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Abstract #2

On the Evolution and Future Development of Electrodermal Diagnostic Instruments

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Objective: To trace the modern development of electrodermal instruments for a better understanding of origins and potentials. Those potentials have already culminated in the invention of ECG, EEG, and EMG technologies. In this paper, Dr. Tiller reviewed electrodermal development to apply modern theories of electrical engineering to medical science and the battery-like effect of given points on the human body. He explores capacitance at those points.

Data Sources & Study Selection: Dr. Tiller references 63 studies in electrodermal research, and includes appendices for diatherapuncture functionality and dielectric response in human skin.

Data Extraction: The author traces the two domains of electrodermal studies, involving macro and micro electrodes. Dr. Tiller summarizes the macro electrode studies conducted during the 1940s, and provides a corresponding summary for micro electrode studies conducted between 1950 and 1985. He also tracks the development of electrodermal diagnostic devices over these time periods.

Results of Data Synthesis: There does appear to be experimental support for, and a possible theoretical model to explain, connectivity between the organs and their specific polarizations. There also appears to be important differences of skin measurements between the hand-held moving electrode modality and the fixed, multiple electrode, automatic switching modality.

Conclusion: Dr. Tiller concludes that there are several effective electrodermal techniques in present use that we understand — both how they work and what they measure. After reviewing the research of the past five decades, Dr. Tiller believes that new applications of electrodermal diagnostics will be developed to supplement or complement current uses that are already standard practice in clinical medicine (such as ECG, EEG, and EMG technologies). Dr. Tiller concludes that these new devices could significantly reduce health care costs.

On the Evolution and Future Development of Electrodermal Diagnostic Instruments

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INTRODUCTION

Expenditures on health services in the U.S. is currently at the rate of well over $1 billion per day. As a percentage of gross national product (GNP), medical care expenditures have risen from 5% in 1960 to 10.5% in 1984. Because of this, in recent years government officials have predicted that the present rate of escalating costs will bankrupt the Medicare system by 1990. Many difficult health policy decisions obviously lie ahead and it is clear that fundamental reform of the U.S. health care system, and not just a minor adjustment of its parts, must become a national priority.

Within this context, I would like to propose that electrodermal diagnosis of human body systems holds the promise of being a much faster, much cheaper and perhaps a more accurate early method of body diagnosis than the present chemical analytic methods. Of course, at the moment, much research needs to be carried out to provide the mapping transforms between the electrical signatures determined by electrodermal measurements and the chemical patterns associated with various medical syndromes or health pathologies.

At this point one might well ask; "What do I mean by electrodermal diagnostic measurements?" In response, I would say that this involves placing electrodes at various locations on the skin of the body, applying a fixed voltage or electrical current between electrode pairs for a specific amount of time and recording the response of the body to this stimulus in the form of a current or voltage, respectively, as a function of time. Analysis of these response magnitudes and patterns is thought to be directly related to the state of the function of the various organs and body systems. Electrodermal studies of human skin have been carried out since the turn of the century with the view to learning more about the body's electrical characteristics and patterns of function, and some of this early work culminated in the invention of the ECG, EEG and EMG technologies, important "linchpins" in modern medical technology.

From one vantage point, the body can be looked at as a complex interconnected electrical power generation, power distribution and power use system much like that found in modern state or province. Thus, the circuit theory concepts of electrical engineering are relevant here. One imagines a type of internal "wiring" into which organs feed a variety of current and out of which other body systems act as electrical loads and draw current. The energy streams from a number of organs appear to flow into one of the many internal conducting channels and appear to flow either to or "through" a set of surface points. It is the degree and character of energy flow that is correlated with the functioning condition of that set of organs, and that degree of energy flow is thought to generate the difference in electrical conductance between these special surface points and the surrounding tissue. Thus, these points become information access windows to the functioning state of specific organ and body systems.

From a larger perspective, every molecule, cell, tissue wall, muscle fiber, organ or bo

separated from each other by narrow channels of electrolyte and are cation (+ve ion) permeable. The moisture content of the inner layers of cells in the stratum corneum is much higher that of the outer layer so that moisture steadily percolates from the inner to the outer layers depending on 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. Its capacitance arises from the 10-100 layers of cells connected in parallel with the single cell capacitance arising from the polar nature of the two membrane layers plus the adjacent space charge in the interior cell medium.

