CORE Metadata, citation and similar papers at core.ac.uk
Provided by Elsevier - Publisher Connector

ELECTRICAL CHARACTERISTICS OF THE SKIN

The Impedance of the Surface Sheath and Deep Tissues*

Captain JAMES C. LAWLER, MC, USA, Major MICHAEL J. DAVIS, MC, USA† and EVERTON C. GRIFFITH, B.S.

There is a need for an accurate method of determining when the skin is normal and when it is not. Except for histopathological examination our judgment of the condition of the skin is limited to what can be seen by the naked eye or felt by the examining finger. The response of diseased skin to various forms of treatment must likewise be judged by what our senses tell us or by the subjective observations of our patients.

It is felt that an understanding of the electrical characteristics of the skin may offer a partial solution of this problem. These characteristics can be accurately determined and changes from normal related to the condition of the skin. This report presents a method for determining the electrical impedance and phase angle of the skin, and a simplified technic for the separation of the impedance of the skin from that of the deeper tissues.

HISTORICAL REVIEW

Many investigators have attempted to utilize the electrical properties of the skin as an indication of the condition of the skin or its underlying tissues. Earliest attempts utilizing direct current encountered the insurmountable problem of polarization currents set up within the body which mask the true electrical resistance of the tissues. Gildemeister (1) was among the first to overcome this difficulty by using an alternating current and measuring the total opposition to its passage through tissue. This total electrical opposition is called impedance and in the skin it has two components, resistance and capacitive reactance.

Many studies (2, 3, 4) have been done relating the impedance of the body to thyroid function. In general it was found that the impedance and the basal metabolic rate were in qualitative agreement in hyperthyroidism but bore no relation to each other in hypothyroidism. During these studies many arrangements were used in an attempt to separate the impedance of the skin from that of the deeper tissues. Brazier (5) in England using immersion electrodes attributed the impedance of the body almost entirely to the deep tissues. Horton and VanRavenswaay (6) and Barnett and Byron (3) developed the multiple electrode technic and were able to show a significant contribution by the skin to the impedance of the body. Gerstner (7) used carbon powder-saline electrodes to separate skin impedance from deep tissue impedance. He found lower values of skin impedance for women than for men, and felt that skin impedance was a characteristic trait of the individual. Gerstner and Gerbstadt (8) attempted to localize the site of the impedance of the skin by measurements before and after burning and scarification. They found that the tops of blisters behaved as the whole skin but that denuded skin had almost no impedance. They also demonstrated that areas of skin with a thick keratin layer had a higher impedance than those areas in which the keratin layer was thin.

In addition to impedance, attention has been given to various other expressions of electrical behavior as used in electrical engineering. Among these have been phase angle, impedance angle, and Q factor, all of which express a relation between pure resistance, capacitive reactance, and inductive reactance in an alternating current

Glossary—Impedance: the total electrical opposition of a circuit to the passage of an alternating current through it.

Phase Angle: the relationship between current and voltage in an alternating current circuit expressed as an angle of lead or lag.

Capacitance: the property of a capacitor to store a charge and to oppose any voltage change across it.

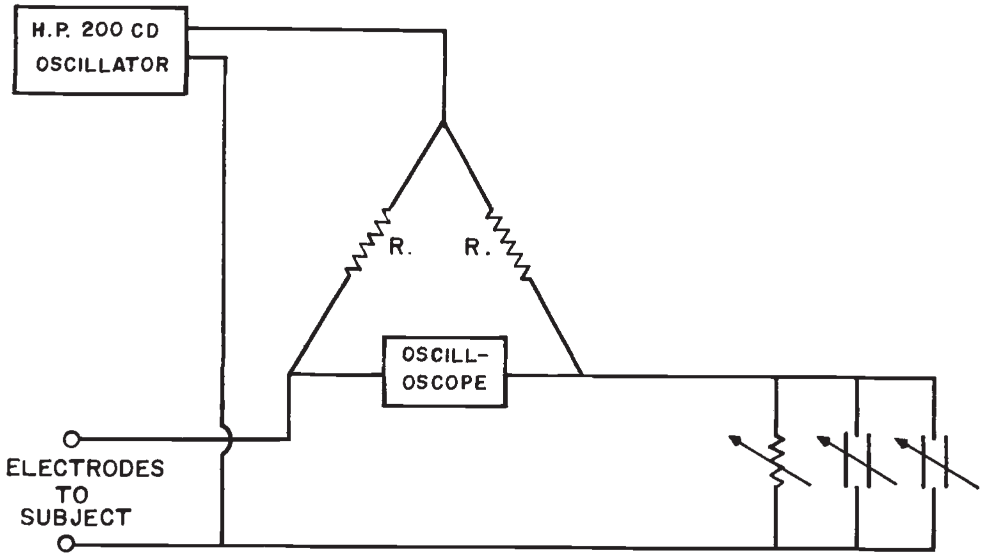
Reactance: the opposition to flow of an alternating current resulting from the electromotive force built up by a capacitor or an inductor.

