DIELECTRIC RESPONSE IN HUMAN SKIN

by

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ABSTRACT

Attempts at modeling the dielectric properties of the skin are reviewed. A new analysis, based on complex electrical quantities, shows that the outer layer of skin and the deeper tissue each has their own frequency-dependent component. An equivalent circuit for the skin is proposed and a procedure for verifying the circuit and determining the values of each component is illustrated. The circuit may be general enough to allow rapid and accurate evaluation of important parameters in any dielectric measurement.

Key Words

skin

dielectric

electrodermal

impedance

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Since the beginning of this century, scientists of varied disciplines have attempted to present a model of the human skin which would account for its electrical properties. The present interest is best evidenced by the rapidly expanding area of clinical psychophysiology. What we have learned from each successive experiment performed over some seventy years is that the task is more formidable than we had ever imagined. Indeed, the issue among the most capable of scientists is no longer to find out how much we can learn but how much we really need to know.

This approach has taken on increasing validity. The phenomenon of galvanic skin response has been attributed to fluctuations in the volume of liquid in sweat ducts. The skin resistance level or d.c. resistance is so dominated by the stratum corneum that contributions from deeper layers of skin are usually considered unimportant. Even the variations in skin resistance levels at different parts of the body seem to correlate well with densities of sweat glands. Considering the complications of electrodics, instrumentation and time-dependent variables, one might conclude that further modeling of the skin as an electrical network is not worth the effort.

There are new considerations, however, which clearly call for a reevaluation of our approach to this area of research. they arise from the obvious but generally unappreciated concept of the skin as an interface between the body and its environment. This concept includes the corollary that the skin is an effective monitor of the internal body processes which further implies that the skin also provides a means of affecting these processes.

To associate this concept with ancient theories, such as Chinese acupuncture, may or may not be valid, but to do so and then to dismiss it as an obsolete or unscientific discipline is clearly inadequate. Consider the observation that the skin resistance level is consistently lower at points on the skin corresponding to those of acupuncture even though these points show no histological difference with their surroundings (Reichmanis, et al., 1975; Tiller, 1972). There is no evidence that this can be explained by anything so simple as density of, or liquid level in, sweat ducts. Even if it could, the observation would be no less intriguing.

If the skin can provide us with new insight into the nature of the human body and its processes, its properties must not remain unexplored. If this insight can best be gained through a study of the skin's electrical properties, then new techniques must be devised to determine by what parameters these properties are best monitored. In the excitement of realizing the clinical applications of this work, many of the underlying electrochemical principles have been ignored, and it is now apparent that these concepts can explain many of the inconsistencies which invalidate so much of the literature.

