

# EXPLANATION OF ELECTRODERMAL DIAGNOSTIC AND TREATMENT INSTRUMENTS: PART I. ELECTRICAL BEHAVIOR OF HUMAN SKIN

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**ABSTRACT:** Using basic information on the electrical properties and response behavior of both macroscopic and microscopic (acupuncture points) areas of human skin, it has been possible to explain all key characteristics of the three major electrical diagnostic instruments on the market: (1) the Voll Dermatron instrument, (2) the Motoyama AMI instrument, and (3) the Schimmel Segment Electrograph instrument. None of these instruments use all information that is available to an electrical measurement and the basis for a new class of measuring instrument, capable of revealing much more information, is presented.

**Keywords:** Skin, electrical impedance, electrodermal, electrical equivalent circuit, biochemical correlates, electrical properties, acupuncture points, diagnostic techniques, AC conductance measurements.

## INTRODUCTION

Over the past decade there has been a growing interest in the electrical characteristics of acupuncture points and in the development of instrumentation to monitor the meridians' condition for diagnostic purposes. At present, at least three significantly different pieces of equipment are on the market,<sup>1-3</sup> each using different electrical techniques for assessing meridian condition. No single method uses all information available to an electrical measuring system nor does any single method explain the electrical results in terms of basic epidermal properties and processes.

Because these leaders<sup>1-3</sup> contribute so greatly to our understanding in this general area, and will be followed by other inventors of instruments designed to achieve the ultimate in diagnostic and treatment capability, we must try to understand what is actually being measured by such devices in sufficiently fundamental biochemical and cellular terms that the physiological correlates of electrical parameters become readily obvious. The purpose of the present article is to make a beginning step toward this desirable goal. This article will restrict its attention to the role of the electrical behavior of skin upon the device measurements.

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### RELEVANT ACUPUNCTURE POINT DATA

It is now well known that an electrical resistance of  $\sim 5 \times 10^4$  ohms exists between any two acupuncture points (A.P.) and that the resistance value increases by a factor of 2-3 during sleep. Over the same length of normal skin, the equivalent resistance is in the range of  $\sim 10^6$  ohms. In the case of emotional excitation, the points increase in diameter (as revealed by conductivity area) and the relative conductivity of an A.P. changes strongly with state of hypnosis.<sup>4</sup> Using electrodes of different work function on two points, a voltage difference is developed between the points of increasing magnitude as the work function difference increases. For nickel/silver electrode pairs, the potential difference is  $\sim 50$  mV and the current developed is  $\sim 1$ - $10 \mu\text{A}$ .<sup>4</sup> This current shrinks to almost zero between skin points which are not A.P.s. Using a ganged electrode technique, Becker, *et al.*, have provided conductance maps around several A.P.s and observed small electrical potential variations along the meridians. It should also be noted that no histological difference exists between an A.P. and the surrounding skin, even though the resistance is lower by a factor of  $\sim 10$ .

When measuring electrical resistance between symmetrical points on the left and right sides of the body, one often finds that the resistance is different in the forward direction ( $R$ ) from the reverse direction ( $R'$ ); i.e., left to right as compared to right to left. If the person is healthy relative to the organs on the meridian, these two resistances will be the same ( $R = R'$ ). However, if pathology is developing in one or more of those organs, the resistance will be different ( $\Delta R = R - R' \neq 0$ ). As the degree of pathological advancement increases, the magnitude of  $\Delta R$  increases. This difference has been called the "semiconductor effect"<sup>4</sup> which is the electrical correlate of the well known heat response time difference between A.P.s.

It has also been noticed that when a serious imbalance exists in meridian circuitry, and as an acupuncture needle is placed in the appropriate point, a suction-like force holds the needle into the point so that, as one tries to withdraw it, the skin pulls up around the needle and it is not easily withdrawn. After the needle has remained in the point for a sufficient length of time to have brought about a temporary balance to the circuits, the needle may be withdrawn with no effort and the skin no longer pulls up around the needle. This suction force, which is probably due to an osmotic pressure difference,  $\Delta p$ , between the points, seems to be proportional to the degree of imbalance; i.e., to  $\Delta R$ . An electrostatic potential difference,  $\Delta \Phi$ , is also noted between the points.<sup>6</sup> Thus the left side/right side imbalance of an A.P. reveals itself via  $\Delta R$ ,  $\Delta p$ ,  $\Delta \Phi$  and  $\Delta K$  where  $\Delta K$  is the thermal conductance difference between the skin surface and the local nerve ending.

More recently, pain killing and analgesic effects have also been noted to occur when magnetic fields are applied to A.P.s. A field from a bar magnet of strength  $> 500$  gauss is found to produce local analgesia, and a mild magnetic

field applied continuously to a specific A.P. is observed to generate a meridian effect.<sup>7</sup> On a slightly different front, some osteopaths and chiropractors observed that distinct muscle reactions are associated with placing small permanent magnets over specific A.P.s. They have begun to use this technique to diagnose organ condition and to treat various ailments with magnets. Certainly, one does not think of organic tissue as having significant magnetic properties so the explanation of such a phenomenon must be explored.

Although it may initially seem unrelated to our present topic, studies in the area of kineseology also provide experimental input that is important for our A.P. considerations. From this body of data, four items are of interest: (1) placing a chemical substance in a jar and then placing the jar on the body surface adjacent to an organ under question can either strengthen or weaken the appropriate muscle response, depending upon the nature of the chemical in the jar; (2) the doctor touching the A.P. of a weakened organ will find a weakened muscle response if tested within  $\sim 15$  seconds but will find no change in the muscle response if a waiting period  $> 20$  seconds is used before testing; (3) if, in item (2), the doctor mentally fixes his attention on the patient's weakened organ throughout a waiting period of  $\sim 60$  seconds before muscle testing, the muscle will still exhibit a weakened response; and (4) if the practitioner moves his finger downward along the trajectory of a particular meridian, in which the energy is expected to flow upwards, but keeps his finger a few inches from the body, the appropriate muscle is found to be weakened by testing. From these observations, we may conclude that the practitioner/subject interaction is sufficient to cause specific neural firing (leading to specific muscle response) via several subtle stimuli.

### KEY ASPECTS OF MACROSCOPIC SKIN PROPERTIES

#### *Structural and Permeability Character*

Figure 1 illustrates a microscopic view of the skin consisting of two main layers: an outer and thinner layer, the epidermis, plus an inner, thicker layer, the dermis. The epidermis consists of stratified squamous epithelial tissue and the dermis of fibrous connective tissue. Since the main electrical impedance resides in the epidermal layer, it is worth noting that the outermost layer, the stratum corneum, consists of flattened dead cells converted to the water repellent protein keratin that continually flakes off. The innermost layer of the epidermis, the stratum germinativum, consists of columnar shaped cells undergoing mitosis. New cells are produced in this deepest stratum at the rate that old keratinized cells are lost from the stratum corneum. New cells continually push surfaceward from the innermost layer into each successive layer, only to die, become keratinized and eventually flake off as did their predecessors.