The simplest electrical equivalent circuit for the case of zero applied voltage is that shown in Fig. 1. Here, C is the capci-tance of these layers of cells connected in parallel, R_2 is the short-circuiting resistance across the cells and $R_1 << R_2$ is the resistance of the deep tissues. If this was a true, fixed parameter, electric circuit, the application of a constant voltage V_o would lead to a current response, I(t), like that shown in Fig. 2 where

$$i_o = v_o/R_1 \qquad (1a)$$

$$I_\infty = v_o/(R_1 + R_2) \qquad (1b)$$

and

$$\tau = R_1R_2C/(R_1 + R_2) \approx R_1C \qquad \text{for } R_1 << R_2 \qquad (1c)$$

Thus i_o relates to deep tissue effects while I_∞ relates to stratum corneum effects.

Rosendal [1] showed that, when a negative DC surface voltage is applied such that a steady current is moved outwards through the skin (cathodal current), the D.C. resistance falls, as shown in Fig. 3, and vice versa for current moving inward through the skin (anodal current). The ratio of the two saturation levels of resistance can be as large as 10:1 and the time constant for the processes many seconds long. When the applied voltage is AC at ~ 1000 Hz, the impedance slowly increases with time, but to a smaller degree than shown in Fig.3. Such an effect is attributed to the selective permeability nature of the cell membranes (they pass +ve ions more easily than -ve ions) and the short-circuit channels between the cells. At very high frequencies, this effect will be absent because there is insufficient time in a half cycle for ion transport between the cell boundaries, and the current passes instead through the body of cells. Thus, a frequency dependent resistance is expected at low frequencies.

Rosendal also found that moistening the stratum corneum with electrolyte revealed a marked decrease of DC resistance that became constant in about 30 minutes at a value 5 to 10 times lower than the initial value. This indicates electrolyte enhancement in the stratum corneum by a diffusion process just as occurred with cathodal current flow. When a voltage between 2 and 4 volts was applied after this constant resistance had been reached, a further decrease in resistance was noted so that the resistance approached that of the internal epidermal tissue. This decrease of resistance at V_o>2 volts was accompanied by a marked feeling of tingling in the skin which became stronger with increasing voltage and which is due to electrolyte dissociation of the water molecules in the stratum corneum and the ultimate generation of H_2 gas at very high dissociation levels.

Assuming the equivalent circuit model of Fig. 1, Lykken [2] applied 100 m sec voltage pulses of $V_o = 0.5$ volts to the skin and studied the relative contributions of the various skin layers to the parameters in Fig. 1. By abrading the skin, he found that C was reduced to undetectable values

From the basic information given earlier [1-6], we note that this technique deals with the low frequency portion of the skin circuit and thus involves ion transport across selective permeability membranes. The driving voltage sees the sum of the resistance from the left and right electrodes so the generated current is cathodal from one and anodal from the other (see Fig. 2). The net resistance increases with time due to ion transport effects so the current trace in the stimulation phase decays with time, as noted in Fig. 8. The subnormal functioning condition is thus due to high skin impedance which comes from a combination of low electrolyte content and/or low tissue fluid content. The hyper functioning condition is thus due to low skin impedance which comes from a combination of high electrolyte content and/or high tissue fluid content.

The stimulation and response current waveforms can be predicted from first principles just as Fig. 2 and eqs. 1 apply to a constant applied voltage. The qualitative results for a positive impulse voltage and for a positive followed by a negative impulse voltage are given in Fig. 10. In each case there is a calculated response current, as shown in Fig. 10 (b) and (c), depending upon R_1, R_2 and C of Fig. 1 and the periods t_1 and t_2 in Fig. 10.

From the foregoing, we see that the Schimmel technique measures the basic ion concentration, the mobility of these carriers and the permeability selective character of the cell membranes in the skin in various sectors of the body. The direct connection between these skin parameters and the body's state of health is not immediately obvious. However, the skin is one of the body's major waste disposal systems and it is a linkage medium to various nerve endings. It is reasonable to deduce that a shift of the skin conductance parameters from the normal range signals either a local waste disposal problem or a local neural problem connected to some organ or body system malfunction. Or it is possible that the local skin conductance parameters, all by themselves, indicate the state of local body health or pathology in ways we do not yet understand. Finally, it is possible that we are kidding ourselves and the local skin conductance parameter values only indicate the local state of hydration, ion content and membrane permeability.