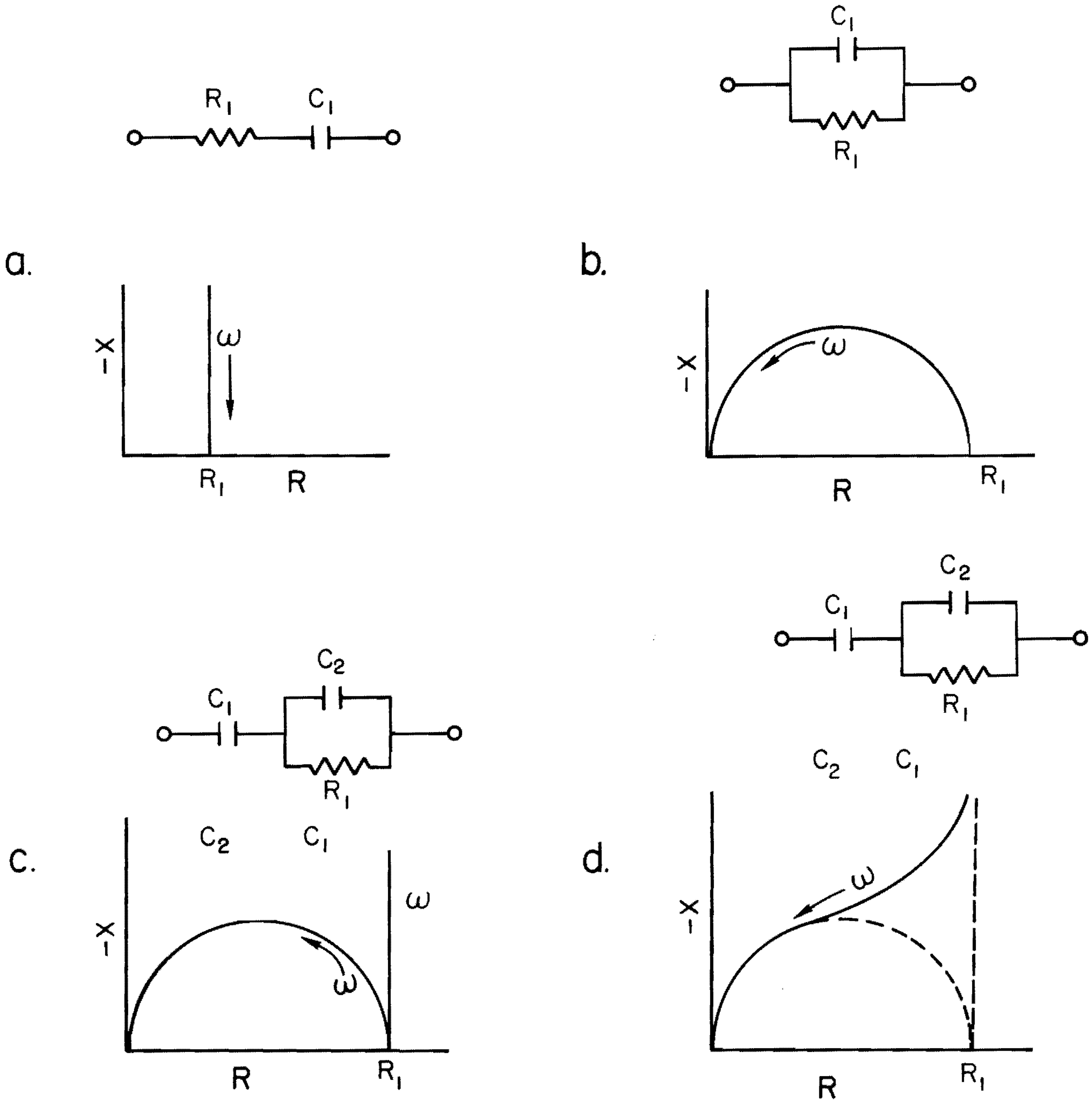
Complex Electrical Quantities

To characterize the skin as an electrical 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-dependent or single relaxation-time determinations, as will be shown later.

The most straightforward expressions of useful electrical quantities are as complex numbers in the 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 Figs. 1a and 1b, where two simple networks are shown along with their corresponding plots of imaginary (X) versus real (R) impedance components.

Figures 1c and 1d illustrate the effects of adding one more parameter to the circuit. Note that in Fig. 1c, the R_1-C_1 and R_1-C_2 relaxation times are sufficiently different that the semicircle and straight line 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. 1d, then, consists of separating out contributions to the curve shape which correspond 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 complementary information obtained by converting impedance values to those of other electrical quantities such as admittance and permittivity (complex dielectric constant). Since



Complex impedance plots for (a) series R-C circuit, (b) parallel R-C circuit, (c) $C_2 << C_1$, (d) $C_2 \sim C_1$.

FIGURE 1

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 1-7 show the simple relations between these quantities.

$$Z^* = \text{impedance} = R - jX \tag{1}$$

$$Y^* = \text{admittance} = G + jB \tag{2}$$

$$\varepsilon^* = \text{permittivity} = \varepsilon' - j\varepsilon'' \tag{3}$$

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

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

$$\varepsilon' = \text{dielectric constant} = B/\omega\varepsilon_o \tag{6}$$

$$\varepsilon'' = \text{dielectric loss} = G/\omega\varepsilon_o \tag{7}$$

where R is resistance, X is reactance, ω is the radial frequency and ε_o is the permittivity of free space. It will also be seen that over a given frequency range, one plot may prove much more valuable than another for the purpose of extrapolation.

If all the components of a real equivalent circuit were discrete frequency-independent parameters, the analysis would be relatively straightforward. This, however, is never the case and considerable controversy has been generated over apparently frequency-dependent resistances and capacitances which cause complex plane semicircles to appear to be centered below the real axis and straight lines to be inclined from the vertical.