The major barrier to diffusion of water or electrolytes through the skin is in the outside layers of the epidermis. Thus, changes in circulation below the

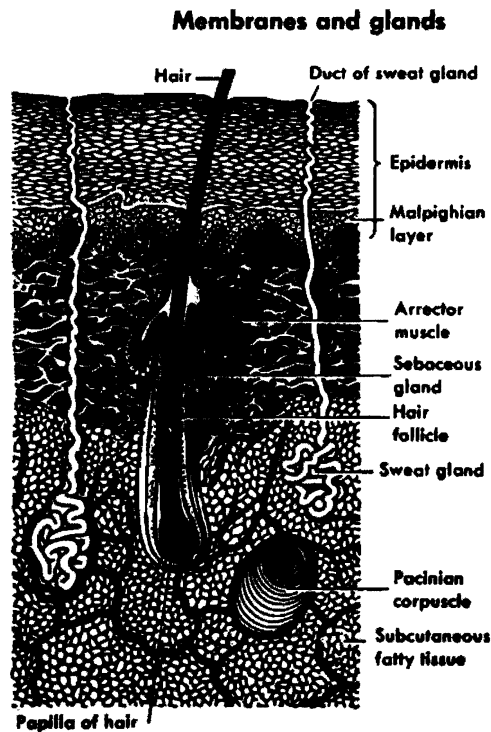


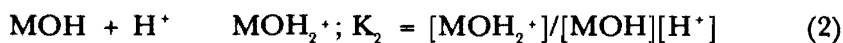
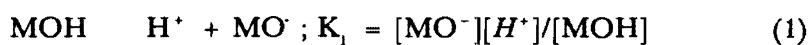
FIGURE 1. Microscopic view of the skin in longitudinal section.

epidermis should theoretically have little effect on the penetration of such molecular species unless the flow of blood is drastically reduced. The overall range of skin permeabilities is large ( $0.004\text{--}600\ \mu\text{cm}/\text{min}$ ). However, most of the aqueous solutes lie in the range  $3\text{--}60\ \mu\text{cm}/\text{min}$  and most non-aqueous solutes lie in the range  $0.2\text{--}10\ \mu\text{cm}/\text{min}$ .<sup>8</sup> Further, the permeability of the skin decreases with age. The stratum corneum consists of a set ( $\sim 10\text{--}100$  layers) of horny plates ( $\sim 25\ \mu$  diameter by  $0.5\ \mu$  thick) bonded together at short intervals and closely locked at their edges so that the channels between them are both narrow and tortuous.<sup>9</sup> The actual route of penetration is probably along the boundaries which would yield a diffusion coefficient for water of  $D = 2 \times 10^{-6}\ \text{cm}^2/\text{sec}$  which is  $\sim 0.1 - 0.2$  of its bulk value, which seems appropriate. Each cell in the stratum corneum will have an electrical double layer  $\sim 10^{-6} - 10^{-7}\ \text{cm}$  thick at each cell wall and these will polarize to give a capacitance under the influence of an electric field. For the order of 100 membrane layers in parallel of dielectric constant  $\sim 50$ , the calculated capacitance would be  $\sim 0.045\ \mu\text{F}/\text{cm}^2$  which is in the proper range observed for skin.

Any cellular membrane contains fixed charge sites which may be predominantly positively or negatively charged, depending upon the pH of the tissue fluid relative to the isoelectric point (IEP) of the cells ( $\text{IEP} \equiv \text{pH solution}$

needed to neutralize the charge state of the surface). For the case of the pH being more acidic than the IEP,  $H^+$  will absorb on the membrane surface and it will become electropositively charged. In this case it will be selectively permeable to anions only. For the case of the pH being more basic than the IEP, the membrane becomes electronegatively charged and is permeable to cations but not anions. The IEP of a membrane will shift depending upon the degree and type of proteins and carbohydrates imbedded in the cell surface. Skin is generally electronegatively charged and is thus permeable to cations.

To illustrate the key features of the isoelectric point, an example of a metal oxide surface will be considered. The existence of hydroxide groups on metal oxide surfaces is well established and plays a central role in the adsorption of surface molecules. Because of these hydroxyl groups, the surface can exchange a proton with the environment. The equilibrium can be represented by the following equations<sup>9</sup>



where [ ] brackets denote chemical activity of the species and the K's are the equilibrium constants for the reactions. Since the isoelectric point occurs at the condition of zero net surface charge, i.e.,  $[MO^-] = [MOH_2^+]$ , we have

$$IEP = [H^+]^0 = (K_1/K_2)^{1/2} \quad (3)$$

and we define

$$IEPS = -\log IEP \quad (4)$$

Therefore, the smaller  $K_1$  compared to  $K_2$ , for fixed pH, the less negative is the surface. The smaller are the absolute values of  $K_1$  and  $K_2$ , the smaller is the total surface charge. In general, we find that

$$\log \frac{MO^-}{MOH_2^+} = 2(pH - IEPS) \quad (5)$$

Figures 2 and 3 illustrate variation of the surface species populations and surface potential respectively as a function of pH. Systems which have an IEPS in the vicinity of 7 (e.g.,  $TiO_2$ ) exhibit a small total surface charge while systems with an IEPS far removed from 7 (e.g.,  $SiO_2 \equiv 2$  and  $MgO \equiv 12$ ) exhibit a large surface charge (negative for  $SiO_2$  and positive for  $MgO$ ). Adsorption of specific surfactants on these surfaces change the state of surface charge via changing the magnitudes of  $K_1$  and  $K_2$ . These considerations can be directly applied to cell membranes which will exhibit values of  $K_1'$  and  $K_2'$  for the formation of negative and positive surface charges respectively. These values of  $K_1'$  and  $K_2'$  depend upon the amount and type of proteins and

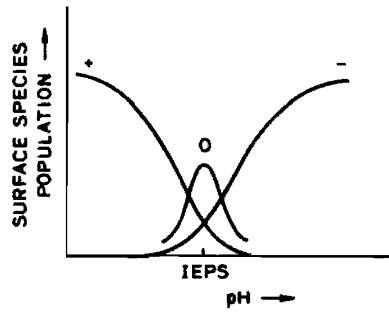


FIGURE 2. Schematic plot of electrical nature of ionized surface states as a function of fluid pH relative to the surface isoelectric point (IEP).

carbohydrates imbedded in the cell membranes and will thus control the selective ion species permeability (permselectivity) of the membrane.

#### *Electrical Impedance Character*

The stratum corneum cells still contain electrolyte, are primarily cation permeable and separated by narrow channels of electrolyte in a perpendicular direction to the surface. Moisture content of the inner layer of cells of the stratum corneum is much higher than the outer layer so that moisture steadily percolates from the inner to the outer layers at a rate depending upon the external humidity. The electrical impedance of the stratum corneum is primarily capacitive in nature but is short-circuited by resistive channels between the cells. The capacitance arises from 10-100 layers of cells in parallel and each cell's capacitance arises from the dipolar nature of its two membrane layers and the adjacent space charge layers in the interior of the cell. The simplest electrical equivalent circuit; for the case of zero applied potential, is thus given in Figure 4. Here  $C$  is the capacitance of these layers of cells in parallel ( $C \sim 0.005 - 0.03 \mu\text{F}/\text{cm}^2$ ).  $R_2$  is the short circuiting resistance ( $R_2 \sim 30 - 5000 \text{ K}\Omega/\text{cm}^2$ ) and  $R_1$  is the resistance of the deep tissues ( $R_1 \sim 0.1 - 3.0 \text{ K}\Omega/\text{cm}^2$ ). The magnitude of  $C$  will shift with electrolyte content, water content, dielectric constant, fixed charge site concentration, dipole strength, etc. The magnitude of  $R_2$  depends on ion content, water content and the ionic mobility in the electrolyte.

