ON THE EXPLANATION OF ELECTRODERMAL DIAGNOSTIC AND TREATMENT INSTRUMENTS
PART I. THE ELECTRICAL BEHAVIOR OF HUMAN SKIN

by William A. Tiller
Department of Materials Science and Engineering Stanford University, Stanford, CA 94305

ABSTRACT

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

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

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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 (1-3), each using different electrical techniques for assessing meridian condition. Neither method uses all the information available to an electrical measuring system and neither explains their electrical results in terms of basic epidermal properties and processes. Since these leaders (1-3), who are contributing so greatly to our understanding in this general area, will be followed by inventors of other instruments designed to achieve the ultimate in diagnostic and treatment capability, it behooves us to try and understand what is actually being measured by such devices in sufficiently fundamental biochemical and cellular terms that the physiological correlates of the electrical parameters become readily obvious. The purpose of the present paper is to make a beginning step towards this desirable goal. This paper, will restrict its attention to the role of the electrical behavior of skin upon the device measurements.

RELEVANT ACUPUNCTURE POINT DATA

It is now well known that an electrical resistance ~5×10^4 ohms exists between any two acupuncture points (A.P.) and the 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 ~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 hypnotization (4). Using electrodes of different work function on two points, a voltage difference is developed between the points of magnitude increasing as the work function difference increases. For Nickel/silver electrode pairs, the potential difference was ~50 mV

and the current developed ~1-10 μA (4). This current shrinks to almost zero between skin points which are not A.P.s. Using a ganged electrode technique, Becker et al. (15) have provided conductance maps 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 and A.P. and the surrounding skin even though the resistance is lower by a factor of ~10.

When measuring the 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 ΔR increases. This difference has been called the "semiconductor effect" (4) 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 the 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 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, Δp, between the points, Seems to be proportional to the degree of imbalance; i.e., to ΔR. An electrostatic potential difference, $\Delta \phi$, is also noted between the points (6). Thus the left side/right side imbalance of an A.P. reveals itself via ΔR, Δp, $\Delta \phi$ and ΔK where ΔK 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 D.C. magnetic field 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 (7). 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 conditions and to treat various ailments with such 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 seem at first sight to be unrelated to our present topic, studies in the area of kinesiology 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 ~15 seconds but will find no change in the muscle response if a waiting period of ~>20 seconds is used before testing; (3) if , in the item (2), the doctor mentally fixes his attention on the patient's weakened organ throughout a waiting period ~60 seconds before muscle testing, then the muscle will still exhibit a weakened response and (4) if the practitioner moves his finger downwards 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 subtle stimuli.

KEY ASPECTS OF MACROSCOPIC SKIN PROPERTIES

1. 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 and 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 repellant 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 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 keratized and eventually flake off as did their predecessors.

FIGURE 1, FIGURE 2, FIGURE 3

The major barrier to the diffusion of water of electrolytes through the skin is in the outside layers of the epidermis. Thus, changes in circulation below the 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 (0.0004-600 μcm/min). However, most of the aqueous solutes lie in the range 3-60 μcm/min and most nonaqueous solutes lie in the range 0.2-10 μcm/min (8). Further, the permeability of the skin decreases with age. The stratum corneum consists of a set (~10-100 layers) of horny plates (~25 μ diameter with 0.5 μ thick) bonded together at short intervals and closely locked at their edges so that the channels between them are both narrow and tortuous (9). The actual route of penetration is probably along the boundaries which would yield a diffusion coefficient for water of $D = 2 \times 10^{-6}$ cm/sec which is ~0.1 - 0.2 of its bulk value and this seems appropriate. Each cell in the stratum corneum will have an electrical double layer ~10^{-6} - 10^{-7} 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 ~50, the calculated capacitance would be ~0.045 μ F/cm 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 isolectric point (IEP) of the cells (IEP ≡ 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, and 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 absorption 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 (9)

$$MOH \rightleftharpoons H^+ + MO^- ; K_1 = [MO^-][H^+]/[MOH] \qquad 1$$

$$MOH + H^+ \rightleftharpoons MOH_2^+; K_2 = [MOH_2^+]/[MOH][H^+] \qquad 2$$

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

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

and we define

$$IEPS = -\log IEP \qquad 4$$

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

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

Figures 2 and 3 illustrate the variation of the surface species population and the surface potential respectively as a function of pH. Systems which have an IEPS in the vicinity of 7 (eg. TiO_2) exhibit a small total surface charge while systems with an IEPS far removed from 7 (eg., $SiO_2 \equiv 2$ 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 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 carbohydrates imbedded in the cell membranes and will thus control the permselectivity of the membrane.