The Electrode Problem

Warburg (1899) first considered the electrical response of the interface between a metal electrode and a liquid electrolyte. He found that , at a single frequency, the reactance and the resistance are equal and that, over a limited frequency range, the values of both X and R vary inversely as the square root of the frequency. Although Fricke (1932) showed that this is only approximately true, it is still generally accepted as Warburg's law that $X \cong R$ and that each varies as $\sim \omega^{-\alpha}$ where α is near 0.5.

The Warburg behavior can be caused by a faradaic process in which current crosses the interface by means of an electrochemical reaction. This is in contrast to a non-faradaic process in which charged particles do not cross the interface but instead charge and discharge the electrical double layer.

Grahame (1952) states as three examples of faradaic processes: (a) a product of electrolysis diffusing away from the reaction site, (b) a reaction product undergoing a second reaction which calls for continuous replacement, and (c) a reaction product reaching an upper limit of chemical potential before the counter electromotive force needed to stop the reaction is attained. These examples all have in common the effect that the electrode is incompletely blocking to species of the electrolyte. An important point is that, since the electrode may be blocking to some species and not to others, a double layer capacitance may and usually does occur in parallel with a faradaic or diffusional admittance. MacDonald (1974) has given this behavior a rigorous theoretical treatment.

The application of the diffusional admittance concept to biological systems is obvious since, in an electrodermal measurement, a metal electrode will be in contact with a sodium chloride solution (sweat). However, there is no fundamental reason why the faradaic process should be limited to metal-liquid systems, and one might envision the highly resistive stratum corneum as a semi-blocking electrode in contact with the less resistive deeper-lying tissues.

In characterizing the behavior of several interface situations, Grahame suggested that an Ag/AgCl electrode in contact with an alkali halide solution might not exhibit a faradaic current since the activity of the AgCl is practically invariant. Investigations by Geddes (1969) and by the authors have verified this by showing that the electrical response of Ag/AgCl electrodes, when used with a sweat-simulating solution such as Beckman Paste, is virtually frequency-independent. Under these conditions, which include the present work, any diffusional process in an electrodermal measurement must originate in the body itself. As we shall see, this is the case, and the question is raised whether Warburg-like behavior actually requires an electrochemical reaction process or whether such a mechanism is only 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 or simultaneous electronic and ionic currents, will also produce this effect.

The Search for an Equivalent Circuit

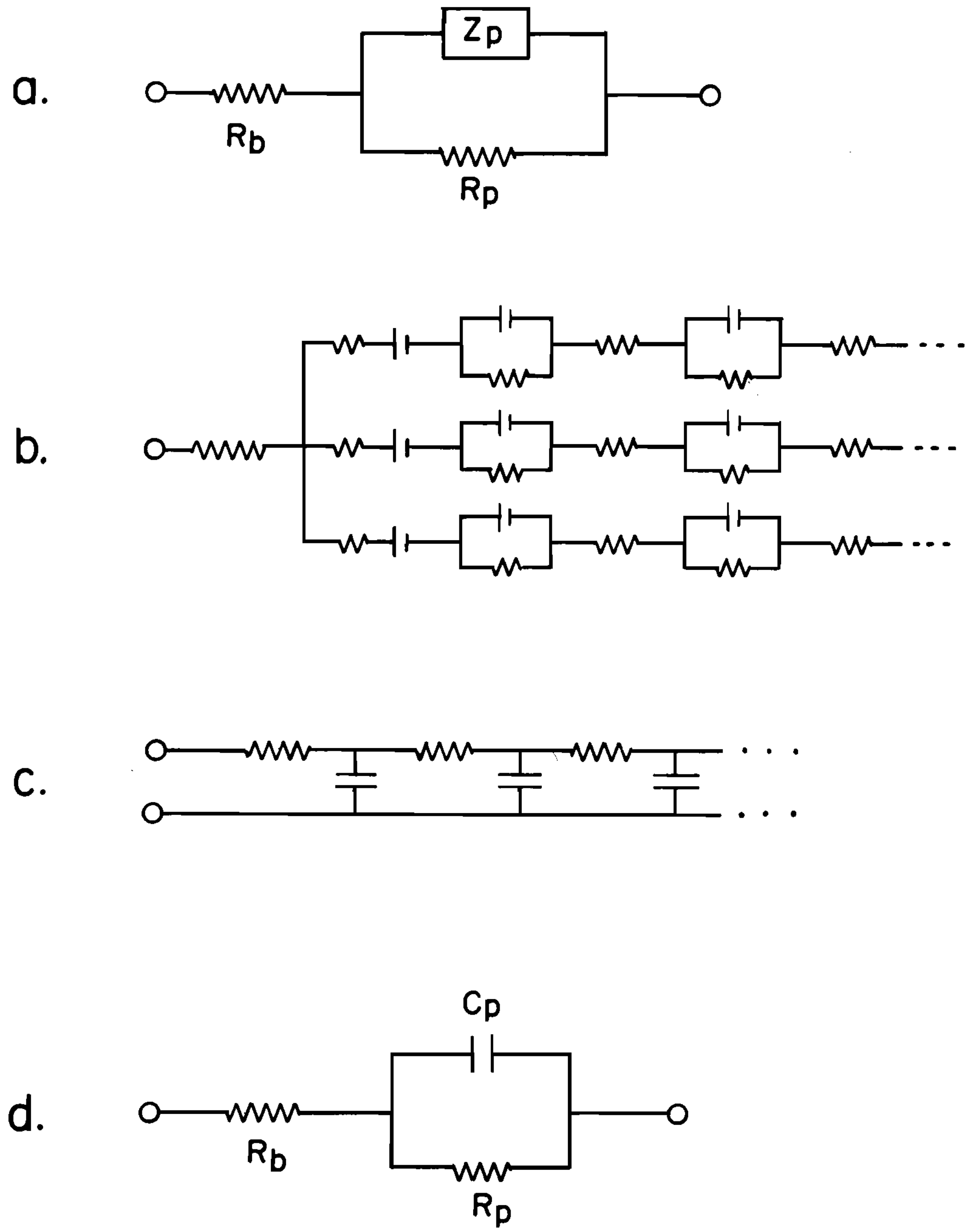
References to the many aspects of electrodermal measurements can be found in reviews by Edelberg (1971), Venables and Martin (1967) and Schwan (1963). A considerable amount of information is presented by Cole (1968), who has rather subjectively traced the developement of electrical measurements on membranes.

