may depend upon age, sex, race, the anatomical position of the skin, the presence or absence of hair, whether alive or dead, the magnitude, frequency, and wave-form

FIG. 9. Examples of distorted current wave-forms. Upper curve: after 3 sec. at 70Vr.m.s. 50 Hz. Middle curve: initial current at 70Vr.m.s. 50 Hz. Lower curve: in itial current at 30Vr.m.s. 50 Hz.

of the voltage applied, the duration of the passage of the current (both the magnitude and the waveform of the current may vary with time), the temperature, the nature, shape, area, and surface of the conductor, and the physical state of the skin, whether dry, wet, sweaty or traumatized. The effects of all these variables have not yet been investigated. It is considered that little purpose would be served in so doing, as far as the understanding of dangerous electric shock at power frequencies is concerned.

It was considered that there could be a difference in the current flow in the initial stages, between the grasping of a 'live' conductor and the holding of a conductor that became 'alive'. In the first case, the contact resistance changes from infinity to some lower value, whereas, in the second case, it will be at this lower value at the beginning of the shock. This was not, however, borne out by our results as no difference could be detected between the curves in such circumstances.

From the curves presented at voltages of 25, 30, 50, and 70, it will be seen that there were considerable differences between the values of current obtained from different pieces of skin (even when they were from the same leg). This is to be expected when it is considered that it had not been possible to fix more than one or two of the variables quoted above. In the opinion of the authors, the precise values on any particular curve are not of major importance for the reasons given above. What are important are the general shapes of the curves. The graphs (Figs 3 to 8) show two typical patterns, exemplified by the 25 and 70 V graphs. At 25 V there is a rapid rise followed by a much slower rise. At 70 V there is a rapid rise followed by a fall after a short period of time. The 50 V graph shows both types of curve.

At 100 V, powers of several hundred watts, and at 250 V, powers of over a kilowatt, would be feeding into the specimen. The portion of specimen between the electrodes had a volume of approximately half a cubic centimetre and this is mainly water. One kilowatt would raise this to boiling point in about 0.2 second and convert it to steam in one second. These times would be modified by the fact that the heat is not generated uniformly throughout the specimen and that heat is lost by conduction to the electrodes and culture medium.

Among the possibilities to be considered in explanation of the current/time graphs are:

(a) movement of fluid into and in the skin which could produce an increase in the current. All the graphs show such an increase initially;

(b) vaporization of fluid by the heat, causing a drying which would decrease the current. This depends upon a sufficient temperature being attained. This will depend upon the power input and upon the cooling effect of (a);

(c) electrical breakdown accompanied by chemical

decomposition and charring which would prevent the fall or even cause an increase of the current.

From these observations, it follows that the impedance of the skin is dependent on voltage and on time. Other investigators have drawn graphs which show impedance against time. Variation with time is discussed by Tregear (1966) but he is careful to qualify it by stating that it is only true when the oscillating e.m.f. is less than 2 V. It often seems to be assumed that the value of impedance obtained is independent of the voltage or current used in the measurement. This is not so for the range of voltages as shown above. It is important for any investigator to state the voltage and the current densities used.

The phase angle, which has been discussed by previous investigators, has not been considered as it has no effect on the severity of an electric shock. The curves in Fig. 9 obviously do not represent sinusoidal current and, since phase angle refers to sinusoidal components, attempts to deduce a phase angle would have little meaning.

This investigation was undertaken as part of an enquiry into electric shock and the relationship of the curves to accidental shock effects will be discussed in a later paper.

Conclusions

1. With constant applied voltages at power frequencies, it has been shown how the current varies with time.
2. It is considered that the general shape of the curves has a bearing on electrical accident shock.
3. A comparison was deliberately not attempted with previous work, where attempts had been made to derive an intrinsic impedance value for skin, but not necessarily living skin.

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Appendix

[This experiment was carried out for us by Dr. A. R. Morley, Lecturer in Pathology at the University of Newcastle upon Tyne.]

Several small fragments of skin from an undamaged portion of a charred specimen were taken at the end of an experimental session, the time from amputation then being three hours. These were cultured for four hours at 37°C. in Trowells' T.8 culture medium to which 3 μ Ci/ml. of thymidine-6-T(n) had been added (activity 5,000 mCi/mM).

Autoradiography was performed by the stripping film technique, the time of exposure being 18 days. Microscopic examination revealed label present in the cells of the basal layer of the epithelium.

The differential uptake of labelled thymidine by the basal cells of the epithelium is indicative of nuclear DNA synthesis. From these findings, it may be inferred that the skin was living three hours after amputation of the limb.

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