THE JOURNAL OF INVESTIGATIVE DERMATOLOGY, 69:324–327, 1977

Vol. 69, No. 3
Printed in U.S.A.

RELATION OF ELECTRICAL PROPERTIES OF SKIN TO STRUCTURE AND PHYSIOLOGIC STATE

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Interpretation of cutaneous electrical measurements in terms of structure or function requires special techniques for identifying the separate contributions of the various elements. Resistance measures have different implications depending upon whether the subject is sweating and whether the electrode preparation is wet or dry. Microelectrode measurement indicates that the stratum corneum and other epidermal layers represent a significant pathway for ion conductance. Impedance measurement allows estimation of skin capacitance and of the thickness of the capacitative element. When applied to data on excised stratum corneum, this analysis indicates the presence of a relatively impermeable layer less than 2 microns thick, a conclusion subject to some doubt because of uncertainty over the dielectric constant of wet keratin. The use of impedance measurement with closely spaced electrodes gives an indication of the hydration of the superficial horny layer and also demonstrates reabsorption of sweat from this region. Potential measurement at the surface reflects the relative internal resistance of two parallel sources, the sweat glands and an "epidermal generator."

Because the skin consists of a series of heterogeneous laminar structures perforated by sweat ducts that are filled to varying degrees, electrical measures are difficult to interpret without special techniques to allow sorting out of the various contributions. In this paper I will consider the properties of these separate components and will examine electrical measurements that may allow their individual or relative assessment.

DC RESISTANCE (OR CONDUCTANCE)

Electrical conductance in biologic tissue depends on the ion-permeability of the tissue in question. The sweat duct is obviously a very accessible route. Dry stratum corneum is an almost impermeable tissue but wet corneum, by virtue of aqueous channels between the keratin plates and possibly between the keratin fibrils, is rather freely conductive [1]. Szakall [2] and Blank [3] have suggested that there is in the stratum corneum a layer of keratinized cells that is so densely packed that its interstitial aqueous channels are minimal; if such a dense layer exists, it could constitute an effective electrical barrier even in wet preparations. The germinative layer, by virtue of the large interstitial canaliculi in which even protein molecules have been observed to migrate [4], is rather freely conductive, but the granular layer possibly constitutes a barrier as does the dermoepidermal junction, where the cells are tightly joined. The membranes of these cells may be relatively ion-impermeable as are those of many cells because of their lipid or protein content. In the corium, with its liberal interstitial spaces, ions move freely.

The interpretation of skin conductance depends on the conditions under which it is measured. Since the sweat ducts are in parallel with the stratum corneum, the conductance of *dry* skin is very much a function of the fullness of the ducts. Thomas and Korr [5], taking dry measurements with 4-sec application of the electrode for each determination, found a median correlation of .91 between conductance and number of filled ducts. By contrast, workers who measured skin conductance with wet electrodes and observed transpired vapor or number of active sweat glands on a nearby site, found correlations ranging from .04 to .45 [6–9]. This reflects the fact that in wet measurement the stratum corneum, in series with other epidermal layers, constitutes an appreciable shunt pathway and the dominant role of the sweat ducts in determining conductance is substantially weakened.

Evidence for the appreciable contribution of this extraductal pathway to overall conductance is provided by microelectrode measurements. If one places a micropipette on a droplet of sweat at the pore of an active sweat gland, the conductance is found to be high as compared with that of the corneum between sweat glands. When a total count of sweat glands, active and inactive, is made in a circumscribed area and this number multiplied by the average conductance of those sampled, an estimate of the *maximum* contribution by the total sweat glands is obtained. If one now applies electrode paste (isotonic with average sweat) to this area and uses a metal plate electrode

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to measure the conductance, it is found to be about twice as great as the estimate from the sweat glands, indicating the considerable contribution of the corneum (48 ± 20% of the total; N = 6).

In the *nonsweating subject*, with dry electrodes briefly applied, the high resistance of the corneum is in series with the much lower resistance of the underlying cell layer [10,11]; the corneum therefore dominates the resistance determination. Resistance then reflects essentially the relative dryness of the stratum corneum and, to a degree, its electrolyte content. When electrolyte solutions are used as electrode media, the soaking of the corneum reduces its resistance to a minimum. Resistance then reflects, not hydration, but the thickness and density of the corneum and the permeability of the underlying layers.

IMPEDANCE

In impedance measurement, the use of alternating currents brings in another factor, namely capacitative elements in the skin. Cell membranes have a capacitance of about 1 mfd/cm^2 [12] and keratinized cells apparently retain this property, at least in part; accordingly the horny layer and other epidermal layers have capacitative properties. With some notable exceptions [13,14], most investigators agree that the circuitry in the skin is best represented by a leaky capacitor, i.e., by a capacitor, C_p, in parallel with a resistor, R_p, this pair being in series with the body resistance, R_s [15,16]. Many believe that R_s consists of two primary elements, the series resistance of the skin and that of the deep tissues.

Thickness Determination

Calculations based on impedance bridge determination of the equivalent series resistance and capacitance at two frequencies can provide a value for C_p, assuming the above configuration. From this and a knowledge of the dielectric constant one can obtain an estimate of the thickness of the capacitative element. This approach was applied to Rosendal's data [17] on wet, freshly excised stratum corneum taken at 1 KHz and 10 KHz. It gave a value of .0046 mfd/cm^2 for C_p, in parallel with a resistance of 34854 ohms·cm^2. R_s was 6168 ohms·cm^2.