SMALL ELECTRODE STUDIES

In the early 1950's, Y. Nakatani [8] used a 12 volt DC source and passed a current through the skin of a patient discovering, thereby, that some points had a much higher electrical conductance than the surrounding sites. He named these "good conductivity points" and linked them up with an imaginary line known as a "good conductivity line" (Ryodoraku). This became known as the "Ryodoraku" technique and the measurement device was called the "Neurometer". Here, the patient holds in his/her hand the mass electrode, and the good conductivity points are tested with the tip of a search electrode. Because of the large voltage used, this response current is largely due to electrolytic dissociation of H_2O. In Europe, Niboyet[9], Bratu [10] and Brunet [11] also studied the properties of these high conductivity points. In China, many similar studies were conducted [12-14]. They found that the location of these high conductivity points and lines coincided amazingly well with the points and meridians of Chinese classical acupuncture. Using a Nakatani neurometer, Matsumoto [15] showed that 80 percent of acupuncture points could be detected.

According to Nakatani [16], acupuncture points have a low resistance due to the fact that excitation of sympathetic nerves had caused enlargement and opening of the sweat and sebaceous glands at these sites. However, others [14] failed to substantiate this proposal. Ishikawa [17] claimed that the high conductivity was due to reflex changes in subcutaneous blood vessels. Howeve Niboyet [18] found that acupuncture points on cadavers also had the characteristic of highest local

properties of acupuncture points or which utilizes the constant current source technique.

In the low frequency domain, the Voll dermatron [31] has been the most popular instrument. Its predecessor was the K&F Diatherapuncteur unit which is no longer being manufactured; however, it forms the basis of all the other EAV (Voll instruments) and its functioning is described in Appendix A.

With the Voll dermatron, shown in Fig. 12, in the diagnostic mode, the A. P. is charged with ~ 8 - 10 μA at a DC voltage of ~ 1 volt. The method of doing this is via a ball electrode contacting the skin at an applied pressure of ~ 500 - 1400 psi, while a large cylindrical electrode is held in the patient's off-side hand to complete the electrical circuit. The meter on the instrument is designed to record the skin's electrical conductance rather than the electrical resistance. 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 as 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.

A second and perhaps more important diagnostic indicator is the indicator drop (I.D.); i.e., the reading decreases from its maximum initial value to a final value with time. As a rule, the 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 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 about 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. This is basically the same type of behavior as noted earlier with the Schimmel device. Here, when the initial skin conductance is smaller (resistance higher), the anodal current flowing through the skin for fixed applied voltage is smaller so it takes longer for the ion transport to occur through the membrane walls. Thus, the resistance rises more slowly with time and the I.D. is slower. This device also measures skin conductance levels (combined electrolyte content and water content) and permeability selectivity of the membranes. Even for the same value of conductances, an increase of I.D. value by a factor of - 5 - 10 in a pathologic versus a healthy case indicates less permeability selectivity for the membranes involved. Once again, it is not readily seen how the electrical conductance and permeability selectivity values of the A.P.'s are directly connected to specific organ or body system. The Biopath System [63] device is a computer-assisted device of the Voll-Dermatron variety functioning with hand-held electrode and records the average rates of current rise and fall.

The Motoyama AMI instrument [32] applies a DC potential of 3 volts between a number of meridian terminal points and a large indifferent electrode on the wrist, as indicated in Fig. 13. It utilizes a skin electrical equivalent circuit like that shown in Fig. 1 and samples the very short time domain (high frequency domain). A current waveform like that shown in Fig.2 is sampled by the instrument. He defines 4 parameters (supposedly independent) for describing this current response: (1) BP (before polarization), the current value before ionic polarization in the skin proceeds against the externally applied electric potential (I(t=0)); (2) AP (after polarization), the current value which still flows even after the completion of this short time polarization (I(t=10^{-3} sec)); (3) IQ (integrated polarization charge), the total transferred electric charge of ions incurred during this short time polarization and (4) TC (time constant), the intercept point of the initial current slope with the AP level.