Fricke (1931) and Cole (1932) first treated the problem of anomalous frequency dependences in cell suspensions and tissues. Complex plane plots of impedance at high frequencies showed semicircles which were lowered below the abscissa by less than the forty-five degrees predicted by Warburg's law; i.e., $\alpha < 0.5$. Results were reported for each system in terms of a constant phase angle where

$$\theta = \alpha\pi/2 \tag{8}$$

Although recognizing the similarity to Warburg's electrode polarization behavior, Cole believed that the marked deviation of α from 0.5 might require an alternative explanation. Cole and Cole (1941) 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 ($\tau = \omega RC$) which would cause a broadening of the frequency dispersion and could result from geometric or cellular inhomogeneities within the sample. Schwan (1966) contrasted the Cole-Cole type distribution to that of a statistical distribution of τ and later (Schwan 1968) proposed ways of determining whether polarization or some other factor is responsible for the frequency-dependent reactance. Cole (1932) proposed the circuit of Fig. 2a 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 (1962), Yamamoto (1976-a) and many others to fit impedance and permittivity data, it remains only a mathematical description which as yet defies physical understanding.

Barnett (1938) 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 (1965) suggested that the electrodermal response be broken down into contributions from each skin layer, as in Fig. 2b. Although this circuit does predict a frequency dependence, it is hardly experimentally comfirmable 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



(a) Equivalent circuit described by the Cole-Cole equation. (b) Circuit describing laminated structure of skin according to Tregear (1966). (c) Equivalent circuit of transmission line described by Warburg's law. (d) Frequency-independent circuit assumed in analog pulse techniques.

FIGURE 2

the infinite transmission line network of Fig. 2c.

More recent attempts to separate out the effects of the stratum corneum from those of the deeper tissues have been performed by Yamamoto (1976-b), Lawler, et al., (1960), and Lykken (1970), through the stripping off of successive layers of skin. This work indicates that nearly all of the resistance is in the epidermal layer, which might allow one to consider anything below this layer as deep tissue.

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 a set of variable capacitors and resistors is the most accurate method for determining impedance. However, there are two major drawbacks to the use of a bridge circuit in measuring frequency response. One is the limited frequency range over which it is reliable. The other is the time required for taking readings at a sufficient number of frequencies. For bridge readings to be self-consistent, one must assume the sample to be in equilibrium, and, in skin measurements, this cannot be assumed until at least thirty minutes after the application of electrodes.