Capacitive Reactance: the opposition to flow of an alternating current resulting from the electromotive force built up by a capacitor.

* From the Department of Dermatology, Walter Reed Army Institute of Research, Walter Reed Army Medical Center, Washington 12, D. C.

† Present address: 2325 University Avenue, New York 68, N. Y.

Received for publication July 13, 1959.



CIRCUIT FOR MEASUREMENT OF IMPEDANCE

FIG. 1

circuit. The most commonly used of these has been the phase angle, the angle between the resistive component and the final impedance.

Gougerot (9) was the first to study impedance and phase angle in various dermatoses. Using an alternating current at a frequency of 4,000 cycles per second and lead electrodes 7.0 by 8.5 cm. he found that the impedance of normal skin was always greater than 300 ohms, and that the phase angle was greater than 55°. In 23 patients with active eczematous lesions the values were pathologically lower, impedance 90 ohms, phase angle 26°. In psoriasis Gougerot found normal values in dry lesions but abnormally high values in uninvolved skin.

EXPERIMENTAL METHOD

The electrical impedance or total opposition of a circuit to the passage of an alternating current cannot be measured in terms of simple ohmic resistance alone. In addition to ohmic resistance, if the circuit contains an inductance such as a coil, the alternating current induces a counter electromotive force across the coil causing the current to lag behind the applied voltage. This lag or opposition to the passage of current through the coil by virtue of this induced electromotive force is called the inductive reactance of the coil. If the circuit contains a capacitor the alternating current charges and discharges the capacitor, the capacitor opposes these voltage changes, and the voltage lags behind the current. This opposition of voltage by a capacitor is called capacitive reactance. Early investigations have shown the skin to have capacitive properties, that is, to exert a capacitive reactance to the passage of an alternating current. Inductive properties have not been attributed to the skin.

Although many methods have been used to measure the impedance of the skin most have shared one basic principle: the construction of an equivalent circuit containing variable resistors and capacitors against which the skin is balanced electrically. It is assumed that at balance the impedance of the skin is the same as that of the equivalent circuit.

For this study a circuit containing variable resistors and capacitors in parallel was constructed. The diagram of this circuit is shown in Figure 1. An audiooscillator provided an alternating current of variable frequency, with an output of 2 volts and 0.1 milliamps. An oscilloscope served as a balancing device. In essence this represents a bridge arrangement with one arm of the bridge being the equivalent circuit and the other arm the circuit through the body. The electrodes were stainless steel disks 2 cm. in diameter. This size was selected for ease of application to comparable areas of skin in different patients and because it permitted easy application to many skin lesions. The electrodes were placed on the skin with a fixed distance of 2 cm.

between their rims. In order to obtain values for comparable areas of skin they were always applied to the ventral surface of the forearm midway between the wrist and elbow in the normal subjects tested. The electrodes were applied with rubber straps as used in electrocardiography, allowing application with about the same pressure each time. The electrical connection with the skin was made through filter paper moistened with normal saline, the skin being in parallel with the equivalent circuit. With the electrodes in position the alternating current was impressed across both the skin and the equivalent circuit and the two balanced by varying the resistance and capacitance of the equivalent circuit. At balance, readings were obtained in terms of resistance and capacitance, and the impedance and phase angle were calculated from the following formulae:

$$Z = \frac{(R)\left(\frac{1}{2\pi fc}\right)}{\sqrt{R^2 + \left(\frac{1}{2\pi fc}\right)^2}}$$

$$\phi = \tan^{-1} \frac{R}{\frac{1}{2\pi fc}}$$

where
Z = Impedance in ohms
R = Resistance in ohms
f = Frequency in cycles per second
c = Capacitance in farads
ϕ = Phase Angle.

