ELECTRICAL PROPERTIES OF THE SKIN

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SUMMARY : *Electrical measures taken from the skin may reflect the level of sweat secretion, the state of the blood vessels of the corium and the state of one or more living cell layers. Electrical changes may be related to structural rather than neural factors. Because of the dependence of the electrical properties on morphology and functional state, the electrical properties may change with cutaneous pathology. In the light of the dynamically changing characteristics of the skin, the treatment of its electrical properties should appropriately focus upon their relation to functional state as well as structure.*

Key Words : *Galvanic Skin Response, Skin, Skin Aging.*

Skin is a structure which protects the internal homeostasis against the variable ambient conditions on the surface of the body. In addition to its role in thermoregulation and water-balance, the skin is also a tactile sensory organ and its mechanical characteristics greatly influence the nature of neural pattern which occurs where it makes contact with an object (Elden, 1971).

The skin is composed of two layers : the epidermis and beneath this the dermis (or corium). These two layers are firmly adherent to each other and form a membrane that varies in thickness from about 0.5 mm to 4mm or more in different parts of the body. Beneath the dermis is a layer of loose connective tissue that varies from areolar to adipose in character. This is a superficial fascia or hypodermis (Fig 1) (Leeson et al. 1988; Tortora and Anagnostakos, 1987).

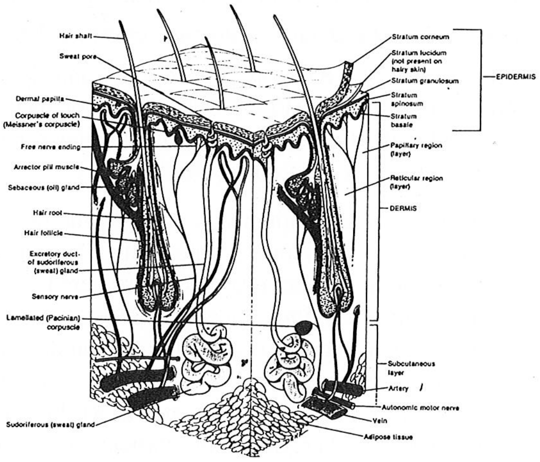

Fig. 1 : Structure of the skin and underlying subcutaneous layer. (Tortora and Anagnostakos, 1987).

ELECTRICAL PROPERTIES OF THE SKIN

Since thermoregulatory and tactile requirements vary in diffrent parts of the body, it is to be expected that electrical characteristics of the skin may show a topographical specificity. The electrical properties of human skin should also show annual periodicity. In addition to short term (phasic) variations and longer (periodic) variations in electrical properties, there are also changes as a function of age. Electical changes may be related to structural rather than neural factors (Elden, 1971; Harkness, 1971).

Structural and Functional Variations of Electrical Properties of the Skin :

Resistance, Conductance :

Skin is a mosaic in which a relatively uniform laminated structure is perforated by structures having markedly different characteristics, namely the sweat ducts and hair follicles. The various layers of the skin also differ amoung themselves in their electrical properties. These various structures account for at least 90 % of the resistance measured between two electrodes, approximately 1 to 2 cm^2 in area, placed at any two spots on the body surface. If the electrodes are considerably larger, the skin's resistance becomes a proportionately smaller fraction of the total, since, the deep tissue resistance is essentially of constant magnitude, while the skin 's resistance decreases with increasing area (Edelberg, 1971). The base levels of the skin resistance range from under 10 $K\Omega.\ cm^2$ (Kilo ohm. cm^2) for damp skin, to over 500 $K\Omega.\ cm^2$ for very dry and skaly skin (Cromwell et al. 1973). Skin also accounts for essentially all of the potential difference measured between the two electrodes (Bahill, 1981).

The electrical conductivity of any structure is directly related to its ionic permeability. The major thickness of the corneum has been considered to be freely permeable to ions since Rein was able to demonstrate that large ionic dye radicals can diffuse as far as the compact layer of corneum near the germinating layer. Although others such as Rushmer et al (Edelberg, 1971) regarded the corneum as an ion impermeable layer; further evidence that the greater part of the corneum is freely permeable to ions is seen in the demonstration by Fleischmajer and Witten (Edelberg, 1971) that thorium - X diffuses passively as far as the stratum conjuctum.