As soon as a voltage is applied to the skin, Figure 4 is no longer the correct electrical equivalent circuit because movement of an electric current through skin alters skin impedance, depending on the sign and magnitude of the applied voltage and upon the time of current flow. A more appropriate electrical equivalent circuit is that presented in Figure 5.<sup>10</sup> In Figure 5,  $Z_1$  is a diffusional admittance associated with Faradaic processes that exhibits Warburg-like behavior.<sup>11</sup> In the skin system both a high frequency and a low frequency diffusional admittance are observed.<sup>10</sup>

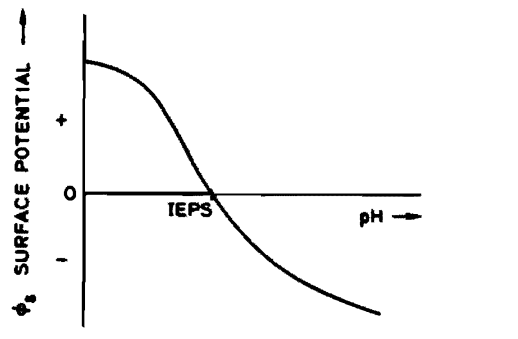


FIGURE 3. Schematic plot of surface electrical potential (zeta potential) as a function of fluid pH relative to the surface isoelectric point (IEP).

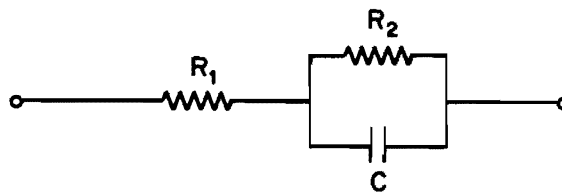


FIGURE 4. Simplest frequency-independent electrical equivalent circuit used for skin measurements<sup>1</sup>.

When a steady current is moved outwards through the skin (cathodal current), the DC resistance falls as shown in Figure 6. The opposite occurs when current moves inward through the skin (anodal current).<sup>12</sup> The net charge transfer required for this effect is  $\sim 10^{-3}$  Coulombs/cm<sup>2</sup> (100  $\mu$ A/cm<sup>2</sup> current flow for 10 seconds). The process becomes saturated in that continued charge transfer no longer changes the resistance. The ratio of the two saturation levels of resistance can be as large as 10:1. The AC impedance at 1 KHz is also changed in the same direction but by a much smaller factor. This is to be expected as a result of the diode-type behavior presented by skin because of the permselective nature of the cell membranes and the short circuit channels. At very high frequency this effect will be absent because there is insufficient time in a half cycle for ion transport over the necessary distance along the cell boundaries and current passes through the cell bodies instead. Thus, a frequency dependent resistance like  $Z_{II}$  in Figure 5 must develop at low frequencies.

Returning to Figure 6, for anodic conduction the current flows inward; therefore, positive ions flow inward and negative ions flow outward. However, an electronegative membrane is cation permeable; only positive ions are blocked from flowing along these channels. Thus, the stratum corneum develops a decreased ion content (lost positive ions) and an increased

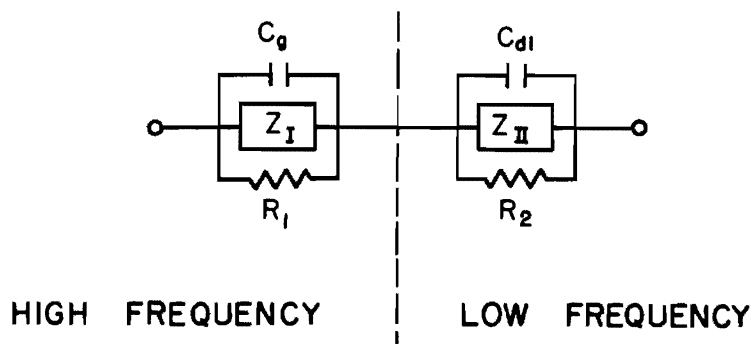


FIGURE 5. Electrical equivalent circuit generated from skin measurements using AC conductance techniques and complex plane analysis<sup>10</sup>.

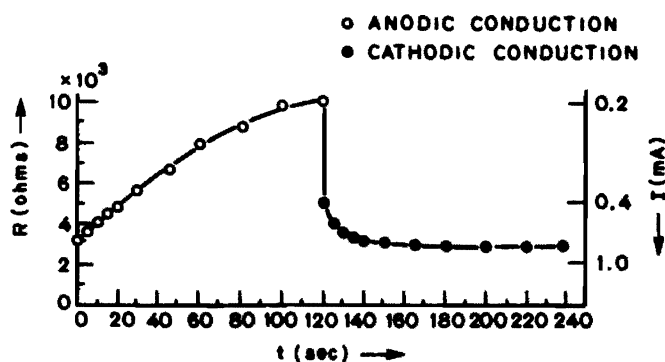


FIGURE 6. Time dependence of the electrical resistance at 2V (7 cm<sup>2</sup> of skin moistened for 20 min with saturated KCl solution).<sup>12</sup>

resistance, as indicated in Figure 6. For cathodic conduction through the same membrane, negative ions try to flow inward but are blocked by charges in the membrane channels. However, positive ions are driven outward by the field and enter the stratum corneum from the deeper epidermis and dermis layers. This increases the electrolyte content in the stratum corneum and gives it a reduced resistance in accordance with Figure 6. These features are illustrated in Figure 7. The rate of change of conductance will depend upon the permeability of the membrane. The amount of conductance change in a given time will depend primarily upon the basic electrolyte content of the stratum corneum.

Studies on the influence of moistening of the stratum corneum, either with 1% KCl solution or with a saturated KCl solution, revealed a very marked decrease in DC resistance of the skin which was most pronounced after the first ten minutes of moistening. After a 30-minute lapse, the resistance approximates a constant value 5 to 10 times lower than the initial value and which corresponds to a saturation of the stratum corneum with electrolyte.<sup>12</sup> When a

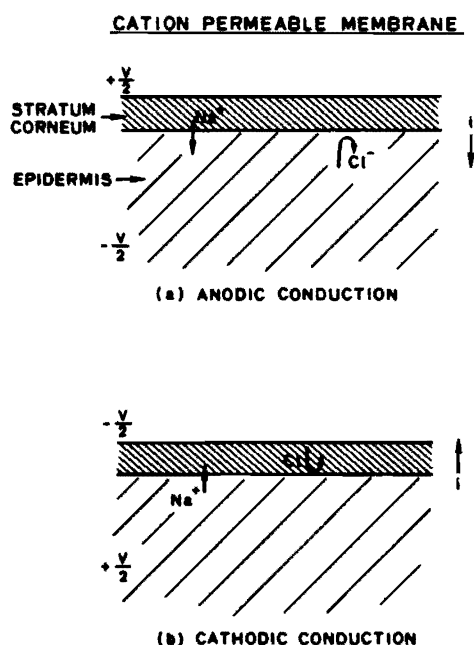


FIGURE 7. Illustration of permselectivity of membrane effect on ionic transport for anodic and cathodic conduction.

voltage between 2 and 4 volts was applied after constant resistance had been reached, a further decrease in resistance occurred. This new resistance approximated the resistance of the internal tissue. The decrease in resistance at voltages  $> 2$  volts was accompanied by a marked feeling of pain in the skin which became stronger with increasing voltage.