Using this technic the impedance of the normal skin of 104 subjects was measured at frequencies of 1,000, 4,000, 10,000 and 20,000 cycles per second. This was done to assess the effect of variation of the frequency on skin impedance and to encompass some of the frequencies used by other investigators. In addition to normal skin, a study was made of sites from which the stratum corneum and barrier zone had been removed by cellulose tape stripping. The effects of gradual removal of the stratum corneum were also determined.

EXPERIMENTAL RESULTS

A. Impedance and Phase Angle of Normal Skin

The mean value of impedance of normal skin at the four frequencies used in this study is shown in Table I. Increasing the frequency of the alternating current results in a decrease of the impedance reflecting a decrease in both the resistance and the capacitance. There is no particular advantage of one frequency over another except that at very high frequencies there is a tendency for the current to travel along the surface of the skin rather than through it. We have selected 4,000 cycles per second as a satisfactory frequency for routine use, and detailed analysis of the data will be limited to this frequency. At 4,000 cycles per second the mean skin impedance of the 104 subjects tested is 1882 ohms with a standard deviation of 468 ohms. 97% of the results fall within two standard deviations of the mean, indicating a normal distribution pattern. This gives a range, within two standard deviations, of 946 ohms to 2818 ohms for the impedance of the skin on the ventral surface of the forearm in this group of normal subjects. The graphic presentation of these results is shown in Figure 2.

TABLE I

Mean impedance of normal skin in 104 subjects

Frequency	Impedance	Standard Deviation
cycles per second	*ohms*	*ohms*
1,000	6487	1733
4,000	1882	468
10,000	861	187
20,000	507	111

If the values for impedance at 4,000 cycles per second are analyzed according to sex (Table II) it is found that for 59 males the mean impedance is 1862 ohms with a standard deviation of 456 ohms. The mean impedance for 45 females at the same frequency is 1910 ohms with a standard deviation of 474 ohms. Within two standard deviations of the mean the range is 950 ohms to 2774 ohms for normal males and 962 ohms to 2858 ohms for normal females. The difference in the mean impedance of the skin of males and females is not statistically significant.

The mean value and standard deviation of the phase angle at the four frequencies used in this study is shown in Table III. As is expected in a circuit containing resistance and capacitive reactance when the frequency is increased the phase angle is decreased. At a frequency of 4,000 cycles per second it is 73.5° for the group of 104 normal subjects. The standard deviation of the mean is 3.6°. There is no significant sex difference in the phase angle of the skin. (Table II).

B. Effects of Altering the Stratum Corneum and Barrier Zone of the Skin

Complete removal of the stratum corneum and barrier zone has a profound effect on the

