ELECTRICAL RESISTANCE OF THE SKIN

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Function and Structure of Skin

In beginning an examination of the electrical resistance of the skin, it is worthwhile to describe the function and structure of the skin. The main functions of the skin are the following: to keep out foreign substances, to protect the underlying tissues from injury, to maintain adequate moisture in the tissues, to regulate body temperature, to aid in the elimination of water and waste materials, such as oil and wax, and to act as the receptor organ for the sense of touch. There are pores that allow bacteria to pass through. These openings are never closed. Fairly frequently the skin experiences injuries, such as, bruises, blisters, cuts, and punctures.

The skin or integument is essentially composed of three layers of tissue, the epidermis, corium (true skin), and the subcutaneous tissue (Figure 1). The epidermis has no blood vessels and consists of a number of layers of cells. Forming the most lateral portion of the epidermis is the stratum corneum or horny layer. This layer is a porous network of coarse fibers that is easily penetrated by ions, large molecules, and even molecular aggregates. Medial to the horny layer is the stratum lucidum or living barrier. It cannot be seen clearly except in the skin of the palms and soles. These are the regions where the galvanic skin response and the endosomatic skin response are the most pronounced. The stratum lucidum blocks the passage of fluids that are applied to the skin. Eighty percent of wet skin resistance resides in this thin membrane of the epidermis that seems to be permeable to cations, but is impermeable to anions.

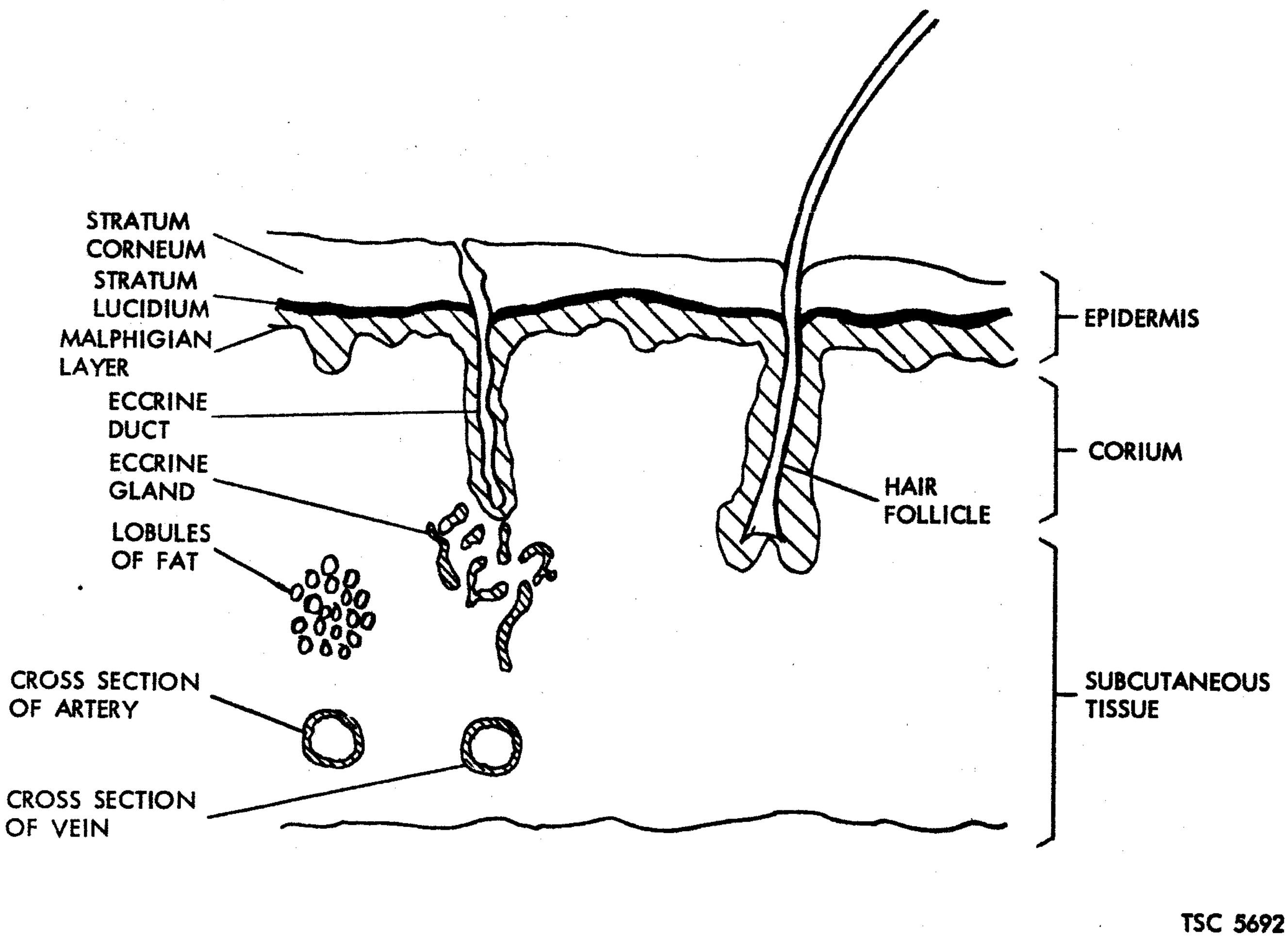


Figure 1. Cross Section of the Skin[1]

Below the stratum lucidum lies the inner portion of the epidermis, the malphigian layer. Substances that have penetrated to this layer find no difficulty in continuing their movement throughout the epidermis.