2. Electrical Impedance Character

The stratum corneum cells still contain electrolyte, are primarily cation permeable and separated by narrow channels of electrolyte in the perpendicular direction to the surface. The 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 the 10-100 layers of cells in parallel and each cell capacitance arises from the dipolar nature of the two membrane layers and the adjacent space charge layers in the interior of each cell. The simplest electrical equivalent circuit; for the case of zero applied potential, is thus given in Fig.4. Here C is the capacitance of these layers of cells in parallel ($C \sim 0.005 - 0.03\ \mu F/^{cm}$). R_2 is the short circuiting resistance ($R_2 \sim 30 - 5000\ K\Omega/^{cm}$) and R_1 is the resistance of the deep tissues ($R_1 \sim 0.1 - 3.0\ K\Omega/^{cm}$). The magnitude of C will shift with electrolyte content, water content, dielectric constant, fixed charge sit concentration, dipole strength, etc. The magnitude 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, Fig. 4 is no longer the correct electrical equivalent circuit because the movement of the electric current through the skin alters the 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 Fig. 5 [10]. In Fig.5, Z_t is a diffusional admittance associated with Faradaic processes that exhibit Warburg-like behavior [11]. In the skin system both a high frequency and a low frequency diffusional admittance are observed [10].
When a steady current is moved outwards through the skin (cathodal current), the D.C. resistance falls as shown in Fig.6 and vice versa for current moving inwards through the skin (anodal current) [12]. The net charge transfer required for this effect is $\sim 10^{-3}$ Coulombs/^{cm} (100 μA/^{cm} current flow for 10 seconds). The process saturates in that continued charge transfer no longer changes the resistance. The ratio of the two saturation levels of the resistance can be as large as 10:1. The A.C. 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 the 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 the current passes instead through the cell bodies. Thus, a frequency dependent resistance like Z_t in Fig. 5 must develop at low frequencies.

Returning to Fig. 6, for anodic conduction, the current flows inward so that positive ions flow inwards and negative ions flow outwards. However, for an electronegative membrane, it is cation permeable so that only the negative ions can readily flow through the channels between cells while the negative ions are blocked from flowing along these channels. Thus, the stratum corneum develops a decreased ion content (lost positive ions) and an increased resistance as indicated in Fig. 6. For Cathodic conduction with the same membrane, negative ions try to flow inwards but are blocked by the charges in the membrane channels. However positive ions are driven outwards 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 Fig. 6. These features are illustrated in Fig. 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, revealed a very marked decrease in D.C. resistance of the skin which was most pronounced after the first 10 minutes of moistening. After a 30 minute lapse, the resistance approximates a constant value which is 5 to 10 times lower than the initial value and which corresponds to a saturation of the stratum corneum with electrolyte [12]. When a 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 Fig.8, we note that the resistance to anodic conduction at 2 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 (12). The ratio is greatest in the case of saturated KCℓ as contact electrolyte. In other experiments [13], the D.C. was overlaid by A.C. with a frequency of 200 Hz of 1000 Hz. At low frequency, the resistive impedance was found to vary in the same sense as the D.C.

resistance with time. The A.C. resistance at 1000 Hz did not show any such variations. This is because, at higher frequencies, the 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 the skin changed its pH from 5.73 to 4.97 in the course of 45 minutes. The conduction of D.C. current by itself, however, had no appreciable effect on the pH of the contact electrolyte. When one does not wait for electrolyte equilibration to occur, it appears as if the conduction process is causing the pH change. We must expect, however, that the migration of H^+ ions in response to a voltage will be in accordance with the direction of the voltage as in Fig.7. As the H^+ ion concentration changes, then so does the pH.