Dry corneum is a poor conductor and its conductivity is altered by the state of its hydration. If one touches a dry microelectrode (Ag/AgCl) tip to the skin surface, resistance may be above 100 $M\Omega$ for a 10 micron tip. If one now places a microdroplet of saline beside the tip, resistance promptly falls; eg, 10 to 20 $M\Omega$. Suchi and Edelberg have pushed pipette microelectrodes throught the dry corneum while recording resistance. As the deeper layers of the stratum corneum are reached, resistance decreases appreciably, but not suddenly, probably as a consequence of increasing hydration. At a certain point, the subject reports the first sensation of mild pain and as the pipette is pushed slightly further, the resistance suddenly falls essentially to the magnitude of the electrode alone. Suchi found this to occur at a depth of 50 μ (micron) on the forearm and 350 μ on the palm (Edelberg, 1971).

The innermost layer, the corium is relatively rich in intracellular spaces through which ions may pass freely. As the ionic current has reached the corium, one may regard it essentially as being inside the body. Free passage through this volume conductor means that most of the potential drop in the current path occurs in the layers above the corium. This is confirmed by microelectrode observations once the electrical barrier has been punctured, further penetration into the corium has no effect on total resistance (R). Other than hair follicles, the sweat glands constitude a major conductive path throught the barrier layer. The lumen of the duct and secretory portion is a good conductor when filled with sweat, so that a secreting sweat gland affords a freely conducting current path from the surface to the secretory portion deep in the corium. The high conductance of the sweat glands is consistent with the observation that electrical conductance is ve ry high on those areas having the highest concentration of sweat glands (Ehrenstein and Ganot, 1981).

The hair follicle constitutes a low resistance pathway throught the skin. Moreover, the scalp was found to be the most conductive of a large number of tested areas on the body surface. The skin on the dorsum of the skin close to a hair follicle has considerably lower resistance than the skin some distance away from the hair.

The vascular plexuses of the corium may also contribute to the electrical properties of the skin. Since those are freely permeable to salts and are highly conductive, vasodilation causes a decrease in the resistance of the tissue.

The resistance of the skin up to this point has been treated as an ohmic resistance, that is, one in which the voltage generated by the current is a linear function of current strength and independent of frequency. In fact, neither of these two requirements hold for the skin. Gildemeister held that the resistance of the skin is largely a reflection of a counter-electromotive force (EMF) generated by the current as a result of membrane polarization (i.e, as a result of differential mobilities of oppositely charged ions.) (Edelberg, 1971).

Potential :

Although a potential difference exists at the phase boundary between most biological structures and the surrounding fluid, created by a fixed charge; this fixed charge influences but does not constitute the potential difference measured between the surface of the skin and the inside of the body. The measurable potential differences across the skin are presumably membrane potentials and, although they could in special cases originate in an oriented dipole layer, they typically arise from diffusion processes in which ionic components possess different mobilities (Bahill, 1981).

They may develop at the interface between two layers of a solution of different concentrations, but the interposition of a membrane usually enhances the differences in ionic mobilities. Membrane potentials could develop across active living cell layers in the secretory portion of the sweat gland. The lumen of the sweat duct is about 40 mV negative with respect to the surrounding dermal tissue (Edelberg, 1971).

The skin surface is normally negative with respect to the inside of the body, the palmar and plantar surfaces being most negative. The mean transcutaneous potential at the palm was found to be -39mV, the mean value for the forearm was -15mV (Edelberg, 1971). The skin potential becames more negative when sweat glands are active. Because when they are filled, the resistance of the sweat ducts is decreased. The deeper layer of the corneum is more negative than the inner layer of sweat gland. Hence, the current flowing between them and the potential difference measured on the surface are the function of the relative resistance of the sweat duct and the corneum. Decreasing the resistance of the sweat duct (i.e., by filling) causes the surface to become more negative; decreasing the resistance of the corneu(i.e., by hydration) causes the surface to become more positive. Thus, depending upon the initial state of the tissue, increased sweating may cause either an increase or decrease in the surface potential.