Medial to the epidermis is the corium or internal dermis that is composed of loose connective tissue. Contained in the corium are capillaries, lymphatics, nerve endings, lobules of fat, roots of hair follicles, sebaceous glands, and sweat glands. The corium is passive to the migration of ions. Below the corium is subcutaneous tissue, which is a good conductor. Portions of sweat glands may penetrate into the subcutaneous tissue.

There are two types of sweat glands, apocrine and eccrine. The latter type outnumber the former and are widely distributed, being most dense in the palmar, plantar, forehead, and axillary regions. The average daily excretion of sweat averages about one pint. Nerve centers in the brain and spine regulate the action of these glands. Sensory stimuli can cause the sweat glands to increase their activity, but fright, nervousness, or severe pain will cause an even more marked increase. As the rate of sweat secretion of an area increases, the skin resistance falls.

Resistance and Capacitance of Skin Layers

Skin resistance, which can be measured by placing electrodes on the epidermis, is a function of the resistances of basically two layers of the skin. The primary sources of skin resistance are the stratum lucidum and stratum corneum. Resistances from 5,000 to 500,000 ohms per square centimeter have been found for the stratum lucidum. This range was established by tests on various parts of the body for subjects in differing conditions. If the stratum corneum is dry, it can contribute more than 1,000,000 ohms per square centimeter to the total resistance.[2] When audio frequencies less than 1,000 cps are impressed on the corneum, the resistance is very high. Increasing the frequency reduces the resistance of the corneum.

When the frequency of the applied current is raised, the impedance falls due to capacitive shunting. Calculations have shown that at frequencies of 250-300 Kc the capacitive reactance through the skin is small (with an electrode area of 2.5 square cm) that the voltage drop in the stratum corneum can be disregarded.[3] Experimental data that has been gathered indicates that the impedance was constant at 7,000 ohms from 10-20 cps and fell to 0.707 of this value at 80 cps, which corresponds to a shunt capacity of 0.28 μF. Capacitance has been found to vary from 0.25-0.35 μF. Attenuation at higher frequencies is less than would be expected from the model that was just cited, since experimental evidence has shown that the impedance at 320 cps was 2,100 ohms and not the expected value of 1,700 ohms. Evidence such as this tends to support the view that the skin capacitance has a phase angle less than 90 degrees.[4]

Dependence of Resistance on Time

Both skin capacitance and skin resistance have been shown to vary with time. Initial resistance is very high, frequently over several hundred thousand ohms per square cm. As the stimulus value is increased, there is a corresponding reduction in skin resistance. This reduction appears to take place simultaneously with the increase in stimulus. In fact, it has been found that skin resistance varies without time lag in accordance with the instaneous magnitude of the voltage across the skin. The prolonged passage of currents at densities exceeding 1 μA per square cm causes a profound fall in resistance. Continued passage of DC brings about a slow and incompletely reversible fall in skin resistance, especially at the cathode. A partial cause of this effect is the influence of the ionic composition of the electrode that is in contact with the skin. Thus ion migration is an important influencing factor of skin resistance.

Experimental evidence has indicated that after an initial rapid fall in impedance, the resistance to voltages between one and 2.5 V was about twice as large for anodal currents as for cathodal currents. If voltages greater than 2.5 V were applied, the skin resistance decreased irreversibly, and the difference between anodal and cathodal effects was diminished.[5] It was found, however, that the initial resistance was the same for currents in both directions. In applying a cathode electrode to a sweat gland, it was found that the negative potential increased, but when an anode was applied, an initial peak EMF was generated that declined as the current continued. For the epidermis, the opposite was found to hold. Two of the subjects reacted to the sweat gland tests as described above, and the remaining two subjects produced results similar to those expected for the epidermal portion of the skin.[6]

Factors Causing Variation in Skin Resistance

The example above illustrates that different subjects can yield differing skin resistance measurements. Beside the variation in skin resistance between subjects, the following factors are also important: size of electrode, type of electrode, bodily area from which the records are taken, temperature of this area, whether the external current passing through the subject is AC or DC, the size of this current, and whether it remains constant or varies with the change of resistance from subject to subject.[7]

Ions that naturally occur on the skin can be a potential source of variation in skin resistance. One source of ions is from the sweat glands that can produce sodium chloride in concentrations of more than 0.05 M. This value can become significantly higher as a result of the evaporation of the sweat. As the amount of perspiration increases, skin resistance falls. Even small quantities of sweat greatly interfere with measurements of skin resistance, and minute cuts or punctures that may be difficult to visually locate can greatly reduce the basal resistance by acting as short circuits through the stratum corneum and stratum lucidum. Electrodes must be applied to clean and dry skin surfaces to sharply define the effective surface area of the electrode and to obtain reproducible contact impedance measurements.

Relationship Between Sweat Glands and Skin Resistance

The three electrode measurements that can be made at the surface of the skin are endosomatic skin response, basal skin resistance, and galvanic skin response. Endosomatic skin response is independent of the area under measurement, while exosomatic skin response varies inversely with area. Basal skin resistance varies inversely, but not linearly, with temperature by approximately three percent per degree centigrade.[8] There is a relationship between galvanic skin response (GSR) and the general level of palmar skin resistance as Figure 2 indicates.

It has been found that the presence and magnitude of the galvanic skin response is directly related to the number of sweat glands present in the area under the electrodes used for measurement. As Figure 2 shows, the galvanic skin response is dependent on skin resistance; thus, since galvanic skin response has been found to be related to the number of sweat glands in a region, the skin resistance of an area is dependent on the number of sweat glands per square cm.