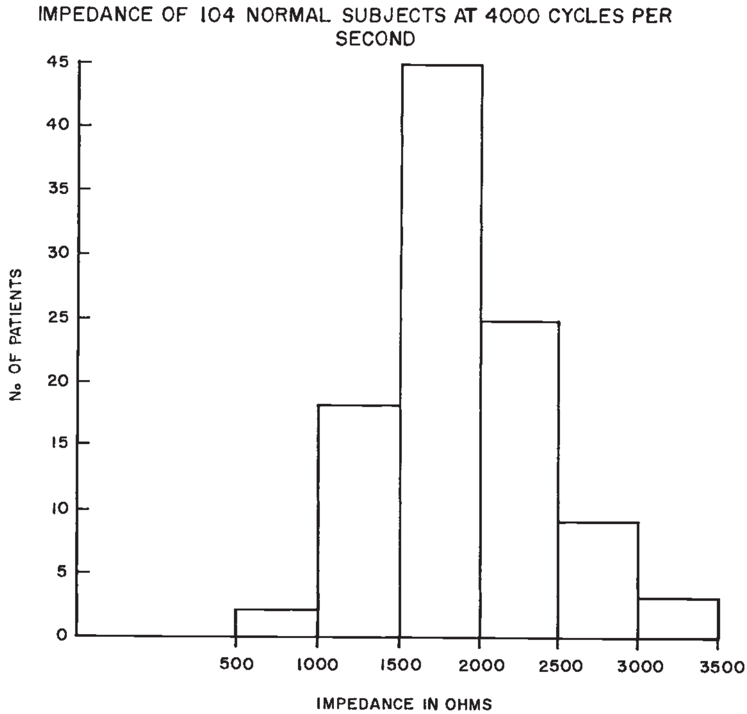


FIG. 2

impedance and phase angle of the skin. Table IV shows the effect of removing the stratum corneum by cellulose tape stripping in 23 subjects. The mean impedance of such sites at a frequency of 4,000 cycles per second is 304 ohms with a standard deviation of 54 ohms. This gives a range within two standard deviations of the mean of 196 ohms to 412 ohms for the impedance of skin from which the stratum corneum and barrier zone have been removed. The mean phase angle of such sites at a frequency of 4,000 cycles per second is 10° with a standard deviation of 1.8°. For both impedance and phase angle 95.5% of our results falls within two standard deviations of the mean.

At low frequencies the capacitance of the stripped sites is higher than that of intact skin while at high frequencies (above 10,000 cycles per second) the capacitance of the stripped sites is lower than that of the intact skin. At all frequencies used the resistance is much lower in areas from which the keratin has been removed.

In six patients the resistance and capacitance were measured at 4,000 cycles per second during the gradual removal of the stratum corneum by cellulose tape stripping. (Figure 4). The removal of a single strip of the superficial keratin may result in an increase in the resistance probably due to the removal of surface electrolytes which are good conductors. As the stripping is continued there is a decrease in resistance and an increase in capacitance. As small shiny areas

TABLE II

Mean impedance and phase angle in 59 males and 45 females

Frequency	Impedance	Phase Angle	Sex
cycles per second	*ohms*	*degrees*	
4,000	1862	73.6	Male
4,000	1910	73.4	Female

TABLE III

Mean phase angle of normal skin in 104 subjects

Frequency	Mean Phase Angle	Standard Deviation
cycles per second	*degrees*	*degrees*
1,000	75	5.0
4,000	73.5	3.6
10,000	66	4.8
20,000	57	5.9

appear in the stripped sites indicating complete removal of the keratin the changes become more marked. When the procedure is continued so that the entire area under the electrode is stripped of keratin the values are the same as those shown in Table IV, and continued stripping produces no appreciable change.

Washing the skin with ether for one minute results in a decrease in resistance attributable to the removal of poorly conducted lipid substances from the surface of the skin.

C. Impedance, Resistance, and Capacitance at Various Body Sites

Measurements were made in the usual manner on the dorsal forearm, ventral forearm, dorsal arm, ventral arm, and on the palms. The impedance and resistance are highest on the palms, greater on the dorsal forearm than on the ventral forearm, and greater on the dorsal arm than on the ventral arm. This would indicate that the resistance and impedance of normal skin are highest in areas having a thick stratum corneum. The capacitance however is lowest on the palms, ower on the dorsal forearm than on the ventrall forearm and lower on the dorsal arm than on the ventral arm. This would indicate that in areas where the stratum corneum is thick the capacitance of intact skin is low.

TABLE IV

Impedance and phase angle after removal of surface sheath

Frequency (cycles per second)	Impedance (ohms)		Phase Angle (degrees)	
	Mean	Standard Deviation	Mean	Standard Deviation
1,000	338	64.9	7	1.3
4,000	304	53.9	10	1.8
10,000	270	43.2	40	2.1
20,000	242	37.5	54	2.7

DISCUSSION

The measurement of the electrical impedance or total opposition of the skin to the passage of an alternating current has been accomplished by many technics based upon the use of an equivalent circuit against which the skin is balanced. This makes necessary the assumption that at balance the resistance and capacitance of the equivalent circuit reflect the resistance and capacitance of the skin. There are several facts which make this assumption a reasonable one. Of primary importance is the fact that the two circuits can be balanced in terms of resistance and capacitance. We have also found that results are reproducible within 10% in the same individual for periods of as long as six months. No seasonal variation in impedance has been observed.