The equation for determining the thickness, t, of the capacitative element in centimeters is:

$$t = 8.9 \times 10^{-8}\ KA/C$$

where K is the dielectric constant, A the area in cm^2, and C the capacitance in mfd. Using a value of 10 for the dielectric constant of dry keratin [17], the thickness of the capacitor in Rosendal's sample of corneum (approximately 1 mm thick) is found to be only 1.93 microns. This could be interpreted as evidence for the presence of a thin, relatively unshunted capacitance in the corneum, i.e., a structure essentially equivalent to the barrier layer hypothesized by Szakall [2] and by Blank [3]. Such a conclusion is placed in doubt, however, by the observations of E. Clar (unpublished data) that the dielectric constant of wet stratum corneum is about 600 (as compared with 2 to 3 in the dry state). This value would give a thickness of 116 microns for the capacitative element.

Impedance at High Frequency

At very high frequencies, capacitors offer little reactance to the passage of alternating currents and in effect short circuit any parallel ion-conducting pathways. The only elements left to contribute to impedance are the unshunted series resistances. The contribution of the deep tissues to resistance can be eliminated by the use of Barnett's 3-electrode system [18]. What remains is a component whose magnitude in relatively dry skin is almost entirely a function of the moisture content of the corneum and hence may constitute an optimal hydration indicator. Clar and her coworkers [19] have used impedance measurement at 25 Hz to indicate degree of hydration. While measurement at such a low frequency is almost equivalent to DC measurement, it has the advantage of reducing electrode polarization.

CLOSELY SPACED ELECTRODES

Electrodes are normally separated sufficiently to render any lateral conductance negligible. As the electrodes are brought closer together an appreciable portion of the total current traverses the surface layer between the two, and if the electrodes, rather than being extensive plates, are fine parallel wires, an even greater fraction of the current is short circuited across the skin surface. These two wires may be embedded in plastic flush with the surface and separated by 0.1 mm [20]. Lateral resistance is then appreciably less than the transverse resistance through the epidermis. This measurement covaries with the high-frequency impedance and probably bears a similar relation to moisture content, but it assesses a layer near the surface while the transverse impedance measure is more an average of the entire depth of corneum.

An interesting effect that has been disclosed by this measurement with closely spaced electrodes is the phenomenon of reabsorption of sweat. A considerable literature affords evidence for the reabsorption of water, as well as solutes, in the deeper region of the duct [21], but in the present case reabsorption of sweat that has already been "excreted" is taking place. It occurs suddenly, in conjunction with the electrodermal response (Fig.) and is signalled by a sudden increase in resistance at the surface [20,22].

SURFACE POTENTIALS

Membrane potentials commonly arise as a consequence of unequal mobilities of oppositely charged ions due either to steric or electrostatic drag imposed by the membrane. The ion-permeable channels in wet corneum are probably too

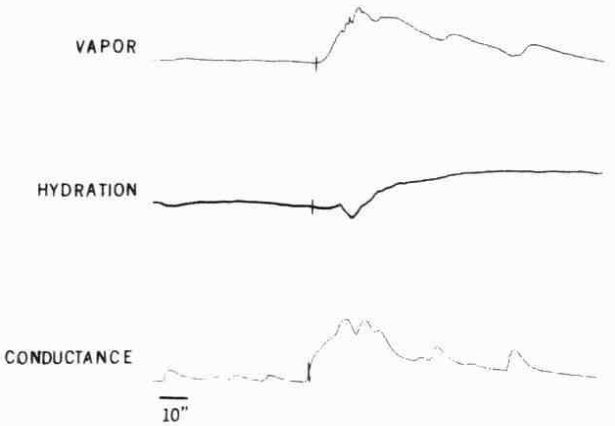

FIG. Demonstration of sweat reabsorption response (*middle trace*). Simultaneous recordings of vapor (sweat evaporation into flowing air stream), surface hydration, and skin conductance from sites on the volar surfaces of three fingers. Vapor concentration, hydration, and skin conductance increase upwards. Center trace is obtained by impedance recording (750 Hz) from closely spaced electrodes in contact with skin. Time line, 10 sec.

large to exert selective steric effects but the fixed charge may have an electrostatic effect, as in Sollner and Gregor's perm-selective collodion membranes [23]. Other likely structures for the origin of potentials are the epithelial lining of the sweat duct and secretory tubule, and the cell membranes of the granular layer and of the germinative layer.

Various findings implicate the sweat gland as a potent source of surface negativity [24]. The stratum corneum (or other epidermal layers), though still negative with respect to the corium, is much less so than the lumen of the sweat duct. The net potential recorded at the surface is a function of the interaction of these two parallel voltage sources and is a measure of their relative internal resistances [25]. As the sweat ducts fill, the internal resistance of the more negative source falls and the surface becomes more negative. If the corneum becomes wet (conductive), the internal resistance of the less negative voltage source is increased and the surface negativity falls. Thus, for dry skin, prior to the appearance of frank sweat at the pore, the degree of surface negativity can serve as a measure of duct filling. As the corneum becomes progressively wetter and its surface negativity is thereby reduced, the relationship becomes considerably weaker.

In the absence of sweating, surface potential in a wet preparation essentially reflects the diffusion potential across the epidermis. The selective permeability of this membrane (or membranes) is a function of its integrity. Thus, if one abraids the corneum with a dental drill [26] or by skin stripping [10], the transcutaneous potential drops essentially to zero when the mucous layer is exposed. It remains close to zero for 3 to 4 days and then over a period of approximately 24 hr rises to normal levels. It appears that the transcutaneous potential is generated across a relatively thin layer of epidermal cells, presumably in the germinative or granular layer. It should be appreciated that similar findings would occur even if no potential were generated in this epidermal layer, if temporary loss of the epidermal electrical barrier were to short circuit the negative potentials arising in the sweat glands.

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