At 55 degrees Fahrenheit, in patients with congenital absence of sweat glands, no areas of low skin resistance could be found. Such results are similar to those for normal subjects, because at low temperatures the sweat glands are inactive. At room temperature the skin resistance

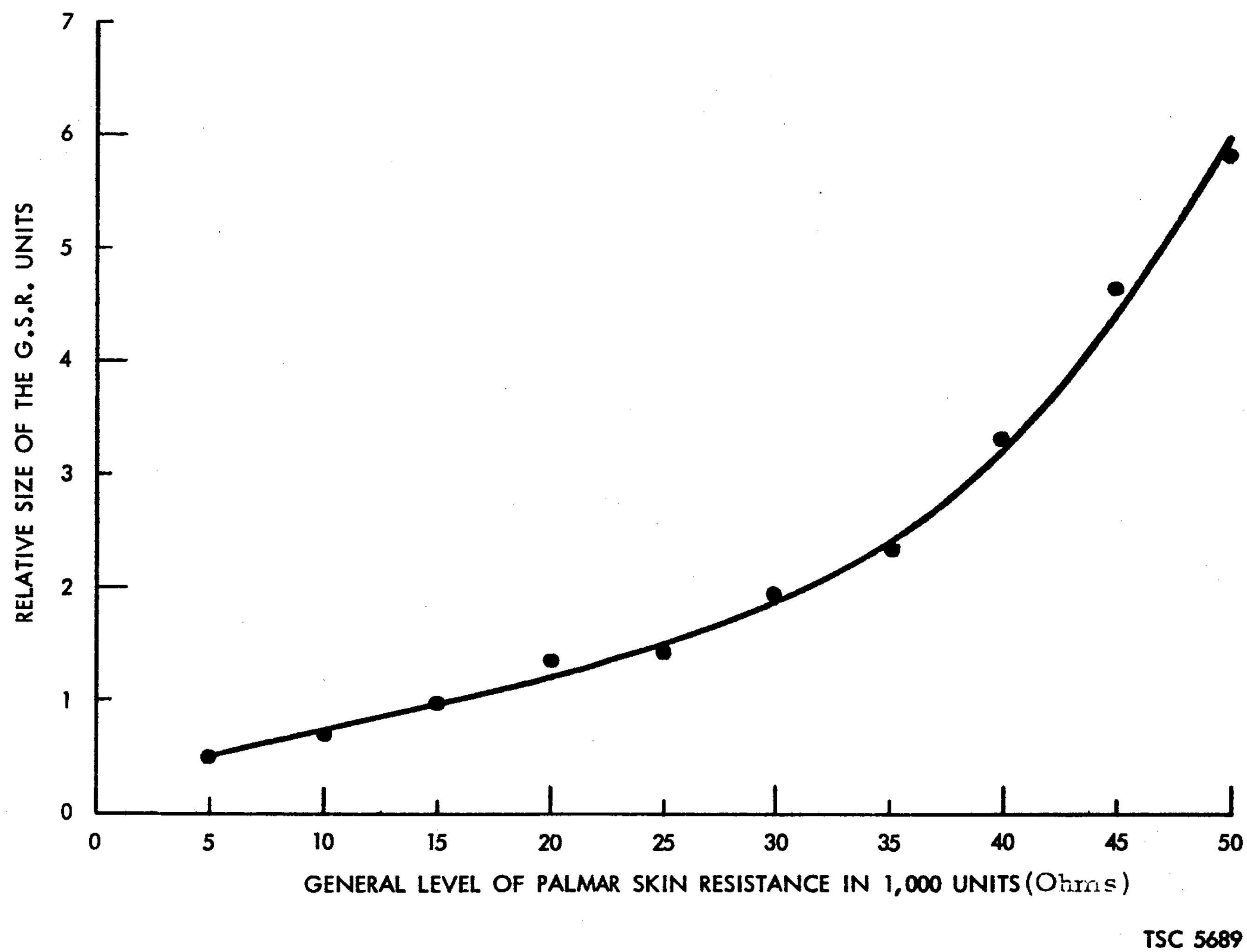


Figure 2. Relationship Between Palmar Resistance and Galvanic Skin Response [9]

for the previously mentioned patients remained extremely high over most of the body, but areas of somewhat lower resistance were detected in the face and over the upper chest. Resistances considerably below these areas were found for the palms, soles, and armpits. After thirty minutes of heating, the patients' skin resistances remained very high except for the five areas just listed where the resistance became very low. In the armpit region, the resistance was 150,000 ohms, while on the trunk it was about 3,000,000 ohms.[10]

The relationship between skin resistance and density of sweat glands is clearly shown by the test results above, and it can easily be comprehended that the most important path in galvanic skin resistance is through the sweat glands. Thus, skin resistance is related to the ducts of the eccrine glands, which provide shunt paths through the stratum corneum and stratum lucidum. The resistance of these shunt pathways is controlled by the sympathetic nervous system by its effect on emotional sweat secretion. In areas where sweat glands are present, the electrical resistance is dramatically lower and varies inversely with environmental temperature and consequent sweat gland activity. Minimal skin resistance is approximately 20,000 ohms per square cm.[11] A hypothesis can be made for areas containing sweat glands that have their excretory duct closed or collapsed. These areas will record a skin resistance that will be very close to that for a body area that does not have any sweat glands.