Lykken (1970) has proposed the use of square wave analysis in which a step voltage is imposed across the sample and the current is monitored to give values of resistance both before and after the charging the capacitative elements. This method provides an effective way of covering a wide frequency range in a matter of seconds, but it also has several drawbacks. First, the initial or peak current value is dependent on the rise times of both the generator and the measuring device (usually an oscilloscope). Indeed, analog measurements have limited accuracy over such short decay times. Second, and most serious, is that only one relaxation time can be monitored, and one must assume a network where the polarization reactance of Fig. 2a becomes a simple double layer capacitance (Fig. 2d).

A steady-state method, which provides an improvement over both the precision and accuracy of analog pulsed measurements, is reported in the Bode plot analysis of Burton, et al. (1974). This procedure permits the synthesis of an equivalent circuit for any passive system through its frequency behavior. Once that circuit is assumed, measurements need only be taken at three or four critical frequencies to obtain values for the components. The circuit that is generated, however, is not unique and may have no bearing on the physical processes of the system.

It also precludes the analysis of frequency-dependent components, which is undoubtedly an oversimplification.

Teorell (1946) was able to account for the frequency-dependent reactance of Fig. 2a using a graphical Fourier analysis to convert data from the time domain to the frequency domain. Although a laborious procedure, it does allow data to be taken quickly. However, it applies only to the frequency range in which the phase angle is constant.

The recent advances in Fourier analysis, notably that of the fast Fourier transform, may ultimately lead to a replacement for the cumbersome bridge technique. There is already a considerable literature relating the application of this method to electrochemical (Sandifer and Buck 1975) and biomedical (Yoganathan, et al., 1976) research. For our purposes, however, its usefulness seems to be contingent on the adequate refinement of an equivalent circuit for the skin. In the following section, we report on preliminary attempts from this laboratory to provide such a circuit from which meaningful component values may be extracted.