From Figure 8, we note that resistance to anodic conduction at two volts is about 60-100 percent higher than the resistance to cathodic conduction, irrespective of the initial direction of conduction and independent of the duration.<sup>12</sup> The ratio is greatest in the case of saturated KCl as contact electrolyte. In other experiments,<sup>13</sup> the DC potential was overlaid by AC with a frequency of 200 Hz or 1000 Hz. At the lower frequency, resistive impedance varied similar to DC resistance with time. AC resistance at 1000 Hz did not show any such variations. This is because, at higher frequencies, capacitive impedance strongly decreases and the current becomes almost completely capacitive. Since the diode-effect arises only as a result of the resistive current and since this current component decreases as the frequency increases, the resistance variation is expected to decrease towards zero as the frequency increases.

As a result of pH studies of the contact electrolyte with time, it was found that the electrolyte in contact with skin changed its pH from 5.73 to 4.97 in the course of 45 minutes. The conduction of direct current by itself, however, had

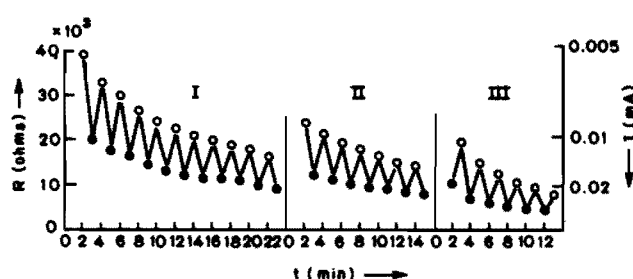


FIGURE 8. Dependence of the resistance on the direction of conduction at 2 volts ( $7 \text{ cm}^2$  of skin moistened for 6 min with 1 percent  $\text{KCl}$  solution (I) and with saturated  $\text{KCl}$  solution (II) and (III). Experiments II and III begin with anodic and cathodic conduction, respectively.<sup>12</sup>

no appreciable effect on pH of the contact electrolyte. With no wait for electrolyte equilibration to occur, it appears that the conduction process causes the pH change. It is expected, however, that migration of  $\text{H}^+$  ions in response to a voltage will be in accordance with the polarity of the voltage as in Figure 7. As  $\text{H}^+$  ion concentration changes, then so does pH.

Some additional experiments which are extremely relevant to an interest in skin come from a study of ionic transport in a sulfonated polystyrene-polyethylene copolymer by Crowley, et al.<sup>14</sup> They studied conductivity of grafted copolymer composed of 21% sulfonated polystyrene and 79% polyethylene, as a function of temperature and absorbed moisture for membranes containing the monovalent counterions,  $\text{H}^+$ ,  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Rb}^+$ ,  $\text{Cs}^+$  and  $\text{Ag}^+$ . Since conductivity of a membrane is a strong function of  $\text{H}_2\text{O}$  content of the membrane, they first determined the amount of water absorbed by this membrane (product name, AMF-C-60 cation exchange membrane) containing  $\text{H}^+$ ,  $\text{Na}^+$  or  $\text{Ag}^+$  as counter ions as a function of relative humidity. These results are shown in Figure 9. We note that the absorbed water content increases linearly with humidity but inversely with temperature and inversely with ionic radius. From Figure 10, we note that conductivity is a strong function of water content, changing by four orders of magnitude at  $27^\circ\text{C}$  as water content changes from  $\sim$  zero to  $\sim 4\%$ . Similar data is found for the  $\text{Ag}^+$  counter ion when it replaces the  $\text{H}^+$  counter ion. A marked change in conductivity occurs when applied voltage is increased from 1.5 to 2 volts or to an electric field  $\sim 0.5$  volts/cm as illustrated in Figure 11. This phenomenon really depends on the potential difference between electrodes and not on the voltage gradient and corresponds to the well known breakdown of electrolytic solutions by electrical dissociation, which is known to occur at a potential of 1.5 to 2.0 volts.<sup>13,14</sup> In Figure 12, the conductivity,  $\sigma$ , the free  $\text{Ag}^+$  ion density,  $n$ , and the free  $\text{Ag}^+$  ion mobility,  $\mu$ , in the membrane are presented as functions of absorbed water content at  $27^\circ\text{C}$ . The  $\text{Ag}^+$  mobility is found to be independent of field strength and its low voltage value was used to determine the density  $n$  of counter ions. Depending on water content, a varying fraction

$n/n_0$  of the available Ag species are ionized. In addition, at high voltage ( $V > 2.0$  volts), the conductivity is an order of magnitude larger than at low voltage ( $V < 2.0$  volts), showing that the generated  $H^+$  dominates the conduction process under high voltage conditions. Finally, these authors<sup>14</sup> also carried out thermal depolarization studies on this membrane and observed a persistent polarization not due to ionic space charges. They found that the observed polarization is a result of homogeneous volume polarization due to the orientation of sulfonic acid side-groups.

All of this data is qualitatively applicable to human epidermis. The strong dependence of absorbed water in skin with humidity, electrolyte nature and temperature will be very similar. The electrolysis of tissue fluids at DC voltages above 2.0 volts, or at increasingly higher voltages with increasing frequency for AC potentials, is expected to occur. Greatly enhanced electrical conductivity is the consequence. Dipole alignment of membrane fixed charge sites is also an expected result of AC fields, with decreasing ability of dipoles to respond at higher frequencies. This would be expected to produce a frequency dependent resistance to conduction through cells at higher frequencies, which would account for  $Z_1$  in Figure 5. Finally, at a DC voltage greater than 2 volts, the passage of small currents moves electrolytically generated  $H^+$  ions which can change local pH of tissue fluids in readily calculable ways. The passage of  $10^3 \mu A$  current for one second is capable of changing the pH of a surface larger than  $1 \text{ cm}^2 \times 1 \text{ micron}$  thick, from a pH7 to pH6.