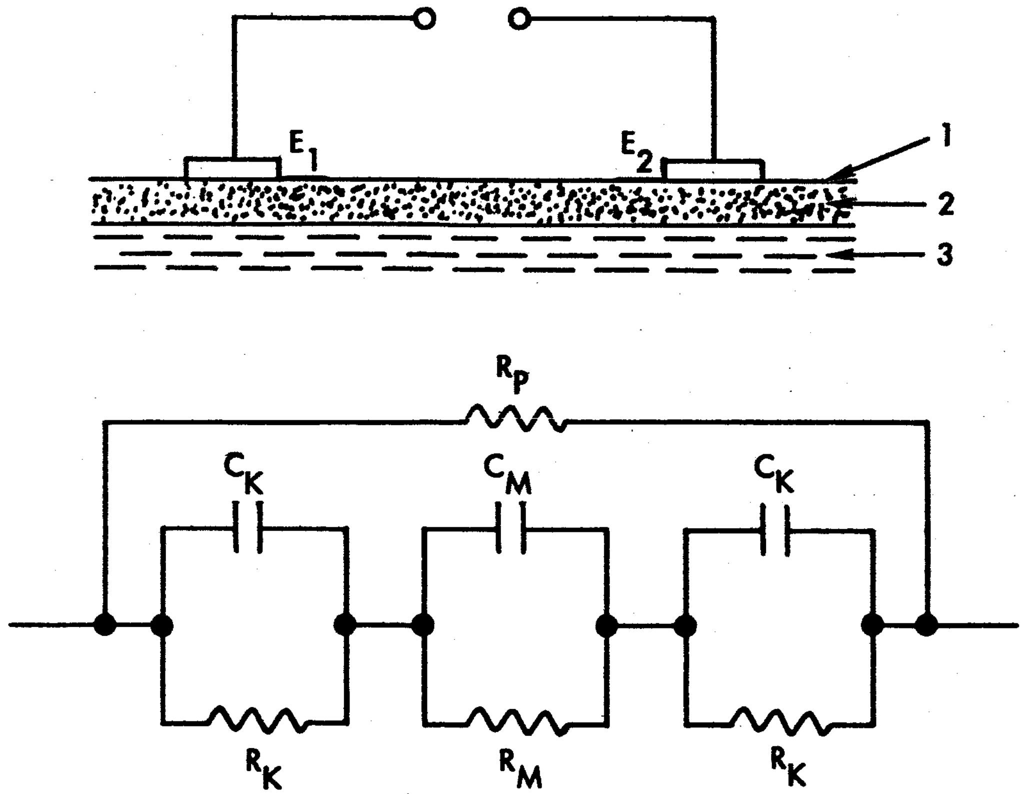
Model of Skin Impedance

Now after presenting date on the function and structure of the skin, resistance and capacitance of skin layers, dependence of resistance on time, factors causing variation in skin resistance, and the relationship between sweat glands and skin resistance, a model of skin impedance can

can be put forth. A rather simple model is shown in Figure 3. Here only the stratum corneum, subcutaneous tissue, and deep tissues are taken into account. At low frequencies, the impedance of the skin is so high that most of the voltage applied will fall across R_K. Since the subcutaneous tissue has a much lower impedance than the stratum corneum, nearly all of the measured skin impedance will be due to the lateral layer. Also the impedance between the two electrodes will be nearly independent of their separation.

A more complete model of the skin and its underlying tissues is shown in Figure 4. Besides including the resistance and capacitance of the outer layers of skin and the resistance and capacitance of the internal tissues, the model in Figure 4 indicates the resistance and capacitance between the source and the subcutaneous tissue. When making a skin resistance measurement, the resistive and capacitive affects of the stratum corneum and stratum lucidum are so much greater than from the subcutaneous tissue that the latter may be considered a short circuit. Since nearly all of the internal tissues within the body are surrounded by ionic solutions that are good conductors, it may be assumed that the electrical signals that propage to the subcutaneous tissue are attenuated only slightly and are nearly undistorted. Thus, the resistance and capacitance from the source to the subcutaneous layer are very small. On the other hand, the surface resistance is so high compared to the stratum corneum-stratum lucidum resistance that the former may be neglected.

Incorporating these assumptions into a schematic representation of the skin and adding a one mesh biogrid into the model, Figure 5 is obtained. This figure indicates that the electrical path from the source to the subcutaneous layer is a short circuit. The resistors that are drawn