One should not confuse the current waveform and circuit parameters involved in Fig. 13 with the current waveform and circuit parameters in Fig. 3, because the time domains are completely

This author checked the data sheets for 30 patients studied via the AMI [37] and found that $\propto$ was not unity but ranged from 0.3 to 0.5 to fit the data. Either the important circuit parameters are time varying in this small time domain or the AMI machine is not responding rapidly enough to accurately measure in the initial 10 secs, or both. although the AMI utilizes a 1 MHZ clock, this only guarantees accurate time sampling in 10 μsec blocks, not 1μsec blocks. A 10 MHZ clock would be needed to accurately sample the initial few μsecs.

Motoyama's technique is to attach electrodes to the distal points of all meridians on the hands and feet and measure each point in turn, a la Fig. 13, automatic with a computerized system. In the Chinese system of notation, the 12 Jing distal points indicated in Fig. 16 have been used for acupuncture point treatment for centuries and quantitatively by Akabane since 1952 [33, 34], and more recently by Ionescu-Tigorviste [35]. These points are thought to play an important role in the "six energy axes" [36], as illustrated in Fig. 17. In the Motoyama notation, these are called the Sei points and there are 14 of them, as indicated in Fig. 18. After the electrode placement stage, which may take ~20 minutes, the measurement stage of the 28 electrodes begins. The automated measurement process of all the BP, AP, TC and IQ requires only a few minutes and the computer prints out these values for each of the points. The computer also prints out the standard deviation for each of these points and the changes between the left and right side values relative to the sum of the values for the 28 points. It also prints out the body averages, left-right differences on average, hand-feet differences on average and the standard deviation. When the values fall outside the expected range for a healthy person, they are "flagged" for the viewer. In a general sense, values that are too high are interpreted to mean that the body is in an excited state--often signaling the beginning o disease. Values that are too low are interpreted to mean that the whole autonomic nervous function is reduced generally through a chronic disease.

In a more specific vein, the following are average values in adults for the Phoenix area [37].

$$BP_{Avg} = 1600\text{-}2000$$

$$AP_{Avg} = 20\text{-}30 \qquad (5)$$

$$TC_{Avg} = 8.5\text{-}12$$

$$IQ_{Avg} = 3500\text{-}4000$$

If the patient's IQ value is high, it is thought to indicate congestion or blockage and the higher it is, the more toxic is the condition. When the value is low, a weakness is thought to exist in the whole reaction of the individual. When the TC is high, the individual is thought to be armored, stressed, chronic tightness; if it is low, the indication is weakness, apathy, given up. If the AP is high, this is thought to indicate an over stressed sympathetic nervous system (sweaty palms, tight individual); if it is low, the indication is for weak defenses and poor recoverability (mediators fall here, but this is normal for them). Finally if the BP is high (.2100), the indications are for a mildly toxic to very ill condition (depends upon the IQ value), perhaps an allergy; if low (<1600), the individual is weak in overall energy and complains of severe fatigue.[37]

Reflecting on both the Voll and the Motoyama devices, the measurements appear to reflect

Aside from conductivity effects (electrolyte concentration and ion mobility) and permeable membrane selectivity effects, which are all localized to the epidermis/dermis region, the one special feature that is unaccounted for is the battery-like effect of the A.P.'s; they will supply current to a high impedance load. another special feature is the enhanced positive potential of several millivolts at the A.P. skin compared to surrounding skin. If one just evaluated the surface potential based on simple diffusion of +ions from the inside of the cell to the surface, the potential would be only ~ several microvolt. Thus, for it to be as large as millivolts requires a driving field pushing the +ions out onto the skin. If a magnetic vector potential field, A, flowed along the meridians, an electric field, E, would exist given by

$$\vec{E} = -\nabla\phi - \frac{\delta \vec{A}}{\delta t} \qquad (6)$$

This additional negative field at the surface of the skin would require a larger transfer of positive ions and a correspondingly larger surface potential, ϕ, such as has been measured. The induced field indicates that this is probably the source of the battery-like effect observed at the A.P.'s and points to an internal body source which may be the organs. Interestingly enough, this same time-varying $\vec{A}$ field gives rise to a microwave EM field passing out through the A.P.'s and this field could dissociate membrane-bound water molecules in the stratum corneum tissue to give the A.P.'s their enhanced electrical conductivity compared to the surrounding tissue. This seems to be the connection that we need to understand better than we presently do. It is perhaps this connection that will reveal the diagnostic efficacy of these new devices that monitor the skin and predict the state of organ pathology. Much more study is needed to test this hypothesis; however, it seems clear that one should at least add a battery to the circuit of Fig. 1.