There are several factors in the design of the experiment which influence the values obtained for impedance and phase angle. The frequency of the alternating current and the size of the electrodes are among the most important. The impedance and phase angle both decrease as the frequency of the alternating current is increased. (Tables I and III). As pointed out by Barnett (4) if frequency and impedance are plotted on a log-log scale they are found to have a linear relationship. (Figure 3). This makes possible the rough comparison of impedance values obtained by using various known frequencies. A

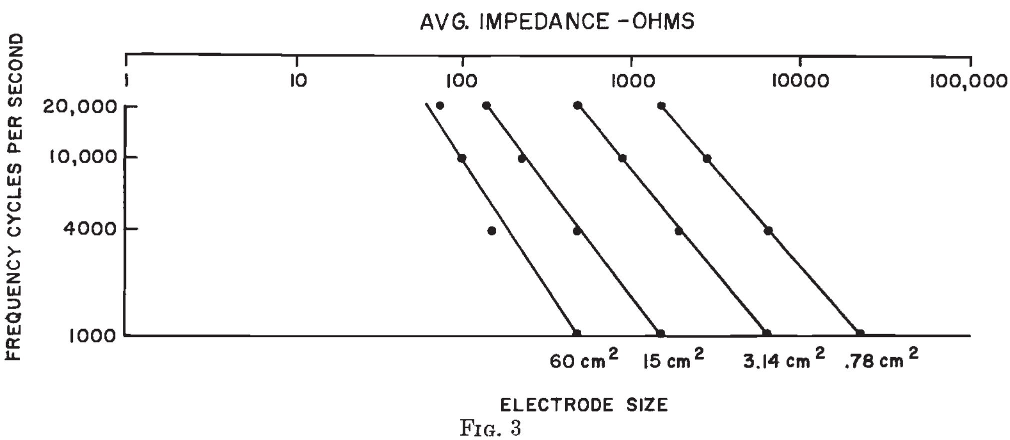


FIG. 3

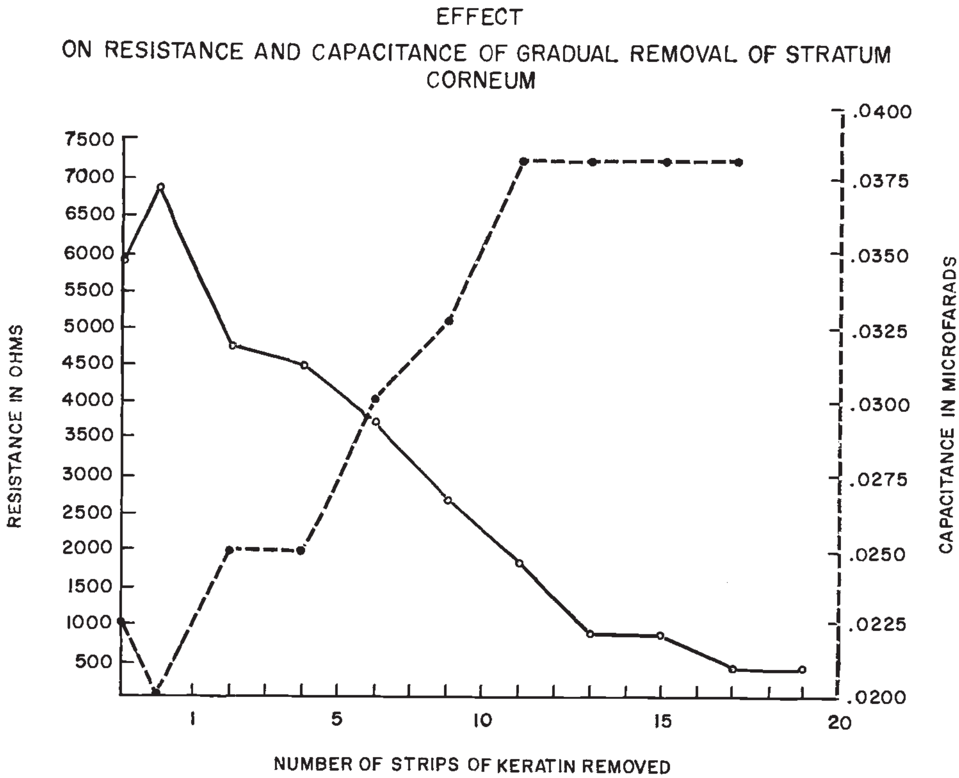


Fig. 4

linear relationship of frequency and impedance is usually found in homogenous substances, and its appearance in a tissue as heterogenous as skin is somewhat surprising.