1 = STRATUM CORNEUM
2 = SUBCUTANEOUS TISSUE
3 = DEEP TISSUES
E_1 = ELECTRODE ONE
E_2 = ELECTRODE TWO

R_P = SURFACE CONDUCTIVITY OF SKIN

R_K = RESISTANCE OF STRATUM CORNEUM

C_K = CAPACITANCE BETWEEN CONTACT SURFACE OF ELECTRODES AND THE SUBCUTANEOUS TISSUE

C_M = CAPACITANCE OF INTERNAL TISSUES

R_M = RESISTANCE OF INTERNAL TISSUES

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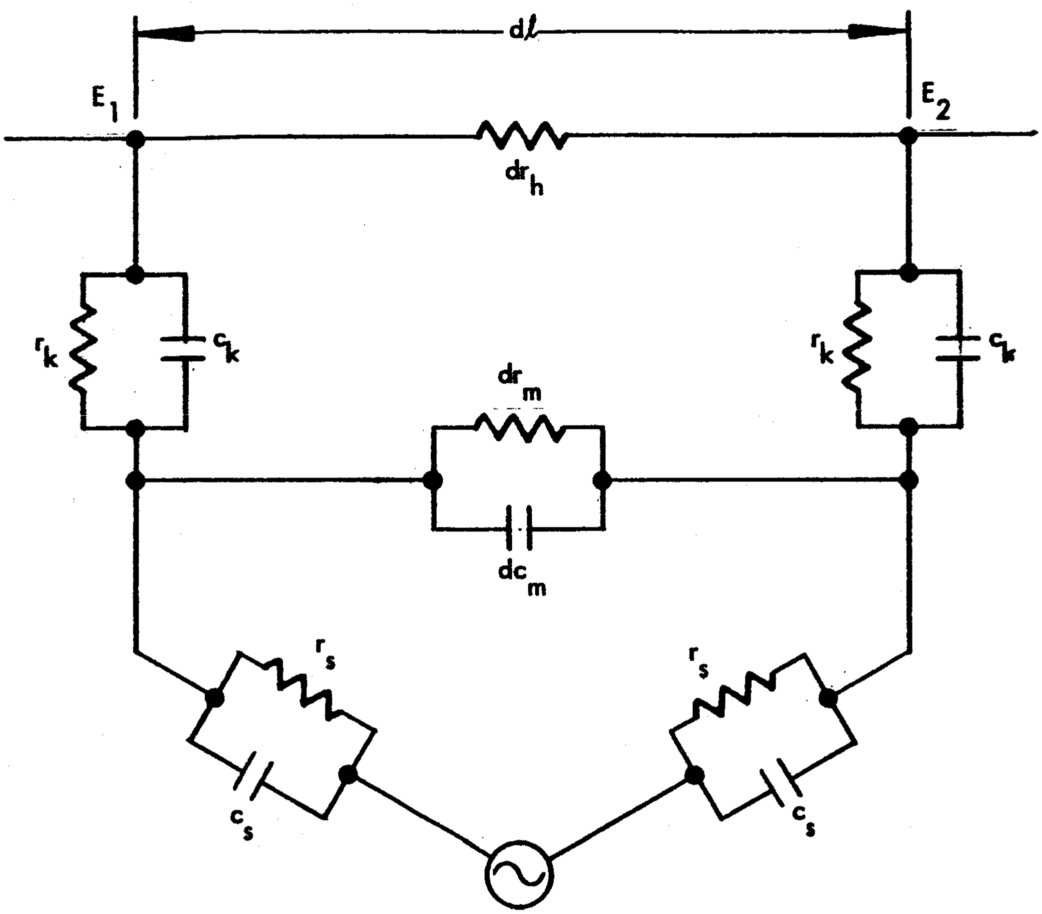
Figure 3. Equivalent Circuit Resulting from Application of Electrodes to Skin [12]



ℓ = LENGTH
E_1 = ELECTRODE 1
E_2 = ELECTRODE 2
r_h = SURFACE RESISTANCE
r_k = RESISTANCE OF STRATUM CORNEUM AND STRATUM LUCIDUM
c_k = CAPACITANCE BETWEEN CONTACT SURFACE OF ELECTRODES AND SUBCUTANEOUS TISSUE
r_m = RESISTANCE OF SUBCUTANEOUS TISSUE
c_m = CAPACITANCE OF SUBCUTANEOUS TISSUE
r_s = RESISTANCE BETWEEN SOURCE AND SUBCUTANEOUS TISSUE
c_s = CAPACITANCE BETWEEN SOURCE AND SUBCUTANEOUS TISSUE

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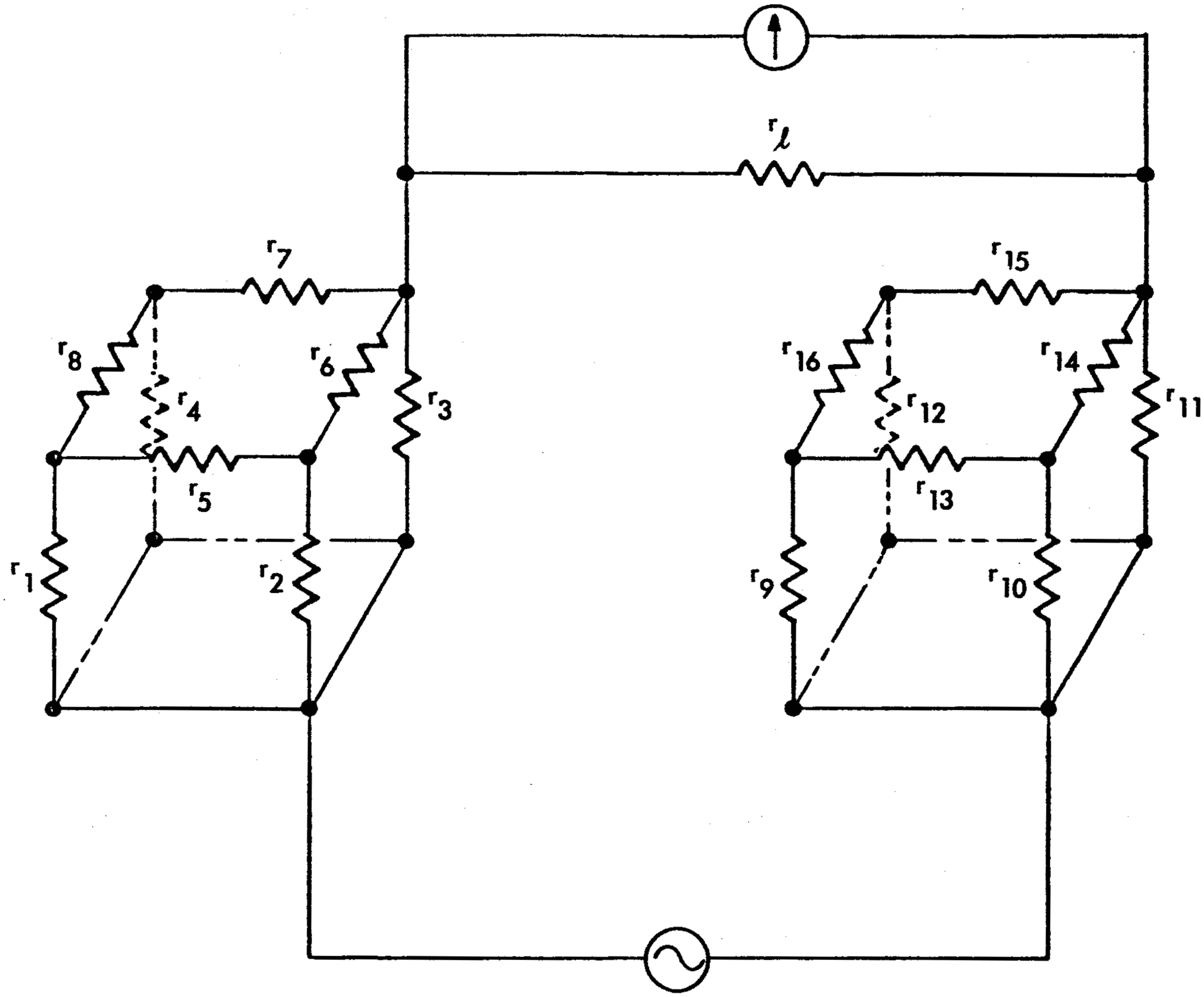
Figure 4. Model of Skin and Underlying Tissues