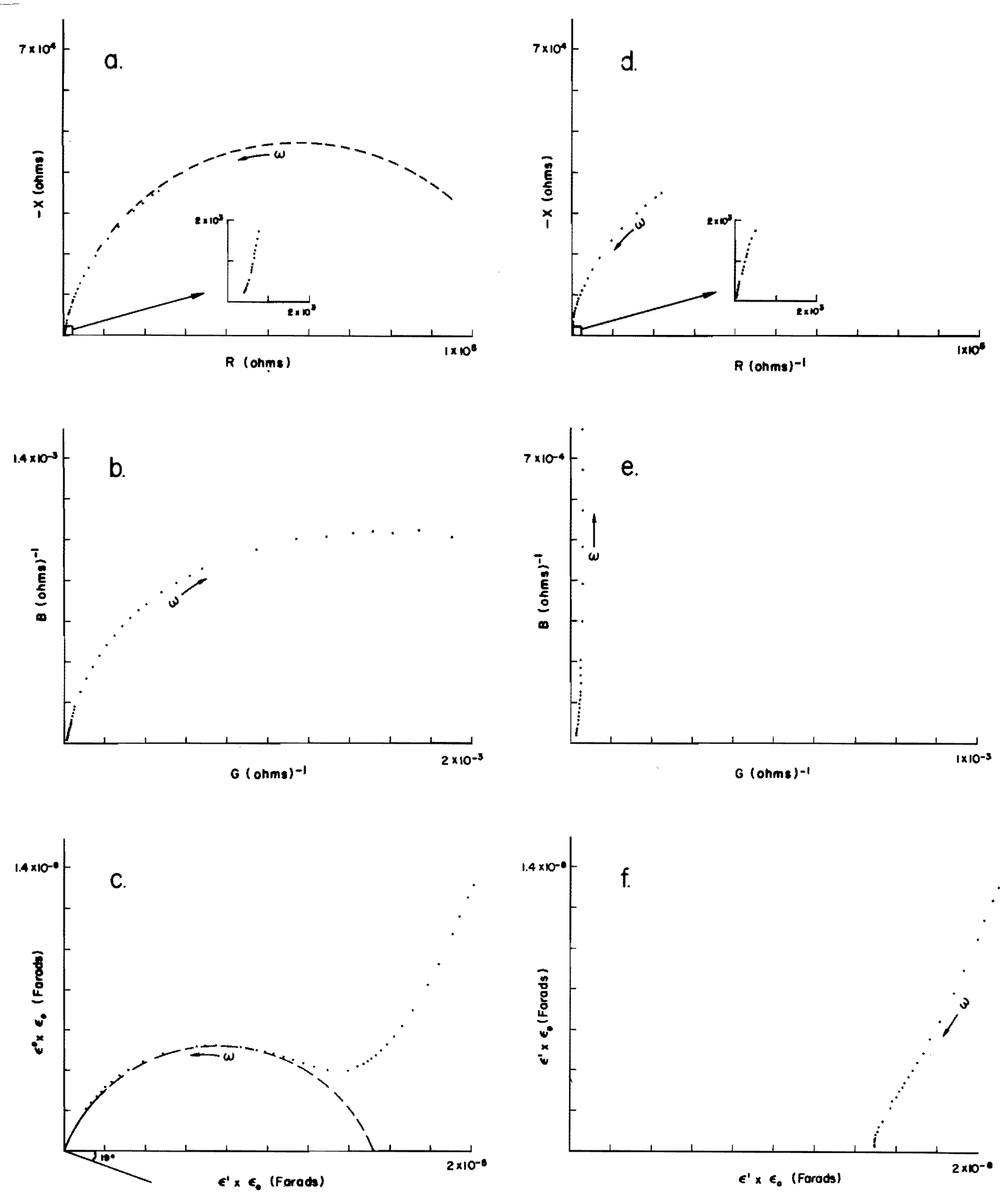
An Analysis of Complex Plane Plots

A comparison bridge circuit was modified to operate in the frequency range from less than 10 Hz to more than 100 kHz. Bridge balance was detected by a low-level differential oscilloscope.

Beckman Ag/AgCl electrodes (.01 m diameter) were attached to the volar forearm of each subject. The electrode spacing was 0.12 m. The subjects, all adult volunteers, were asked to relax in a reclining position inside a Faraday cage. Impedance data were taken at various frequencies during the first thirty minutes and were time-dependent. Once the readings stabilized, a series of about 40 readings was taken at frequencies from 40 Hz to 100 kHz. Voltage accross the system was maintained at 0.4 V. The data was either in the form of series capacitance vs. dissipation factor or of parallel capacitance vs. quality factor. A small computer was used to convert these data to complex impedance, admittance and permittivity.

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 3 shows typical complex plane plots obtained in



(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) contribution.

FIGURE 3

this laboratory. The depressed impedance semicircle (3a) seems well described by the Cole circuit (Fig. 2a), 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 (3b) 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 (3c), which is often ignored in these treatments, indicates a completely different interpretation.

In Fig. 3c, 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^o and that its low frequency intercept corresponds to an apparent capacitance of $\sim 1.4 x 10^{-8}$ 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 admittance (Z_I) of the general form

$$Y^*_{Z_I} = A_1 \omega^{\alpha_1} + jA_2 \omega^{\alpha_2} \qquad (9)$$

in series with the apparent low frequency capacitance. Implicit in this expression is that θ of eq. 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. 4a). Note that this combination is inconsistent with any portion of the previously proposed circuits.

If Z_I 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_I alone. This manipulation replaces the semicircle of Fig. 3c 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 eq. 9 to an expression of permittivity:

$$\varepsilon_o \varepsilon^*_{Z_I} = A_2 \omega^{(\alpha_2 - 1)} - jA_1 \omega^{(\alpha_1 - 1)} \qquad (10)$$