The selection of electrode material is somewhat arbitrary. Other investigators have found lead and monel metal satisfactory; we have used stainless steel. The pressure with which the electrodes are applied is not of critical importance as long as they make good electrical contact with the skin. The application of pressure up to 300 gm./cm^2 to our electrodes had no effect on the values of resistance and capacitance which were measured. The size of the electrodes is of considerable importance since this determines the actual area of the skin which is included in the circuit. We have found that as the size of the electrodes is increased the values for impedance decrease. (Figure 3). If the impedance measured with various sizes of electrodes is plotted against frequency on a log-log scale the curves for the various electrodes demonstrate a parallelism, and the position on the graph of the curve for an electrode of a given size is predictable. (Figure 3). This permits comparison of results obtained when using electrodes of various sizes.

Using lead electrodes of the same size as those used by Gougerot (9) we obtained values for impedance in the same range as those he reported. In the equivalent circuit used by Gougerot the resistors and capacitors were in a series arrangement, while in our equivalent circuit they are arranged in parallel. (Figure 1). Our ability to duplicate his results confirms the observation of Horton and Van Ravenswaay (6) that in the equivalent circuit the resistors and capacitors may be placed in either a series or a parallel arrangement to produce the same final results.

Gerstner (7) reported that females have lower impedance values than males. Determinations on 45 females and 59 males by our technic reveal no significant sex difference in impedance. (Table II).

Separation of the superficial or surface sheath impedance from that of the deeper tissues has been accomplished previously by the use of special electrodes or by using multiple electrodes and calculating the impedance of the current pathways between the various electrodes. These methods are cumbersome and some are based on assumptions which are open to criticism. The use of cellulose tape stripping provides a rapid, direct, and histologically controllable method of removing the superficial portion of the skin from the circuit. It should not be assumed however that one can isolate a barrier zone in terms of a single anatomical area by stripping. The skin surface with its system of ridges and furrows presents an uneven surface which precludes removal of solid sheets of keratin. Simple observation of the tape after stripping confirms this. As an area is stripped very small, shiny spots appear indicating exposure of the moist living epidermis. With continued stripping these areas enlarge and coalesce until the entire area is devoid of keratin. Effects produced by a limited number of strippings may erroneously be attributed solely to the removal of loose keratin, when in fact, very small areas of the barrier zone have also been removed. We have seen small moist areas appear after 5 to 7 strippings, and if vasoactive substances such as histamine are applied at this time reactions in every way comparable to those produced by intradermal injection are seen. Measurements of potential difference made at this time show that between normal skin and the partially stripped sites there is a potential difference of 15 to 25 millivolts in contrast to a potential difference of 0 to 5 millivolts between two areas of intact skin. This offers further evidence that a limited number of strippings with cellulose tape may produce changes in the barrier zone of the skin.

We consider the keratin layers and the epidermal barrier zone, whatever its precise location, to comprise the surface sheath. This area has different electrical properties than the living epidermal cells which can be considered to be part of the deep tissues. Biopsy studies were taken of the stripped sites when electrical measurements indicated that the surface sheath had been removed from the circuit. These showed that in most areas the keratin layers had been completely removed and the granulosa cell layer remained. In some areas it was possible to find portions of the compact keratin remaining. These biopsy specimens demonstrate that cellulose tape stripping results in uneven removal of the keratin layers and offer little help in determining the exact site of the epidermal barrier zone.

The removal of the surface sheath by stripping results in a decrease in impedance and resistance at all frequencies used. The effect of stripping on capacitance and capacitive reactance however is frequency dependent. The decrease in resistance as the keratin is removed (Figure 4) indicates that the surface sheath is the site of the high ohmic resistance of the skin. The changes observed in the capacitance are somewhat more difficult to interpret. At frequencies of 4,000 cycles per second and below, the removal of the keratin and barrier zone results in a higher capacitance (Figure 4) than that of intact skin. The exact explanation of this cannot be offered since the precise composition of the electrical circuit of the skin is not known. There are however two ways in which stripping could alter the circuit and produce the observed increase in capacitance: (1) removal of the surface sheath, may in effect, remove a capacitance from the circuit which is in series arrangement with the capacitance of the deeper tissues, thus causing an increase in the total capacitance of the circuit; (2) the removal of the surface sheath may also be thought of as bringing the plates of the capacitive element of the circuit closer together and in this way the capacitance of the circuit increases. The finding of a high capacitance in normal skin areas where the keratin is thin and a lower capacitance where the keratin is thick will support either of these explanations. It should be emphasized that these are possible explanations of the observed phenomenon, and, lacking knowledge of the exact structure of the circuit in the skin, no proof can be offered for either one.