Considering an E-field directed outwards along a meridian to the surface in the stationary state, the electric force will cause the ions to pile up until the back-diffusion force exactly cancels the $\vec{A}$ - generated $\vec{E}$ - field. This moves positive ions outwards from the inner body to the dermis and epidermis regions so that the ionic conductivity of these regions experience a net increase of magnitude of the $\vec{E}$ - field. This manifests itself in the magnitudes of R_1 and R_2 and probably also of C. Thus, by measuring the change in magnitude of these parameters with changes in the subject's health state, one is gaining a measure of the state of the internal organs via the $\vec{A}$ - generated $\vec{E}$ - field linkage.

CONCLUSIONS

1. There are several effective electrodermal techniques in present use and we understand both

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APPENDIX B
Dielectric Response in Human Skin

A. Complex Electrical Quantities

To characterize the skin as an electric network means that both resistive (ΣR_i) and capacitative (ΣC_i) parameters must be measured. This eliminates any reliance on d.c. measurements (purely resistive) and greatly limits the usefulness of time-dependant or single relaxation-time determinations, as will be shown later.

The most straightforward expressions of useful electrical quantities are as complex numbers in frequency domain. A valuable technique for the representation of these quantities is to plot the real versus the imaginary parts of the quantity at various frequencies. The frequency dispersion of these values then produces geometric loci of points which are combinations of, or variations on, semicircles and vertical lines. These shapes allow for extrapolation to critical frequency ranges at which actual property values for particular network components can be obtained. As an example, consider Fig. 19a and b, where two simple networks are shown along with their corresponding plots of imaginary (X) versus real(R) impedance components.

Figures 19c and d illustrate the effects of adding one more parameter to the circuit. Note that in Fig. 19c, the R_1-C_1 and R_1-C_2 relaxation times are sufficiently different that the semicircle and straight lines are distinct. However, if C_1 and C_2 are similar (say within two orders of magnitude), the shapes will overlap. The analysis of Fig. 19d, then, consists of separating out contributions to the curve shape which corresponds to a particular relaxation time or R-C combination.

The complexity of any real system makes this a difficult problem which is compounded by the limitation of the experimentally available frequency range. Often not realized, however, is the considerable complimentary information obtained by converting impedance values to those of other electrical quantities such as admittance and permittivity (complex dielectric constant). since admittance is the reciprocal of impedance, a series R-C combination now plots as a semicircle in the complex plane while a parallel combination gives a straight line. The permittivity plot offers the advantage of extrapolating to values of dielectric constant on the abscissa. Equations B1-B7 show the simple relations between these quantities.

$$Z^* = \text{impedance} = R - jX \qquad \text{(B-1)}$$

$$y^* = \text{admittance} = G + jb \qquad \text{(B-2)}$$

$$\epsilon^* = \text{permittivity} = \epsilon^{I} - j\epsilon^{II} \qquad \text{(B-3)}$$

$$G = \text{conductance} = R/(R^2 + X^2) \qquad \text{(B-4)}$$

$$B = \text{susceptance} = X/(R^2 + X^2) \qquad \text{(B-5)}$$

one explanation. In fact, this behavior is indicated whenever the current flow is diffusion limited rather than activation limited. Further investigations may find that seemingly unrelated phenomena, such as the selective permeability of biological membranes of simultaneous electronic and ionic currents, will also produce this effect.

C. The Search for an Equivalent Circuit

References to the many aspects of electrodermal measurements can be found in reviews by Edelberg (45), Vanables and Martin (46) and Schwan (47). A considerable amount of information is presented by Cole (48) who has rather subjectively traced the development of electrical measurements on membranes.