Some additional experiments which are extremely relevant to our interest in skin come from a study of ionic transport in a sulfonated polystyrene-polyethylene copolymer by Cowley et al. [14]. They studied the conductivity of a grafted copolymer composed of 21% sufonated polystyrene and 79% polyethylene as a function of temperature and absorbed moisture for membranes containing the monovalent counterions H^+, Li^+, Na^+, K^+, Rb^+, C_s^+ and Ag^+.
Since the conductivity of a membrane is a strong function of the H_2O content of the membrane, they first determine the amount of water absorbed by this membrane (product name - AMF-C-60 cation exchange membrane) containing H^+, Na^+ or Ag^+ as counter ions as a function of relative humidity. These results are shown in Fig. 9. We note that the absorbed water content increases linearly with humidity but inversely with temperature and inversely with ionic radius. From Fig. 10, we note that the conductivity is a strong function of water content changing by 4 orders of magnitude at 27°C as the water content changes from ~zero to ~4%. Similar data is found for the Ag^+ counter ion when it replaces the H^+ counter ion. A marked change in the conductivity occurs when the applied voltage is increased to 1.5 to 2 volts or an electric field ~0.5 volts/cm as illustrated in Fig.11. This phenomenon really depends on the potential difference between the 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 [13,14]. In Fig. 12, the conductivity, ---, in the free Ag^+ ion density, n, and the free AG^+ ion mobility, μ, in the membrane is presented as a function of absorbed water content at 27°C. The AG^+ mobility is found to be independent of field strength and this low voltage value was used to determine the density n of counter ions. Depending on the water content, a varying fraction n/n_o 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 the high voltage conditions. Finally, these authors [14] 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 the 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 ell be very similar. The electrolysis of tissue fluids at D.C. voltages above 2.0 volts or at increasingly higher voltages with increasing

frequency for A.C. voltages is expected to occur and greatly enhanced electrical conductivity is the consequence. Dipole alignment of the membrane fixed charge sites is also expected due to A.C. fields with the ability of the dipoles to respond decreasing at high frequencies. This may be expected to produce a frequency dependent resistance to conduction through the cells at high frequency which would account for Z_1 in Fig. 5. Finally, at a D.C. voltage greater than 2 volts, the passage of small currents moves electrolytically generated H^+ ions which can change the local pH of the tissue fluids in readily calculable ways. The passage of 10^{-3} μA current for 1 second is capable of changing pH of a surface larger than 1 ^{cm} x 1 micron by one unit from a pH7 to pH6.

UNDERSTANDING ELECTRODERMAL MEASURING INSTRUMENTS

1. 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 (see Fig. 13). He applies a large indifferent electrode to the wrist and consecutively applies a 9 volt D.C. battery between this large electrode and one of the 28 at the ends of the meridians. He measures the initial current, i_o, and the final current , i_∞, of the current waveform (see Fig. 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_o, i_∞ and i_o-i_∞ and the changes Δi_o and Δi_∞ between the left side and the right side values for all the meridians in the body. When the values of i_o and i_∞ fall within the accepted range they print out in black. When they fall above or below this range, they are printed out in red. Values that are too high are diagnosed to mean that the body is in an excited state, often signaling the beginning of a disease. Values of i_o and i_∞ that are too low are diagnosed 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 the correlates between the electrical diagnostic description and the conventional western medicine description for various pathologies.

Because 9 volts exceeds the dissociation potential for H_2O in the tissue fluids, these electrical conductance measurements will be dominated by H^+ ions and they will be of approximately constant concentration for fixed water content of the skin. Thus, the difference in i_o and i_∞ for various points indicate differences in either (i) the mobility, m_{H^+}, of the proton in the tissue fluids or (ii) the dissociation constant, K_{H2O}, will depend strongly upon the structure of the water in the tissue fluids.

Analysis of the equivalent circuit in Fig.4, which is the one utilized by Motoyama, indicated that i_o, i_∞ and τ in Fig. 14 are given by

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

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

$$\tau = R_1R_2C/(R_1 + R_2) \underline{\Pi\Pi} R_1C \text{ for } R_1 << R_2 \qquad (8)$$

Thus, i_o relates to the deep tissue effects while the i_∞ values relate to stratum corneum effects. In the initial AMI device, Moyotoma did not utilize the information inherent in the relaxation time, τ, of Fig. 14. However, in his most recent work [15], 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, the conductance is determined by the H^+ ions generated rather than by natural electrolyte of the A.P.s. Second, here, the differences Δi_c or Δi_a refer to either cathodic or anodic current for the two symmetrical A.P.s whereas, in the Soviet work, the 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 be able to determine this for us.