The microelectrode measurements of a potential difference between sweat glands and epidermis may have special significance as an adaptive mechanism. Negatively charged bacteria accidently entering the sweat pore would be moved outward along the potential gradient between the duct and surrounding tissue. It is suggested that such a mechanism could be effective at an injured area, but in that case the relative positivity of the demaged area would tend to attract rather than repel negatively charged bodies (Edelberg, 1971).

A voluminous literature exists describing the variation in electrical properties of the skin when an individual is startled or frightened or when he is engaged in various tasks, some involving motor behaviour, others purely intellectual, such as problem solving (Edelberg, 1971).

When central stimulation is adequate and it should be appreciated that this system is exquisitely responsive, a discharge of sympathetic impulses to the skin causes a sudden change in skin resistance and surface potential known as the electrodermal response (EDR).

At a point about 1.5 to 2.0 sec after a brief stimulus, for example 85 dB tone, a reduction in skin resistance starts, most easily measured on the palmar or plantar surfaces. This reaches a peak usually in less than 1 sec, and may amount to as much as a 20 % decrease, although it is more commonly of the order of 0.5 to 5 %. Base levels range from 10 KΩ. cm^2, even within the same individual (Ackerman et al, 1979).

In addition to responses of central origin one may elicit localized responses by mechanical stimulation in the immediate region of the electrode. It was reported by Ebbecke (Edelberg, 1971) that a reduction of resistance occured on nonpalmar surfaces in response to local stimulation with pressure, alternating current or heat. They were interprated as due to direct stimulation of excitable cells, resulting in their depolarization. Local responses apparently originate in the epidermis, since they may be recorded from microelectrode on the surface, but not from one whose tip is situated in the dermis (Edelberg, 1971).

Capacitance :

Capacitance in tissue may arise when a thin structure in the current path interrupts the flow of ions, but, because of its dielectric property and thin dimension, allows interaction of the electrical potentials on either side of it. Frequently, in living tissue, sites of capacitance are in parallel with "ohmic" conductance pathways. Such a condition can exist at numerous loci, even in the corium, where aqueous channels are distributed in a reticular arrangement within a nonconducting material. These nonconductive materials possess an appreciable dielectric constant, and can, therefore constitute effective seperators between the "plates" which are the aqueous areas. These miniature condensors are in parallel with other portions of these aqueous channels and are sometimes in parallel with each other, sometimes in series (Dewhurst, 1976).

One major source of capacitance in biological systems is polarization capacity which is not due to the static dielectric properties of structures in the current path, but is generated by the effect of current passage upon ionic distribution. Gildemeister measured the resistance of the skin with alternating currents and found that impedance at 5 to 6 KHz was only 2 to 3 % of the value. This difference was the result of the polarization capacity of the skin (Dewhurst, 1976; Edelberg, 1971). In accordance with the membrane theory of the time, the electrical resistance of the skin was apparent rather than real, and it was in fact a counter - EMF generated by the passage of current through an ion-selective membrane. In effect unequal mobilities of the ions generates an electrostatic drag, which gets greater as current density increases. The increase in this counter - EMF is proportional to the increase in current, and, therefore behaves much the same as the potential difference generated across an ohmic resistor, that is, as a capacitor in parallel with a resistor. This view was expanded and suggested an electrical model of the skin made up as shown in Fig 2. The capacitor in this case is part of a polarization element, a capacitor in series with a resistor for the case of polarization at the phase boundary of an electrode, but applicable to membranes as well (Ehrenstein and Ganot, 1981). Whether the skin's capacitance is static or is a polarization phenomenon is still uncertain.

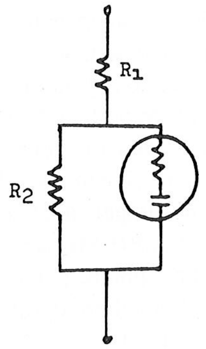

Fig. 2 : Electrical circuit of the skin represented by a polarization model. R_1 is the series ohmic resistance, R_2 is the ohmic resistance in parallel with the polarization element, P. (Edelberg, 1971).