#### UNDERSTANDING ELECTRODERMAL MEASURING INSTRUMENTS

##### *Motoyama's AMI Device*

Motoyama's technique involves applying electrodes (with electrode paste) to the ends of the 14 meridians on the fingers and toes (Figure 13). He applies a

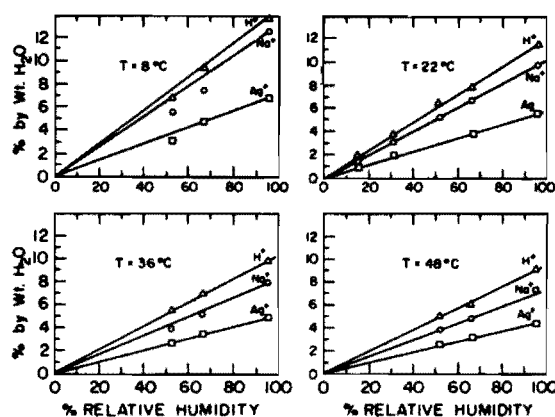


FIGURE 9. Absorbed  $H_2O$  content in  $H^+$ ,  $Na^+$  and  $Ag^+$  counterion forms of AMF C-60 membrane as a function of temperature and relative humidity. Reprinted with permission from the *Journal of Polymer Science*, 1976;14:1769-1787, John Wiley & Sons, Inc.

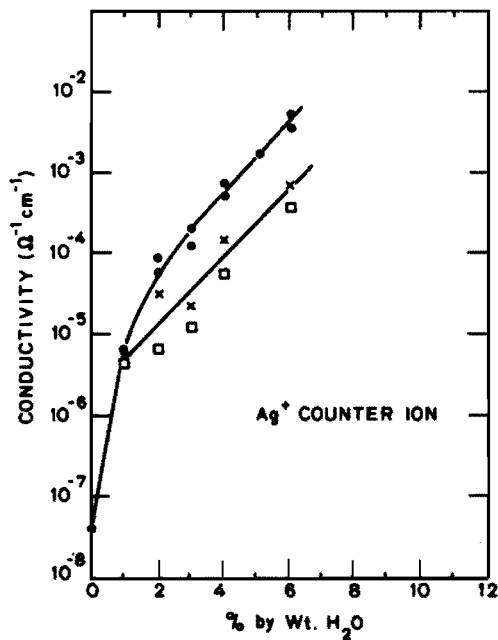


FIGURE 10. Conductivity vs. percentage by weight  $\text{H}_2\text{O}$  for  $\text{Ag}^+$  counterion forms of AMF C-60 measured at 300 °K with high voltage ( $> 2.0 \text{ V}$ ) and low voltage ( $< 2.0 \text{ V}$ ) applied. Reprinted with permission from the *Journal of Polymer Science*, 1976;14:1769-1787, John Wiley & Sons, Inc.

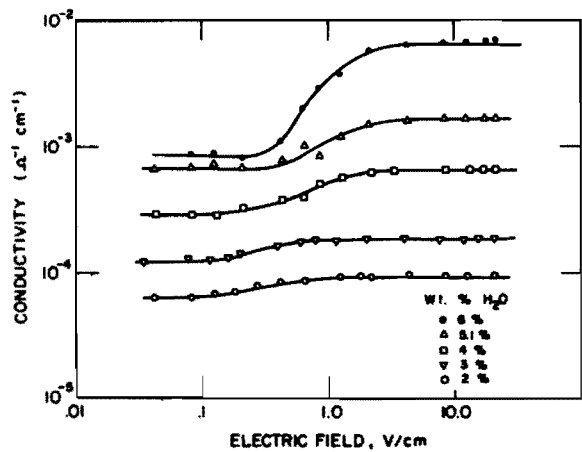


FIGURE 11. Conductivity vs. applied electric field for  $\text{Ag}^+$  counterion form of AMF C-60 containing various amounts of adsorbed  $\text{H}_2\text{O}$ . Reprinted with permission from the *Journal of Polymer Science*, 1976;14:1769-1787, John Wiley & Sons, Inc.

large indifferent electrode to the wrist and consecutively applies a 3-volt DC battery between this large electrode and one of the 28 electrodes at the ends of the meridians. He measures the initial current,  $i_0$ , and the final current,  $i_\infty$ , of the current waveform (Figure 14) and stores these values in a small on-line computer. Within a few minutes, all the meridians can be measured and the computer can print out the standard deviation of  $i_0$ ,  $i_\infty$  and  $i_0 - i_\infty$ , and the changes  $\Delta i_0$  and  $\Delta i_\infty$  between left side and right side values for all meridians of the body. When values for  $i_0$  and  $i_\infty$  fall within the accepted range, they are printed out in black. When they fall above or below this range, they are printed out in red. Values that are too high are interpreted to mean that the body is in an excited state, often signaling the beginning of a disease. Values of  $i_0$  and  $i_\infty$  that are too low are interpreted to mean that the whole autonomic nervous function is reduced, generally through a chronic disease. Extensive clinical studies are now being carried out in several Japanese hospitals to provide correlates between the electrical diagnostic description and the conventional western medical description for various pathologies.

Because 3 volts exceeds the dissociation potential for  $H_2O$  in tissue fluids, these electrical conductance measurements will be dominated by  $H^+$  ions which will be of approximately constant concentration for fixed water content of the skin. Thus, the differences in  $i_0$  and  $i_\infty$  for various points indicate differences in either (i) the mobility,  $m_{H^+}$ , of the proton in tissue fluids or (ii) the dissociation constant,  $K_{H_2O}$ , and will depend strongly upon the structure of the water in the tissue fluids.

Analysis of the equivalent circuit in Figure 4 for no  $H^+$  generation, which

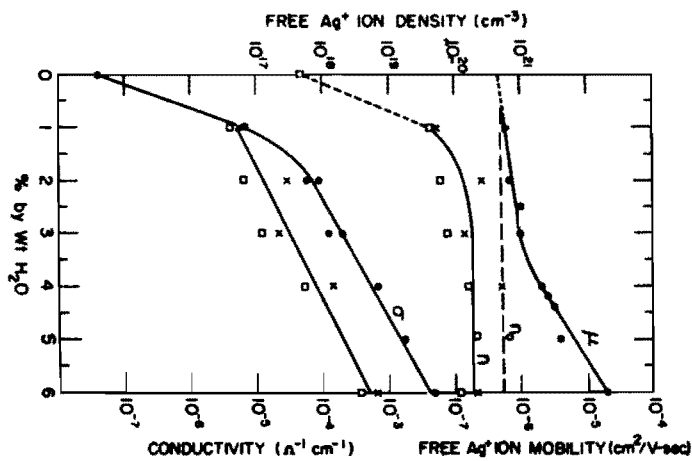


FIGURE 12. Free ion mobility, carrier density and conductivity as a function of percent by weight  $H_2O$  for an  $Ag^+$  counterion sample at 300 °K. Reprinted with permission from the *Journal of Polymer Science*, 1976;14:1769-1787, John Wiley & Sons, Inc.