By writing the real part of the permittivity as

$$\ln \varepsilon' = \ln A_2 + (\alpha_2 - 1) \ln \omega \qquad (11)$$

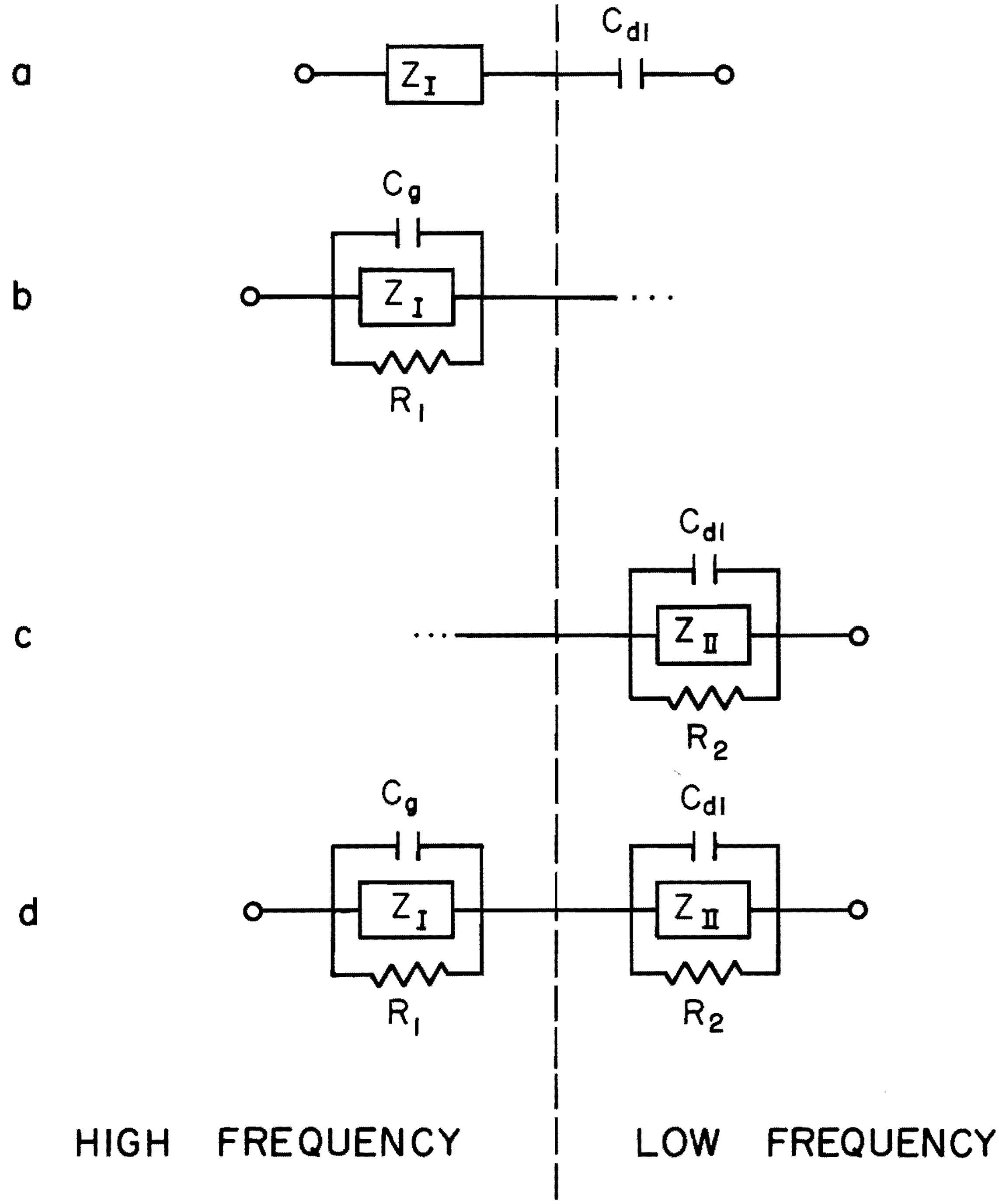
and similarly for the imaginary part, the parameters A_1, A_2, α_1 and α_2 can be evaluated through a first order polynomial regression. The values of these parameters for the present set of data are listed in table 1. Note that

$\alpha_1 \cong \alpha_2 = 2\theta/\pi$ and that $\theta \cong \tan^{-1}(A_2/A_1)$.

To check whether Z_I 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. Figure 3f 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 region remains inclined (Fig. 3e). The new impedance curve of Fig. 3d, however, has only been shifted to the origin at high frequency. This very important observation shows that the assumption of extrapolating the impedance data to a high frequency fixed resistance value is erroneous. In other words, Fig. 3a may not continue to a finite point on the abscissa, but may slowly go to zero with increasing frequency. What one is seeing in Fig. 3a, then, is the effect of the polarization reactance as it overrides Z_I and brings the data into an experimentally observable range. This also means that, in the pulse or square wave techniques, the initial current value does not correspond to a fixed bulk resistance but instead is a function of the rise time (effective upper frequency limit) of the measuring system.