Yokota and Fujimori demonstrated that the change in impedance during the electrodermal response is due solely to change in parallel resistance, capacitance remaining constant. Various measurements of the magnitude of this capacitance have been made and seem in general agreement, ranging between 0.02 and 0.06 μF.cm^{-2}, usually about 0.03 Gildemeiter's assumption is that the dc skin resistance is actually a counter-EMF, since membrane polarization would due its very nature be associated with a polarization capacitance. Teorell, in a brilliant analysis of the origin of potentials in membranes during the passage of current, points out that a selective membrane behaves as a nonlinear system, since as current is increased a readjustment of concentrations occurs in the membrane and its phase-boundary interfaces. When the current reaches an adequate value, the membrane channels become "saturated" with ions. At very low currents, membrane polirazation does not occur, and a measurement of membrane resistance in terms of the voltage generated by the current yields a true measure of ohmic resistance. As current increases polarization should become increasingly apparent and should show as an increase in apparent resistance of the membrane, that is, as an increase in the voltage generated by the passage of current (Edelberg, 1971).

At even higher currents, the apparent resistance of the skin decreases again. This seemingly paradoxical effect may reflect an alteration in barrier-membrane structure, rendering it more permeable.

In the Lawler's experiments, the impedance and capacitance of the skin was determined at each step in stripping procedure. Both conductance and capacitance were found to increase progressively as successive strips were removed. This would imply that at least some of the so-called "membrane" electrical properties of the skin may in fact be explained by the corneum (Ehrenstein and Ganot, 1981).

Skin's capacitance measured by Barnett and by Lawler can be attributed to the corneum's being-remote. Consider, for example, the dry corneum which may have a thickness of as little as 0.1 mm. Even at this optimum thickness for capacitance and allowing a generous value of 10 as a dielectric constant, the maximum capacitance per squared centimeter of corneum would be far too low. It can be calculated from the expression (Dewhurst, 1976)

$$CA = 0.089 \frac{K\,A}{t} \text{ X } 10^{-6}\,\mu\text{F}$$

where K is the dielectric constant, A is the area in squared centimeters, t is the thickness in centimeters. This expression gives a maximum value of 0.00009 μF. cm^{-2}, which is only a fraction of 1 % of the capacitance value of 0.02 to 0.06 μF found for skin. If the corneum is considered to be broken into a series of much thinner capacitors, whose total gives the thickness of the corneum (due to aqueous channels) the capacitance may be higher but would stil be unlikely to account for the observed value.

Hozawa and Lykken investigated (Edelberg, 1971) the skin's capacitive properties by the use of ac measurements. In this method, where the electrical impedance of the skin is represented by the circuit in Fig 3, a voltage step is applied to the skin, the current strength is measured during the initial transient and in the subsequent state region. During the initial infinite rate of change of voltage the capacitor offers essentially no reactance and the current strength is determined purely by R_1. When after a few milliseconds the capacitor is fully charged the current is determined by R_1 plus R_2.

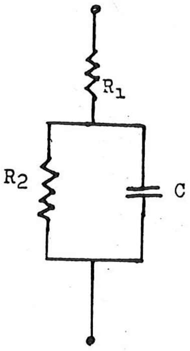

Fig. 3 : Electrical circuit of the skin, C is a static capacitance. R_1 is a series ohmic resistance, R_2 is the ohmic resistance in parallel with C (Edelberg, 1971).

For deep tissue, only R_1 is nearly 102 to 190 Ω (The ohmic resistance of the deep tissues is constant while that of the skin varies reciprocally with area). For inner-tissue, R_1 is near to 380-500 Ω. Values of R_2 can be obtained from comparison of the peak and steady-state currents (Dewhurst, 1976). Range of R_2 was calculated 32 to 710 KΩ. cm^2, for different experiments (Edelberg, 1971).

Impendance :

As a result of the skin's capacitance its impedance decreases with increasing frequency of the measuring current. At higher frequencies (e.g. above 10 KHz) the reactance of the shunt capacitance in the skin is very low and after subtracting deep-tissue resistance, the impedance should be equal to the ohmic resistance of the skin. Because polarization does not occur at high frequencies, the electrodermal response does not appear (Dewhurst, 1976; Edelberg, 1971).

If one uses a representative value, 0.025 μF. cm^{-2}, assuming it is a static capacitance, the reactance of 1 cm^2 capacitive element may be calculated as follows (Edelberg, 1971) :

1	Hz	6.3 M Ω
10	Hz	630 K Ω
100	Hz	63 K Ω
1	KHz	6.3 K Ω
10	KHz	630 Ω
100	KHz	63 Ω

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