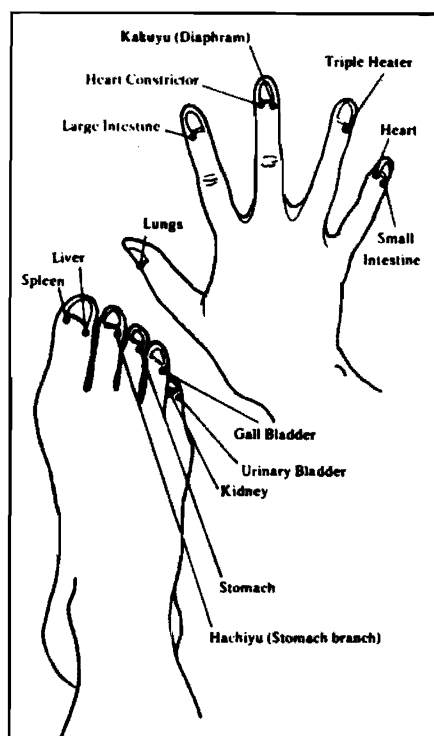


FIGURE 13. The special acupuncture points at the ends of the meridians (fingers and toes).

is the one utilized by Motoyama, indicates that  $i_o$ ,  $i_\infty$  and  $\tau$  in Figure 14 are given by

$$i_o = V/R_1 \quad (6)$$

$$i_\infty = V/(R_1 + R_2) \quad (7)$$

$$\tau = R_1 R_2 C / (R_1 + R_2) \approx R_1 C \text{ for } R_1 \ll R_2 \quad (8)$$

Thus,  $i_o$  relates to deep tissue effects while  $i_\infty$  values relate to stratum corneum effects. In the initial AMI device, Motoyama did not utilize information inherent in the relaxation time,  $\tau$ , of Figure 14. However, in his most recent work,<sup>15</sup> this parameter is also being utilized as a valuable diagnostic aid.

Although on the surface, this technique seems to be measuring the "semiconductor" effect of the A.P.s, it differs from the Soviet measurement in two unique ways. First, because of the large applied voltage, conductance is determined by the  $H^+$  ions generated rather than by the natural electrolyte of the A.P.s. Second, the differences  $\Delta i_o$  or  $\Delta i_\infty$  refer to either cathodic or anodic current for two symmetrical A.P.s whereas, in the Soviet work, the

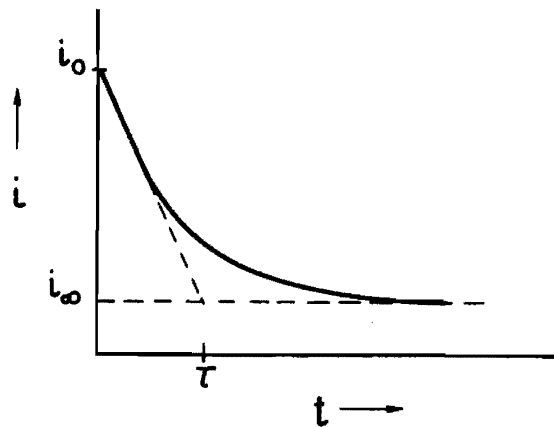


FIGURE 14. Plot of the current waveform rising from the application of a small DC voltage to the skin.

semiconductor effect is due to the difference between (a) anodic current at left A.P. plus cathodic current at right A.P. and (b) cathodic current at left A.P. plus anodic current at right A.P. This distinction between the two techniques may not be greatly significant but only future experiments will determine that fact.

#### *Voll's Dermatron*

An extensive prior publication<sup>2</sup> has already been devoted to "Electroacupuncture According to Voll," and only a brief review of the essential operating features of that device will be presented here.

**Diagnostic Mode.** The A.P. is charged with 8-10  $\mu\text{A}$  at a DC voltage of approximately 1 volt. The method for doing this is with a ball electrode contacting the skin at the A.P. at an applied pressure of  $\sim 500$ -1400 psi while a large cylindrical electrode is held at the patient's contralateral hand to complete the electrical circuit. The meter on the instrument is designed to record the electrical conductance, rather than the electrical resistance, of the skin between the two electrodes. The scale of the meter has been adjusted so that a reading of  $>50$  indicates "normal" while a reading of 50 is defined as indicating an "irritated" situation with the degree of irritation increasing as the reading increases. A reading of  $< 50$  is defined as a "degenerative" condition with the degree of degeneration increasing as the reading drops.

The actual meter reading is only one diagnostic indicator of this method. The second is called the "indicator drop"<sup>2</sup>; i.e., the reading decreases over time from its initial maximum value to a final lower value. As a rule, the indicator drop (I.D.) occurs within 1 to 3 seconds. In a retarded I.D., suggestive of an incipient functional disturbance, the period is thought to depend upon the intensity and the scope of the pathologic process in the organ being measured. The interval of the I.D. is usually 10-20 seconds when the

initial measurement value is above 50; it is 20-30 seconds when the measurement value drops to 30 and it is greater than 30-60 seconds when the reading drops to 20 or less.<sup>2</sup>

To determine the various homeopathic remedies that a patient should take to restore harmony to the body, a metal receptacle for holding a number of such remedies is connected by a wire to the measuring circuit. The testing remedies are nosodes contained within sealed glass vessels and these are placed either in or on the metal receptacle. Experimental data indicate that, if a particular nosode is not potentially beneficial to the patient's condition, no change will occur in the meter reading when the appropriate A.P. is again tested. If the remedy is to be beneficial then, with the remedy in the measuring circuit a change in the reading towards 50 is observed. One checks various readings until the smallest set of nosodes has been found which reduce the meter reading to 50.

*Therapy Mode.* This consists of applying constant current electrical impulses in the 0.8 to 10 Hz range to a specific A.P. or set of A.P.s. To produce a sedation effect (bring the reading down to 50), a positive saw-tooth shaped current pulse is applied to the A.P., producing a voltage in the 1.5 to 2.0 volt range ( $\sim 20\text{-}30\mu$  watts total power). To produce a tonification effect (bring the reading up to 50), a negative amplitude saw-tooth shaped current pulse is applied, when only small changes are needed. However, when large changes are needed, an AC current pulse of  $\sim 50$  millisecs duration at 1 to 10 Hz is usually applied to the A.P. In this case, the voltage used is in the 60 V to 400 V range ( $\sim 60\text{-}100\mu$  watts total power).

*Rationale.* When small voltages are applied to the skin, as in the therapy mode, we are dealing with either the anodic conduction or the cathodic conduction case of Figure 7. For the general skin case, i.e., a cation permeable membrane, anodic conduction (positive voltage pulse) reduces the electrolyte content of the stratum corneum so that the local skin resistance increases and the meter reading falls toward 50 (sedation). For the negative voltage pulse (cathodic conduction) the positive ion content of the stratum corneum increases so the skin resistance falls and the meter reading increases toward 50 (tonification). Since back diffusion of these positive ions from the stratum corneum to the dermis will occur, only a limited increase in positive ion content in the stratum corneum can be generated by these small negative voltage pulses. When this voltage is insufficient (because the dermis does not have a sufficiently large positive ion count) to bring the skin conductance up to 50, the large voltage pulses are needed. The large voltage pulses produce bursts of dissociation of water content in the tissue field to generate  $\text{H}^+$  and  $\text{OH}^-$ . This will increase skin conductance directly, without any partitioning between stratum corneum and dermis, causing the meter reading to increase to 50. The larger the magnitude of voltage needed and the lower the frequency of this voltage, the smaller is the  $K_{\text{H}_2\text{O}}$  of the patient's tissue fluids.