r_ℓ = RESISTANCE OF GRID AS A FUNCTION OF LENGTH

r_1, r_2, r_3, r_4, r_9, r_{10}, r_{11}, AND r_{12} = RESISTANCE OF STRATUM CORNEUM AND STRATUM LUCIDUM

r_5, r_6, r_7, r_8, r_{13}, r_{14}, r_{15}, AND r_{16} = RESISTANCE OF BIOGRID MESH

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Figure 5. Schematic Representation of a Pair of Single Mesh Biogrids and the Associated Skin Resistances

in the vertical direction have their lower ends shorted together in each biogrid square. These resistors represent the path from the surface of the skin to the subcutaneous tissue. Thus the subcutaneous tissue has been assumed to have negligible resistance in comparison to the resistance of the stratum corneum and stratum lucidum.

Taking only the squares of the biogrid and the associated skin resistances, the cube configuration in Figure 6 is formed. For a square of small dimensions, it can be assumed that the four resistances through the skin (r_1, r_2, r_3, and r_4) are all equal. The four segments of the biogrid (r_5, r_6, r_7, and r_8) can also be assumed to have the same resistance.

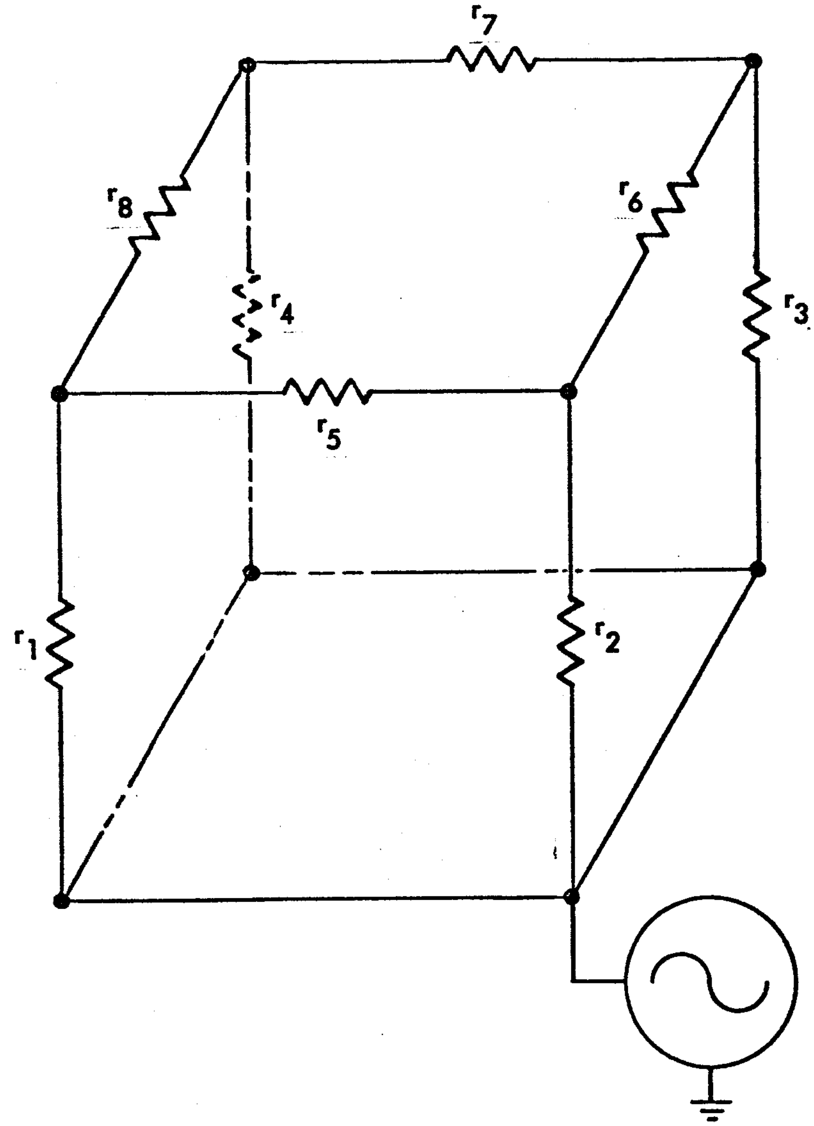
Thus we can let:

$$r_a = r_1 = r_2 = r_3 = r_4 \qquad \text{and}$$

$$r_b = r_5 = r_6 = r_7 = r_8$$

Now the equivalent resistance taken from any of the four corners of the biogrid mesh can be derived. This equivalent resistance will take the effect of the biogrid into account as well as the resistance of the stratum corneum and stratum lucidum skin layers. A comparison of the equivalent resistance and the resistance measured by using just a problem can be made after deriving an expression for the former resistance.

As a first step in deriving the equivalent resistance, the parallel resistance of r_1 and the series resistance of r_5 and r_2 can be written.



r_1, r_2, r_3, AND r_4 = RESISTANCE OF STRATUM CORNEUM AND STRATUM LUCIDUM
r_5, r_6, r_7, AND r_8 = RESISTANCE OF BIOGRID MESH

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Figure 6. Schematic of a Single Mesh Biogrid

Let the parallel resistance be given by r_m.

$$r_m = \frac{r_1 (r_2 + r_5)}{r_1 + r_2 + r_5}$$

Using $r_a = r_1 = r_2$ and $r_b = r_5$ as previously defined,

$$r_m = \frac{r_a (r_a + r_b)}{r_a + r_a + r_b} = \frac{r_a (r_a + r_b)}{2r_a + r_b}$$

Including the parallel resistance of the $r_8 - r_4$ combination in the overall resistance and setting equal to r_n.

$$r_n = \frac{r_m (r_4 + r_8)}{r_m + r_4 + r_8}$$

$$r_4 = r_a \text{ and } r_8 = r_b$$

$$r_n = \frac{r_m (r_a + r_b)}{r_m + r_a + r_b}$$

Now the remaining parallel paths are the $r_7 - r_3$ arm and the $r_6 - r_3$ arm of the cube. Since

$$f_6 = r_7 = r_b \text{ and } r_3 = r_a \text{ ,}$$

this two arm path may be reduced to a single arm composed of the series resistance

$$\frac{r_b}{2} + r_a \text{ .}$$

If r_p is set equal to the parallel resistance of r_n and $\frac{r_b}{2} + r_a$, then

$$r_p = \frac{\left(r_n \; \frac{r_b}{2} + r_a\right)}{r_n + \frac{r_b}{2} + r_a}$$

Substituting for r_n yields

$$r_p = \frac{\frac{r_m (r_a + r_b)}{r_m + r_a + r_b} \left(\frac{r_b}{2} + r_a\right)}{\frac{r_m (r_a + r_b)}{r_m + r_a + r_b} + \frac{r_b}{2} + r_a}$$

Substituting for r_m yields

$$r_p = \frac{\dfrac{\frac{r_a (r_a + r_b}{2r_a + r_b} (r_a + r_b)}{\frac{r_a (r_a + r_b)}{2r_a + r_b} + (r_a + r_b)} \left[\frac{r_b}{2} + r_a\right]}{\dfrac{\frac{r_a (r_a + r_b)}{2r_a + r_b} (r_a + r_b)}{\frac{r_a (r_a + r_b)}{2r_a + r_b} + r_a + r_b} + \frac{r_b}{2} + r_a}$$

$$r_p = \frac{\dfrac{r_a(r_a + r_b)^2 \left(\frac{r_b}{2} + r_a\right)}{r_a(r_a + r_b) + (r_a + r_b)(2r_a + r_b)}}{\dfrac{r_a(r_a + r_b)^2}{r_a(r_a + r_b) + (r_a + r_b)(2r_a + r_b)} + \left(\frac{r_b}{2} + r_a\right)(2r_a + r_b)}$$

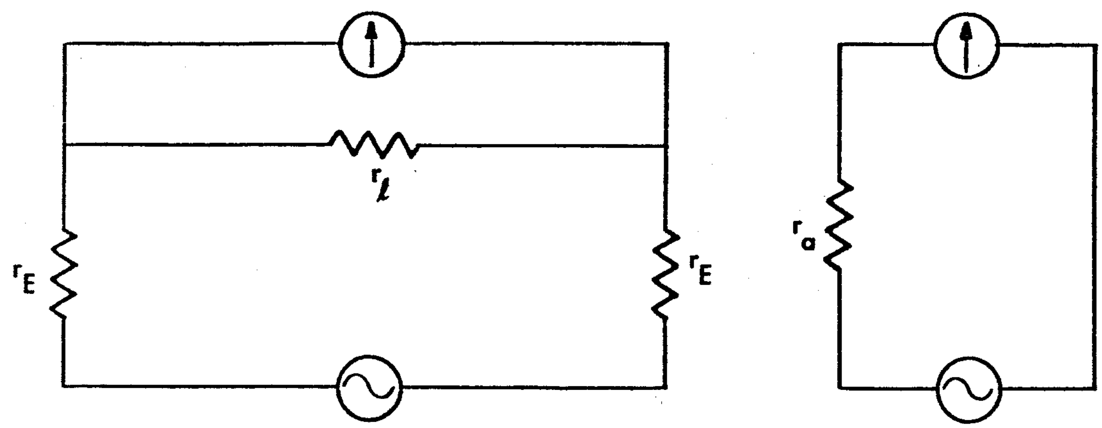
$$r_p = \frac{\dfrac{r_a(r_a + r_b)\left(\frac{r_b}{2} + r_a\right)}{r_a + 2r_a + r_b}}{\dfrac{r_a(r_a + r_b)}{r_a + 2r_a + r_b} + \left(\frac{r_b}{2} + r_a\right)(2r_a + r_b)}$$