2. Voll's Dermatron

Because a special journal issue [2] has already been devoted to "Electroacupunture According to Voll'" only a brief review of the essential operating features of the device will be presented here.

(a) Diagnostic Mode: The A.P. is charged with 8-10 μA at D.C: voltage of approximately 1 volt. The method for doing this is via a ball electrode contacting the skin at the A.P. at an applied pressure of ~500-1400 psi while a large cylindrical electrode is held at the patient's offside hand to complete 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" [2]; i.e., the reading decreases from its initial maxim value to a final lower value. As a rule, the indicator drop 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 measurement value drops to 30 and it is greater than 30-60 seconds when the reading drops to 20 or less [2].

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. The experimental data indicates that, if a particular nosode is not 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 beneficial then, with it 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.

(b) 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. leading to a voltage in the 1.5 to 2.0 range (~20-30 μ watts total power). To produce a tonification effect (bring the reading up to 50), a negative amplitude sawtooth shaped current pulse is applied when only small changes are needed. However, in general, when large changes are needed, an A.C. current pulse of ~50 millisecs duration at 1 to 10 Hz is applied to the A.P. In this case, the voltage used is in the 60 V to 400 V range (~60-100 μ watts total power).

(c) 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 Fig. 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 certain increase in positive ion content in the stratum corneum can be generated by these small negative voltage pulses. When this is insufficient (because the dermis does not have 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 the water content in the tissue field to generate H^+ and OH^-. This will increase the skin conductance directly without any partitioning between stratum corneum and dermis so that the meter reading will increase to 50. The larger is the magnitude of voltage needed and the lower the frequency of this voltage, the smaller is the K_{H2O} of the patient's tissue fluids.

It is quite remarkable that this procedure of adjusting the 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 the treatment or recombine to form natural species. Since it does not, or at least it does not do so at an appreciable rate, one can deduce that these additional ions absorb on the surface of the 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 these states and so the treatment has lasting value. The important details of this process need to be explored.

Using the instrument in the therapy mode with ~ +1 volt applied D.C. voltage 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.) is just the increase resistance as a function of the time (Fig.6) due to the positive ion depletion of the stratum corneum illustrated in Fig.7. The difference in rates between Fig.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 the 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 the 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 the local skin conductance of the stratum corneum stay constant under the 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 membrane so that lost positive ions are replaced by gained negative ions (of comparable mobility). After the applied voltage phase, the 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.

3. 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 for the four major segments with a further subdivision into 8 anatomical quadrants; i.e.,

Head	left (1)	-right (2)	=	Segment C_1 -C_7
Thorax	left (3)	-right (4)	=	Segment C_7 - Th_4
Abdomen	left (5)	-right (6)	=	Segment Th_4 - L_3
Pelvis	left (7)	-right (8)	=	Segment L_3 - S_4

Stimulation of the tissue in a quadrant is carried out by using alternatively 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 Fig. 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. Finally, there is the current reverse current flow resulting from the previous stimulation cycle.

In this system, the 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 centripetal signal (drop amplitude) 1-2 mm long plus a clear cut border line (see Fig. 17a). the subfunctioning energy condition is illustrated by a shortening or almost total absence of the centripetal signal (see Fig. 17b) and the transformation of the lightly curved swinging shape towards a rectangular shape. This is interpreted by Schimmel [3] 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 (see Fig. 17c). This is interpreted as an indication of rising energy flow, of 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. (I) A normal reverse current (see Fig. 18a) exhibits a leading edge of amplitude 2 ½ to 1 square in height. This is interpreted as a normal energy situation with a normal tissue reaction. (ii) A weak reverse current (see Fig. 18b) exhibits a leading and trailing edge of less than 2 ½ square respectively. This is interpreted as an energy deficiency with abnormal tissue reaction. (iii) A strong reverse current (see Fig. 18c) exhibits a leading and trailing edge of greater than 2 ½ and ½ 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 discrete interpretations concerning the body or organ condition.
The explanation of these current traces follows in a straight forward fashion from our previous discussion concerning the "semiconductor effect". In this technique, as in the others, the 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 and 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 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 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 current should let one say a great deal about the quantitative features of the membrane permselectivity, electrolyte content and electrolyte mobility for the positively and negatively charged species.