It is quite remarkable that this procedure of adjusting skin conductance into the normal range has such a marked therapeutic value and that the treatment endures for an appreciable time. One might expect that the excess ion count coaxed into the stratum corneum would either leak back into the dermis region after treatment or recombine to form neutral species. Since it does not, or at least it does not do so at an appreciable rate, one can deduce that these additional ions adsorb on the surface of cell membranes to change the isoelectric point into a more favorable range for carrier conduction. Because these ions are in local bound states they do not readily depopulate those states and the treatment therefore has lasting value. The important details of this process need to be explored.

Using the instrument in the therapy mode with  $\sim +1$  volt of applied DC potential again gives rise to anodic conduction at the A.P. (cathodic conduction at the large electrode surface) but at a constant applied current. The indicator drop (I.D.) represents the increased resistance as a function of time (Figure 6) due to positive ion depletion of the stratum corneum illustrated in Figure 7. The difference in rates between Figure 6 and the I.D. is presumed due to the large difference in active electrode surface area for the two cases. The rate of the indicator drop will depend upon both the mobility and density of positive ions in the stratum corneum. To first order, we might expect that the lower the conductance (lower  $n^+$  and lower  $m^+$ ), the slower would be the I.D., which is generally consistent with the data. However, other effects related to the permselective nature of stratum corneum are also involved and there does not seem to be any good *a priori* reason why they should vary linearly with the skin conductance. We must also ask why no indicator drop occurs when the A.P. gives a healthy reading. Since this requires that local skin conductance of the stratum corneum stay constant under a condition of anodic conduction, this requires that either (a) positive ions desorb from membrane surfaces at the needed rate to replace those lost during the applied voltage or (b) negligible permselectivity exists in the membranes so that lost positive ions are replaced by gained negative ions (of comparable mobility). After the applied voltage phase, ions must quickly readjust between the dermis and the stratum corneum. Both of these mechanisms may be operative to some degree.

The use of this instrument for the selection of the proper homeopathic treatment remedies requires a description that goes beyond the scope of this paper and it will be left to another paper of this series. Likewise, the effects of magnetic fields on A.P.s will be left to a future paper.

#### *Schimmel's Segment Electrography*

Segment electrography is a diagnostic method utilizing a series of electrodes, grouped in target fashion, for conducting 13 Hz voltage impulses into predetermined skin segments. Figure 15 illustrates the electrode placement

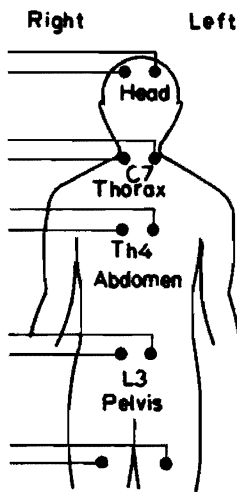


FIGURE 15. Body placement of electrodes in the Segment Electrograph technique.

for the four major segments with a further subdivision into 8 anatomical quadrants:

|         |         |            |                                            |
|---------|---------|------------|--------------------------------------------|
| Head    | left(1) | - right(2) | = Segment C <sub>1</sub> - C <sub>7</sub>  |
| Thorax  | left(3) | - right(4) | = Segment C <sub>7</sub> - Th <sub>4</sub> |
| Abdomen | left(5) | - right(6) | = Segment Th <sub>4</sub> - L <sub>3</sub> |
| Pelvis  | left(7) | - right(8) | = Segment L <sub>3</sub> - S <sub>4</sub>  |

Stimulation of tissue in a quadrant is carried out by using alternately negative and positive 13 Hz saw-tooth voltage impulses, each lasting for 18 seconds. At the end of this 36-second period, the applied voltage is set to zero and the reaction or response current, in the form of a reverse polarity current flow, is recorded for 26 seconds. This is followed by a pause of two seconds before a new cycle of stimulation begins. In Figure 16, the strip chart recording illustrates the current registered by the system during these three phases: first, there is a calibration pulse followed by the negative current trace due to the negative 13 Hz saw-tooth voltage pulse. Then there is a positive current trace due to the positive 13 Hz saw-tooth voltage pulse. Finally, there is the reverse current flow resulting from the previous stimulation cycle.

In this system, diagnostic information is implicit in the following features:

1. The current pulse under stimulation. It can fall in either the normal region, above the normal region (hyper-function) or below the normal region (subfunction).
2. The shape of the current trace in the stimulation cycle. The normal shape is a slightly curved trace at about 35 degrees to the horizontal with a

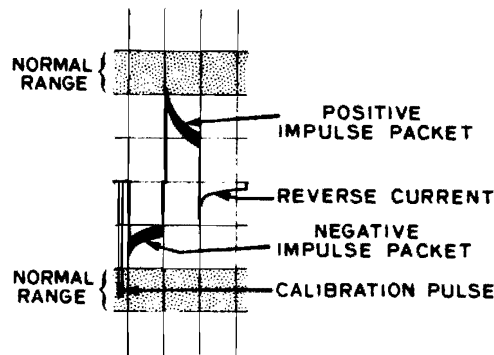


FIGURE 16. Illustration of electrical pulse cycle on recording paper: (i) calibration pulse, (ii) current from negative-going saw-tooth stimulation voltage wave at 13 Hz for 18 seconds, (iii) current from positive-going saw-tooth stimulation voltage wave at 13 Hz for 18 seconds, (iv) response current trace for 26 seconds.

centripetal signal (drop in amplitude) 1-2 mm long plus a clear cut border line (Figure 17a). The subfunctioning energy condition is illustrated by a shortening or almost total absence of the centripetal signal (Figure 17b) and transformation of the lightly curved swinging shape towards a rectangular shape. This is interpreted by Schimmel<sup>3</sup> as increased energy rigidity combined with decreased energy flow. The hyper-functioning energy condition is illustrated by an increase in the trace angle above 35 degrees, which yields a corresponding lengthening of the centripetal signal (Figure 17c). This is interpreted as an indication of rising energy flow, of an increasing degree of inflammation and of oxidation.

3. The magnitude and shape of the response current wave form. With respect to the reverse current forms, there is a certain interdependence between these and the stimulation current traces. With increasing trace angle for the stimulation cycle, the reverse current flow may also increase; however, this is not the rule. Three basic forms of reverse current are distinguished: a normal reverse current (Figure 18a) exhibits a leading edge amplitude of  $2\frac{1}{2}$  squares in height and a trailing edge amplitude of  $\frac{1}{2}$  to 1 square in height. This is interpreted as a normal energy situation with a normal tissue reaction; a weak reverse current (Figure 18b) exhibits a leading and trailing edge of less than  $2\frac{1}{2}$  squares, respectively. This is interpreted as an energy deficiency with abnormal tissue reaction; a strong reverse current (Figure 18c) exhibits a leading and trailing edge of greater than  $2\frac{1}{2}$  and  $\frac{1}{2}$  squares, respectively. This is interpreted as an energy surplus indicating also an abnormal tissue reaction.