Fricke (41) and Cole (49) first treated the problem of anomalous frequency dependencies in cell suspensions and tissues. Complex plane plots of impedance at high frequencies showed semicircles which were lowered below the bascissa by less than the forty-five degrees predicted by Warburg's law: i.e., $\propto$, 0.5. Results were reported for each system in terms of a constant phase angle where

$$\theta = \propto \Pi/2 \qquad \text{(B-8)}$$

Although recognizing the similarity to Warburg's electrode polarization behavior, Cole believed that the marked deviation of from 0.5 might require an alternative explanation. Cole and Cole (50) then derived an expression which described their data in terms of the observed phase angle for each system. they assumed a distribution of relaxation times ($\tau = RC$) which would cause a broadening of the frequency dispersion and could result from geometric or cellular inhomogeneities within the sample. Schwan (51) contrasted the Cole-Cole type distribution to that of a statistical distribution of τ and later (Schwan 52) proposed ways of determining whether polarization or some other factor is responsible for the frequency-dependent reactance. Cole (49) proposed the circuit of Fig. 20a to describe his results where R_b, the bulk resistance, is in series with Z_p, a frequency dependent admittance, and R_p, the polarization resistance. although the Cole-Cole equation has been used by Yokota (53), Yamamoto (54) and many others to fit impedance and permittivity data, it remains only a mathematical description which as yet defies physical understanding.

Barnett (55) dealt with the inconsistent results obtained for the phase angle of human skin in an attempt to separate the skin impedance from that of the deeper-lying tissues. Although his experimental approach was unconvincing, he successfully pointed out that more than one phenomenon may be superimposed in a single set of measurements. Tregear (56) suggested that the electrodermal response be broken down into contributions from each skin layer, as in Fig. 20. b. although this circuit does predict a frequency dependence, it is hardly experimentally confirmable and one might consider whether such a nearly infinite array of circuit elements might be lumped into one frequency-dependent element. It should be noted that the Warburg admittance itself is described by the infinite transmission line network of Fig. 20c.

More recent attempts to separate out the effects of the stratum corneum from those of the deeper tissues have been performed by Yamamoto(57), Lawler, et al. (58), and Lykken (2), through the stripping off of successive layers of skin. This work indicated that nearly all of the resistance is in the epidermal layer, which might allow one to consider anything below this layer as deep tissue.

D. The Speed for Accuracy Trade-off

The measurement of impedance was made possible by modification of the Wheatstone bridge to operate over a range of frequencies. And still, the comparison of the sample-electrode system to

If an appropriate equivalent circuit were known, values for the components of the circuit could be readily obtained through iterative curve fitting. Since this is not the case, we must search the data for clues that will suggest certain component configurations and eliminate others. The following paragraphs briefly illustrate the use of a complex plane analysis for examining data from the human body.

Figure 21 shows typical complex plane plots obtained in this laboratory. the depressed impedance semicircle (Fig. 21a) seems well described by the Cole circuit (Fig. 20a), and one is tempted to extrapolate to a high frequency value of R_b and a low frequency value of $R_b + R_p$, where R_p is now the resistance of the stratum corneum. The complex admittance (Fig. 21b) seems also to support this circuit with the extra advantage of allowing a more accurate extrapolation to low frequency. However, the complex permittivity, or Cole-Cole plot (Fig. 21c), which is often ignored in these treatments, indicates a completely different interpretation.

In Fig. 21c, there is additional information at high frequency that is masked in the previous figures. If we extrapolate the high frequency arc as a semicircle, we see that it is lowered below the axis by about 19^0 and that its low frequency intercept corresponds to an apparent capacitance of ~ 1.4×10^{-8}F. Similar values have been assumed for the double layer capacitance of the skin. the lowering of the semicircle is consistent with a high frequency diffusional admitance (Z_I of the general form.

$$Y^{\#}_{ZI} = A_1\omega^{\alpha 1} + jA_2\omega^{\alpha 2} \qquad \text{(B-9)}$$

in a series with the apparent low frequency capacitance. Implicit in this expression is that θ of eq. B-8 is the angle by which the semicircle is lowered. As a first approximation, then, we have isolated both a high and a low frequency component from the total circuit (Fig. 22a). Note that thi combination is inconsistent with any portion of the previously proposed circuits.

If Z_1 does describe the high frequency regime, then we can subtract the assumed double layer capacitance directly from the impedance data of this region and a replotting in the permittivity plane should give a curve shape corresponding to Z_1 alone. This manipulation replaces the semicircle of Fig. 21c by a line inclined from the vertical which is straight within the limits to which the capacitance value can be estimated. The straight line can now be analyzed by converting e.g. B-9 to an expression of permittivity.

$$\epsilon_o\epsilon^*_{ZI} = A_2\omega^{(\alpha 2-1)} - jA_1\omega^{(\alpha 1-1)} \qquad \text{(B-10)}$$

By writing the real part of the permittivity as

$$\ln\epsilon^1 = \ln A_2 + (\alpha_2 - 1)\ln\omega \qquad \text{(B-11)}$$

and similarly for the imaginary part, the parameters A_1, A_2, α_1 and α_2 can be evaluated through a first order polynomial regression. The values of these parameters for the present set of data are listed in Table 1. Note that $\alpha_1 \approx \alpha_2 = 2\theta/\pi$ and that $\theta \approx \tan_1 (A_2, A_1)$.