The high frequency portion of the equivalent circuit can now be modified for electrochemical consistency, as in Fig. 4b, where C_g is the geometric or optical capacitance corresponding to the infinite frequency dielectric constant (ε_∞). The value for this capacitance is expected to be low (10^{-12}- 10^{-11} F), and its effect on data below 50kHz should be negligible. R_1 functions as the faradaic admittance which necessarily shunts Z_I. Further experimentation should determine whether R_1 denotes a bulk resistance or whether it is a parameter dependent on the values assigned to Z_I.

This model assumes that all high frequency phenomena correspond to the bulk or deeper-lying tissues of the skin and that they will act in series with any polarization, epidermal or electrode effects. We can now evaluate the low frequency behavior from Fig. 3, since it appears that the major high frequency contribution has been successfully subtracted out of the data. Figure 3f indicates that a fixed double layer capacitance does exist and is in parallel with a large resistance which is undoubtedly that of the stratum corneum. From the admittance plot of Fig. 3e, this resistance value can be estimated. The lowered semicircle of Fig. 3d, however, indicates that a frequency-dependent parameter is still present and adding a Warburg-like behavior to the circuit. According to Grahame (1952), this component can be considered in parallel with the double



Sequence of equivalent circuit generation by complex plane analysis described in text.

FIGURE 4

layer capacitance and, if so, the low frequency circuit might be represented as in Fig. 4c. Reasonable values for C_{dl} and R_2 can now be subtracted from the remaining admittance and the result for all three plots is a straight line with a slope from the vertical corresponding to Z_{II}. This can be analyzed by polynomial regression of the logarithm of eq. 9 to give approximate values for its frequency dependence and coefficients. These estimates are shown in Table 1.

At this stage, the approximations become decreasingly valid because of the complex interactions between parameters. For example, the reactance of Z_{II} is of the same order as that of C_{dl} and the influence of Z_I on the low frequency region will depend upon the frequency at which it is shunted by R_1. Undoubtedly, there are other minor contributions to the circuit which haven't been considered, and the configuration may not be unique or even correct in spite of its response to physical interpretation.

An iterative curve-fitting computer program has successfully eliminated several other circuit configurations and is now being used in an attempt to best fit the present twelve parameters of Fig. 4d to the data. However, more advanced instrumentation and particularly a wider frequency range may be required before further understanding can be obtained.

Table 1

Estimates of parameters in the diffusional admittances of Figure 3d.

$$Y_Z^* = A_1\omega^{\alpha_1} + jA_2\omega^{\alpha_2}$$

	$Z=Z_I$	$Z=Z_{II}$
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}

Analogies from Solid Electrolytes

It is interesting to note possible correlations between the electrical properties of biological and ceramic electrolytes. The analogy was perhaps first suggested by Cole (1965) in relating his work on solid hydrogen bromide; however, the use of complex impedance analysis in solids was not made popular until Bauerle (1969) reported his measurements on calcia-stabilized zirconium oxide. Since then, several theoretical (MacDonald, 1974; Franklin, 1975; Jonscher, 1975; Armstrong,1974) and experimental (Jonscher,1975) considerations have been proposed which are increasingly pertinent to the work presented here. Studies of lithium ion conductors in lithium silicates by one of us (L.E.N.) and by Raistrick, et al. (1976) have also shown the possible existence of more than one diffusional admittance where one appears to be related to conduction in the bulk of the solid, and the other to a polarization reactance. Where MacDonald (1975) treats the polarization behavior electrochemically, Armstrong, et al. (1974) have attributed it to inhomogeneities or roughness of the interface. We suggest that a more general interpretation of the diffusional admittance is needed and that it may be found to some degree whenever a charge carrier or combination of carriers is affected by an inhomogeneous conducting path. Jonscher (1977) has shown evidence for a "universal" dielectric response in solids. Our electrodermal measurements indicate that this universality might extend to biological systems as well.

Conclusions

Although the previous discussion is necessarily incomplete, there are several observations to be made at this point. The diffusional admittance appears to be a more general concept than has previously been recognized. In this system, two such admittances have been isolated, and neither seems related to Warburg's original treatment of polarization at metallic electrodes. Indeed, should metal electrodes have been used, one might expect that additional polarization complexities would have been encountered. Contributing mechanisims have only tentatively been assigned to this behavior.

Other conclusions fron this work are more straightforward. The limitations of pulsed techniques which rely on a three-component equivalent circuit become obvious. The fallacy that 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 body functions, then further investigations based on an adequate equivalent circuit are called for.

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