4. Proposal for the Next Generation of Diagnostic Instrument

The Motoyama device assumes the simple electrical equivalent circuit of Fig.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 the key information is missed. Indeed, analogue measurements have limited accuracy over such short decay times. Second, and most serous, is that only one relaxation time can be monitored and one must assume a network where the polarization reactance of the equivalent circuit becomes a simple double layer capacitance, as given in Fig.4. Although the τ information is not presently utilized in the Motoyama technique, its magnitude is ~50 μsec and it changes significantly between infants and the aged and varies somewhat with body condition. The relaxation times in the Voll device ate several orders of magnitude longer than this involving ion migration through the stratum corneum. The circuit of Fig. 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 on biological systems, such a circuit has two major drawbacks: (1) the frequency range and ration of capacitance to resistance are seriously limited and (2) 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 4-5 years ago, we decided to try and overcome one of these drawbacks. We first focused on maximizing the amount of information obtainable without worrying about the sampling time aspects. This was to have been followed by the second step of designing and building a very short sampling-time device to gather the desired information. Because of unavailable funding, this has never been built.

Our initial experimental work proceeded with an entirely new type of theoretical analysis via a complex plane treatment and we undertook some human subject measurements to test out the procedures [10]. The complex plane mathematical analysis of dielectric response in human skin leads to a new interpretation of the skin's 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 the 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 than100KHz. Beckman Ag/Agℓ 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 vs 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 used to best fit the twelve-parameter low frequency/high frequency model of Fig.5 that 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 the skin and that the information is not limited to surface effects, such as sweat, which tend to dominate conventional measurements of galvanic skin response. The technique is clearly able to yield sensitive data on the dielectric constant, and thus on both the moisture and electrolyte properties of the 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, i.e., the Motoyama AMI instrument, the Voll Dermatron instrument and the Schimmel Segment Electrograph. Since none of these instruments use 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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REFERENCE

1. Motoyama, H., How to measure and Diagnose the Functions of Meridians, Int. Assoc. for Religion and Parapsychology 1, 1-29, Sept. 1975.
2. Voll, R., Special EAV Issue, Am.J. of Acupuncture, 1978.
3. Schimmel, H.W., The Segment Electrogram. (Vega, Grieshaber KG, Postfach 10, D-7622 Schiltack (Schwarwald).

4. Tiller,W.A., Some Energy Field Observations of Man and Nature, in Galaxies of Life, Eds. S. Krippner and D. Rubin (Interface, New York, 1973, pp. 71-112).
5. Reichmanis, M.A., Marino, A., and Becker, R.D., Electrical Correlates of Acupuncture Points, IEEE Trans. on Biomed. Engrg. BM013, 533-535, 1975.
6. Motoyama, H.., Private Communication.
7. Tany, M., And Sawatsugawa, S., New Development: Electromagnetic Acupuncture, Am. J. Acupuncture, 3, 58-67, 1975.
8. Tregear, R.T., Physical Functions of the Skin, (Academic Press, New York, 1966).
9. Bolger, J.C., and Michaels, A.S., Molecular Structure and Electrostatic Interactions at Polymer-Solid Interfaces in Interface Conversion for Polymer Coatings, Eds: P. Weiss and G.D. Cheever (American Elsevier Publishing Co., Inc., New York, 1968).
10. Nagel, L., and Tiller, W.A., Dielectric Response in Human Skin, to be published.
11. Warburg, E., Uber das Verhalten sogenannter unpolisirbarer Electroden gegen Whselstrom, Annelen der Physik und Chemie, 67, 493-499, 1899.
12. Rosendal, T., Studies on Conductivity Properties of the Human Skin to Direct Current. Acta Physiol. Scand. 5, 130-151, 1943.
13. Rosendal, T., Further Studies on the Conducting Properties of Human Skin to Direct and Alternating Current, Acta Physiol. Scand. 8, 183-202, 1944 and 9, 39-49, 1945.
14. Crowley, J.L., Wallace, R.A., and Bube, R.H., Ionic Transport in Sulfonated Polystyrene-Polypropylene Copolymer, J. of Polymer Science, 14, 1769-1787, 1976.
15. Motoyama, H., Electrophysiological and Preliminary Biochemical Studies of Skin Properties in Relation to the Acupuncture Meridian, Int. Assoc. for Religion and Parapsychology, 6, 1-36, June 1980.