In all of these current traces, a great deal of potential information is imbedded in the shape of the wave and thus it is given great diagnostic weight. Many subtle variations of the current trace are noted and these are given

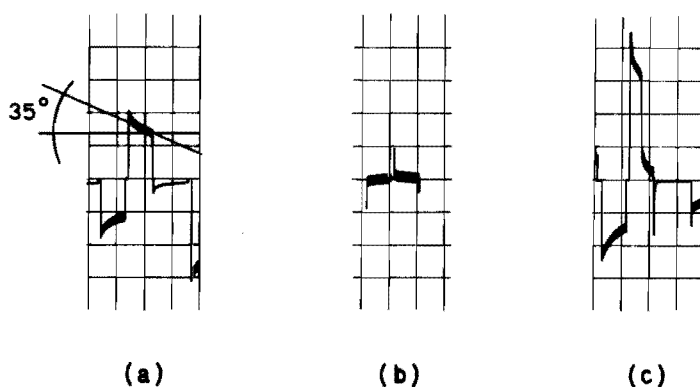


FIGURE 17. Illustration of the general types of current trace resulting from the stimulation voltage wave: (a) normal body function, (b) subnormal body function, (c) hyper body function.

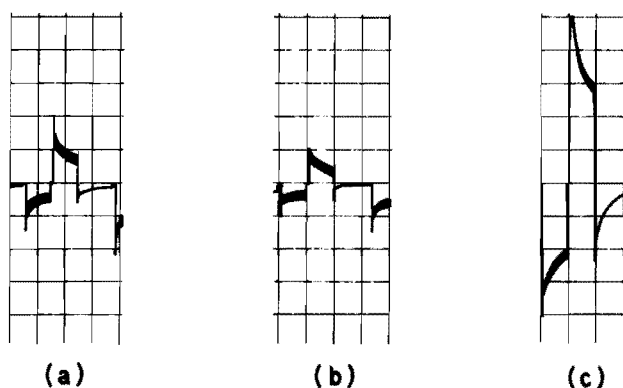


FIGURE 18. Illustration of the response current trace: (a) normal body function, (b) subnormal body function, (c) hyper body function.

discrete interpretations concerning the body or organ condition.

The explanation of these current traces follows in a straightforward fashion from our previous discussion concerning the "semiconductor effect." In this technique, as in the others, height of the leading edge of the current trace in the stimulation cycles is a measure of the electrical conductivity of the stratum corneum (electrolyte content and electrolyte mobility). The slope of the trace is a measure of the permselective nature of the membrane because one electrode exhibits cathodal current while the other exhibits anodal current. The net cycle-to-cycle (1/13 sec) resistance change is positive due to depleted electrolyte content. The slope of the trace is a direct measure of the permselectivity of the membrane, a steep slope indicates a strong permselectivity so that the incremental change of resistance in 1/13 of a second (one saw-tooth pulse) is

large; a shallow slope indicates the reverse. A large response current pulse corresponds with a large stimulating current pulse of the previous half cycle and indicates a movement of excess ions out of the stratum corneum at each electrode and of the oppositely charged ions back into the stratum corneum as the system, at each electrode, returns to the equilibrium electrolyte state (often a new equilibrium condition). The mobility of the different ions is also a factor here. A careful tally of these currents should provide considerable information about quantitative features of membrane permselectivity, electrolyte content and electrolyte mobility for the positively and negatively charged ion species.

*Proposal for the Next Generation of Diagnostic Instrument*

The Motoyama device assumes the simple electrical equivalent circuit of Figure 4 and, although this pulse method provides an effective way of covering a wide frequency range in a matter of seconds, it has several serious drawbacks. First, the initial or peak current value is dependent upon the rise times of both the voltage generator and the measuring device (usually an oscilloscope) so that key information is missed. Indeed, analogue measurements have limited accuracy over such short decay times. Second, and most serious, only one relaxation time can be monitored and a network must be assumed in which the polarization reactance of the equivalent circuit becomes a simple double layer capacitance, as given in Figure 4. Although the  $\tau$  information is not presently utilized in the Motoyama technique, its magnitude is  $\sim 50$   $\mu\text{sec}$  and it changes significantly between infants and older patients and varies somewhat with body condition. Relaxation times in the Voll device are several orders of magnitude longer than this, involving ion migration through the stratum corneum. The circuit of Figure 4 could not begin to account for such a phenomenon.

It is well known that the most accurate and reliable method for measuring electrical impedance is by comparing a test sample to a variable resistor and capacitor, in a modification of the Wheatstone bridge circuit. However, for *in vivo* measurements of biological systems, such a circuit has two major drawbacks: the frequency range and the ratio of capacitance to resistance are seriously limited; and the time required for bridge balancing at a sufficient number of frequencies is too great to detect changes in the steady state condition of the system. In work carried out at Stanford University, four to five years ago, this author and co-workers attempted to overcome one of these drawbacks. Attention was initially focused on maximizing the amount of information obtainable without considering the sampling time aspects. This was to have been followed by a second step of designing and building a very short sampling-time device to gather the desired information. Because of unavailable funding, this device was never built.

Initial experimental work proceeded with an entirely new type of theoretical analysis involving a complex plane treatment and human subject measurements to validate the procedures<sup>10</sup>. Complex plane mathematical analysis of

dielectric response in human skin leads to a new interpretation of the skin's electrical properties. By converting electrical impedance values to those of other electrical quantities, such as admittance and permittivity, considerable complementary information can be obtained. Over a given frequency range, one plot often proves much more valuable than another for the purposes of discriminating specific components of the skin's equivalent electrical circuit.

A comparison bridge circuit was modified to operate in the frequency range from less than 10 Hz to more than 100 KHz. Beckman Ag/AgCl electrodes were attached to the volar forearm of adult volunteer subjects reclining inside a Faraday cage. A series of about 40 readings were taken in this frequency range and the basic data was either in the form of series capacitance versus dissipation factor or as parallel capacitance versus quality factor. A small computer was used to convert these data to complex admittance and permittivity. An iterative curve-fitting computer program was successfully utilized to eliminate several possible equivalent circuit configurations and was found to best fit the twelve-parameter low frequency/high frequency model of Figure 5, which was found to be the most logical candidate for the skin's true equivalent circuit.

This preliminary data indicates that a great deal of information can be obtained from such impedance measurements of skin and that the information obtained is not limited to surface effects, such as sweat, which tend to dominate conventional measurements of galvanic skin response. This technique is clearly able to yield sensitive data on the dielectric constant, and thus on both the moisture and electrolyte properties of skin. The complexity of the equivalent circuit allows one to read changes in both the deep level or bulk properties (high frequency response) as well as the surface level stratum corneum properties (low frequency response) and to distinguish small changes of a single component in one of these circuits. Thus a richer diagnostic spectrum of human, animal, plant, cellular or membrane condition is possible with such a system.

### CONCLUSION

Using basic information on the electrical properties and response behavior of both macroscopic and microscopic (A.P.) areas of the skin, it has been possible to account for all the key characteristics of the three major electrical diagnostic instruments on the market; the Motoyama AMI instrument, the Voll Dermatron instrument, and the Schimmel Segment Electrograph. Since none of these instruments uses all the information that is available in an electrical measurement, the basis for a new class of measuring instrument capable of revealing much more information has been given.

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