In contrast to the results obtained at 4,000 cycles per second, when the capacitance of the stripped sites is measured at frequencies of 10,000 cycles per second or higher it is found to be lower than the capacitance of intact skin. This can be understood if the capacitance is thought of as being due to ionic displacement within the

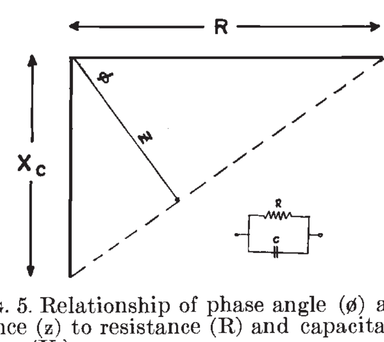


FIG. 5. Relationship of phase angle (ø) and impedance (z) to resistance (R) and capacitance reactance (X_c).

dielectric of the capacitor element of the circuit. At high frequencies movement of the ions is restricted by the frequency with which the charge on the plates of the capacitor changes sign, and the circuit has a lower capacitance. At high frequencies this effect outweighs the effects produced by removal of the surface sheath, and the stripped areas have a lower capacitance than the intact skin.

Removal of the surface sheath also results in a marked decrease in the phase angle. (Table IV). This may seem unreasonable in the face of an increase in capacitance, as is obtained at low frequencies, since ordinarily in a capacitive circuit a small phase angle indicates a low capacitance. Phase angle however is a function of both capacitive reactance and resistance, and, as can be seen from the vector diagram (Figure 5), if the resistance decreases more than or at a faster rate than the capacitive reactance a smaller phase angle will result.

Preliminary studies with this technic support the finding of Gougerot that patients with atopic dermatitis have a characteristically low impedance both at the sites of lesions and in uninvolved skin, and that patients who have psoriasis have an abnormally high impedance in uninvolved skin. It is planned to expand these studies. Measurement of the electrical characteristics of the skin may also prove useful in quantitating improvement in diseased skin during therapy, and in the study of genetically determined dermatoses by allowing one to detect abnormal members of a family who do not have clinically evident disease.

SUMMARY

A method for the determination of the impedance and phase angle of human skin and the results of measurements in 104 normal subjects are presented.

The use of cellulose tape stripping to separate the electrical behavior of the surface sheath from that of the deeper tissues is described, and the effects of this separation are discussed.

Possible uses of this technic in the study of diseased skin are briefly outlined.

We wish to thank Mr. Robert E. Robinson III, Division of Neuropsychiatry and Dr. Irvin Levin, Division of Instrumentation, Walter Reed Army Institute of Research, for their many helpful suggestions during the course of this study.

REFERENCES

1. Gildemeister, M. and Kaufhold, R.: Uber das elektrische Leitungsvermogen der ubertebenden menschlichen Haut. Pflugers Arch. f. d. ges. Physiol., **179:** 154, 1920.
2. Brazier, M. A. B.: An electrical method for use in the diagnosis of disease of the thyroid gland. Lancet, **2:** 742, 1933.
3. Barnett, A. and Byron, C. S.: A comparative study of impedance angle and B. M. R. in 325 consecutive cases. West. J. Obst. and Gyn., **44:** 387, 1936.
4. Barnett, A.: The basic factors involved in proposed electrical methods for measuring thyroid function; the phase angle and impedance of the skin. West. J. Obst. and Gyn., **45:** 540, 1937.
5. Brazier, M. A. B.: A method for the investigation of the impedance of the human body to an alternating current. J. Inst. Elect. Eng., **73:** 203, 1933.
6. Horton, J. W. and Van Ravenswaay, A. C.: Electrical impedance of the human body. J. Franklin Inst., **220:** 557, 1935.
7. Gerstner, H.: Statistische Untersuchungen uber den Wechselstromwiderstand der menschlichen Haut in Tonfrequenzgebiet. Arch. f. d. ges. Physiol., **250:** 125, 1948.
8. Gerstner, H. and Gerbstadt, H.: Der Wechselstromwiderstand der menschlichen Haut. Arch. f. d. ges. Physiol., **252:** 111, 1949.
9. Gougerot, L.: Recherches sur l'impedance cutanee en courant alternatif de basse frequence au cours de differentes dermatoses. Ann. de dermat. et. syph. (series 8), **7:** 101, 1947.