$$r_p = \frac{r_a(r_a + r_b)\left(\frac{r_b}{2} + r_a\right)}{r_a(r_a + r_b) + (3r_a + r_b)\left(\frac{r_b}{2} + r_a\right)(2r_a + r_b)}$$

A comparison between the equivalent resistance (r_p) of a biogrid square, stratum corneum and stratum lucidium layer with the resistance obtained by measuring with a probe can be made. Figure 7 presents the schematic for the biogrid-skin equivalent circuit and the simple probe skin resistance measurement. The equivalent resistance (r_E) has been derived and is given by the equation for r_p, while the resistance encountered by the probe is simply r_a.

(a) Schematic of Biogrid-Skin Equivalent Circuit

(b) Schematic of Resistance Measurement by Probe



r_ℓ = RESISTANCE OF GRID AS A FUNCTION OF LENGTH

r_E = r EQUIVALENT

r_a = RESISTANCE OF STRATUM CORNEUM AND STRATUM LUCIDUM

TSC 5706

Figure 7

Now we are in a position to use these two resistances (r_a and r_p) in order to find the effect of the biogrid on measured skin potential. Figure 8 indicates the schematic for the skin resistance (r_a) encountered by a probe. The resistance (r_g) represents the addition of the biogrid. As Figure 7 indicated, the resistance for the case with the biogrid is represented by the parallel resistance of $\frac{r_E}{2} = \frac{r_p}{2}$ and r_ℓ. In Figure 8 this same resistance is indicated by the parallel resistance of r_a and r_g. Thus

$$\frac{\frac{r_p (r_\ell)}{2}}{\frac{r_p}{2} + r_\ell} = \frac{r_a (r_g)}{r_a + r_g}$$

$$\frac{r_a r_\ell r_p}{2} + \frac{r_g r_\ell r_p}{2} = \frac{r_a r_g r_p}{2} + r_a r_g r_\ell$$

$$r_g = \frac{r_a r_\ell r_p}{2 r_a r_p + r_a r_\ell - r_\ell r_p}$$

With this expression for r_g, the potential variation caused by the biogrid can be evaluated.

It is, of course, realized that the case examined was for a one-mesh biogrid. For a continuous biogrid, the values of the grid resistances and the skin resistances become fractions of those assumed in the one-grid case, but the approach and derivation of r_g will be the same.

An additional report is being prepared which will include analysis of actual performance and will be based on experimental values.

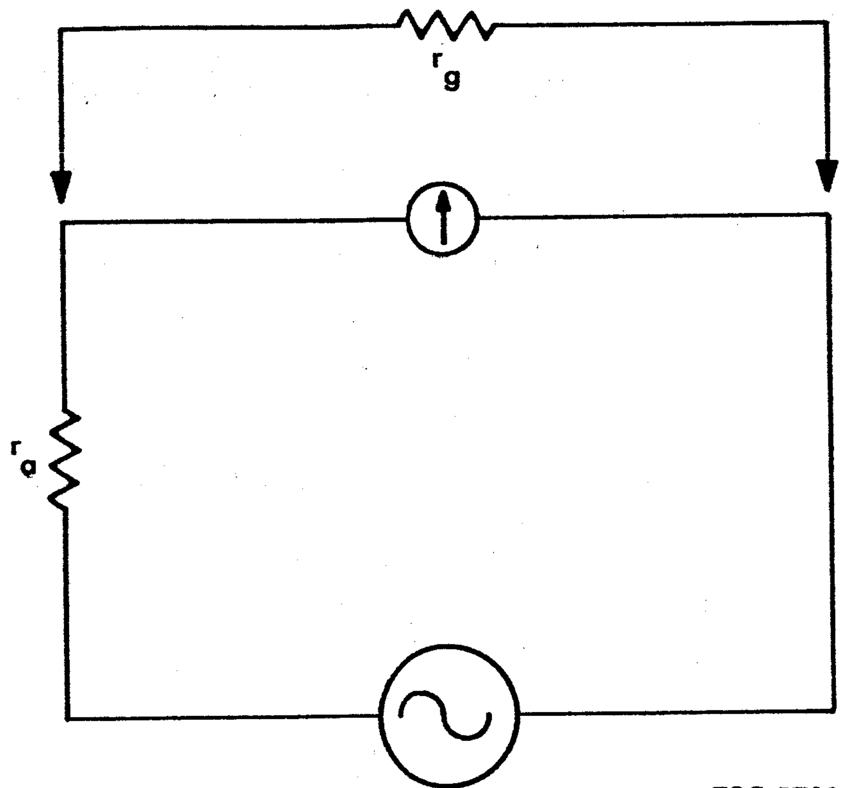


Figure 8. Skin Potential as Measured by a Probe or by a Biogrid

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