To check whether Z_1 adequately characterizes the high frequency response, we can subtract it from the original impedance data and begin the analysis again as though the component were not present. Fig. 21f shows that the high frequency semicircle is now removed from the permittivity plot but that the low frequency range is relatively unaffected. The equivalent effect is seen in the admittance plot where the high frequency portion is a straight line, but the low frequency reg remains inclined (Fig. 21e). The new impedance curve of Fig. 21 d, however, has only been shifted

frequency-dependent bridge measurements can be extrapolated to values of resistance or capacitance without appropriately considering diffusional admittances has also been pointed out. If the electrical properties of the skin are to be elucidated, and, indeed, if changes in these properties monitor changes in the body functions, then further investigations based on an adequate equivalent circuit are called for.

Table 1

Estimates of parameters in the diffusional admittances of Figure 21d.

$$Y^*_Z = A_1\omega^{\alpha 1} + jA_2\omega^{\alpha 2}$$

	$Z=Z_I$	$Z=Z_{II}$
α_1	0.18	0.54
α_2	0.18	0.54
A_1(mho)	1.8×10^{-4}	1.4×10^{-7}
A_2(mho)	6.4×10^{-5}	1.7×10^{-7}

FIGURES

1. The simplest frequency independent electrical equivalent circuit used for skin measurements.
2. Current waveform arising from the application of a constant DC voltage to the circuit of Fig.1.
3. Time dependence of the electrical resistance, R, of the skin for a 2 volt applied DC potential ($7cm_2$ of skin moistened for 20 min with saturated KCl solution). (Courtesy of T. Rosendal).
4. (a) Form of the electrical equivalent circuit of the skin and electrode system which matches the experimental data without assuming frequency dependent parameters.
   (b) Alternate system viewpoint circuit.
   (c) Important circuit elements after neglect of the electrodes.
5. electrical equivalent circuit generated from skin measurements using AC conductance techniques and complex plane analysis.
6. Stimulus current corresponding to a constant voltage pulse applied to the skin through a concentric electrode.
7. (a) Body placement electrodes in the Segment Electrograph technique.
   (b) Illustration of electrical pulse cycle on recording paper.
8. Illustration of the general types of current trace resulting from the stimulation voltage wave: (a) normal body function, (b) sub-normal body function and (c) hyper body function.
9. Illustration of the response current trace: (a) normal body function, (b) sub-normal body function, (c) hyper body function.
10. Response current waveforms to various voltage waveforms being applied to the circuit of Fig.1.
11. (a) Diagram of connections for the diagnostic part of the K+F-Diatherapunteur apparatus.
    (b) Calibration curve for the above apparatus.
12. Schematic illustration of the Voll dermatron with electrodes.
13. Single electrode arrangement in the Motoyama technique, applied voltage impulse and response current waveform for the system.
14. Generalized diagram of the ionic accumulations in the dermis and epidermis.
15. Schematic representation of the current vs. time plot over the entire time domain (9 decades).
16. The location of the 12 Jing distal points.
17. Schematic illustration of the six energy axes.
18. The location of the 14 Sei points.
19. Complex impedance plots for (a) series R-C circuit, (b) parallel R-C circuit, (c) $C_2 << C_1$, (d) $C_2 \sim C_1$.
20. (a) Equivalent circuit described by the Cole-Cole equation.
    (b) Circuit describing laminated structure of skin according to Tregear (56).
    (c) Equivalent circuit of transmission line described by Warburg's law.
    (d) Frequency-independent circuit assumed in analog pulse techniques.
21. (a, b, c) Complex plane representation of electrical response at volar forearm of human subject: impedance, Z*; admittance, Y*; permittivity, ϵ^*. (d, e, f) Complex plane representation of a, b and c after subtracting assumed high frequency (deep tissue)