FREQUENCY DISPERSIONS OF HUMAN SKIN DIELECTRICS

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ABSTRACT The electrical properties of many biological materials are known to exhibit frequency dispersions. In the human skin, the impedance measured at various frequencies closely describes a circular locus of the Cole-Cole type in the complex impedance plane. In this report, the formative mechanisms responsible for the anomalous circular-arc behavior of skin impedance were investigated, using data from impedance measurements taken after successive strippings of the skin. The data were analyzed with respect to changes in the parameters of the equivalent Cole-Cole model after each stripping. For an exponential resistivity profile (Tregear, 1966, Physical Functions of Skin; Yamamoto and Yamamoto, 1976, *Med. Biol. Eng.*, 14:151–158.), the profile of the dielectric constant was shown to be uniform across the epidermis. Based on these results, a structural model has been formulated in terms of the relaxation theory of Maxwell and Wagner for inhomogeneous dielectric materials. The impedance locus obtained from the model approximates a circular arc with phase constant $\alpha = 0.82$, which compares favorably with experimental data. At higher frequencies a constant-phase, frequency-dependent component having the same phase constant α is also demonstrated. It is suggested that an approximately rectangular distribution of the relaxation time over the epidermal dielectric sheath is adequate to account for the anomalous frequency characteristics of human skin impedance.

INTRODUCTION

It has been known for some time that the electrical properties of many biological materials undergo characteristic frequency dispersions (Schwan, 1957). Whereas the mechanisms responsible for various tissues might be different, few of these have been adequately elucidated. The electrical impedance of the human skin is an interesting example of this effect. In the complex plane, the impedance at various frequencies exhibits a characteristic circular-arc locus (Khalafalla et al., 1971; Yamamoto and Yamamoto, 1976*a,b*). Such an impedance characteristic can be described by the Cole-Cole equivalent model consisting of a resistive component R in shunt with a frequency-dependent, constant-phase component of the form $(j\omega C)^{\alpha}$. The impedance function of the equivalent model can be written as (Schwan, 1957; Plonsey, 1969; Cole and Cole, 1941):

$$Z = R_{\infty} + \frac{R}{1 + (j\omega C)^{\alpha}R} = R_{\infty} + \frac{R}{1 + (j\omega/\omega_0)^{\alpha}}, \tag{1}$$

where R_{∞} is the series resistance of the subepidermal network and ω_0 is the characteristic frequency. The resistance R can be attributed to all ionic paths through the skin, and includes passages through the epidermal cellular structures and their periphery, as well as any

appendages that may be present. The parameter α is the phase constant of the frequency-dependent component, and is given by the half-angle subtended by the circular-arc at the center (Plonsey, 1969).

Although the Cole-Cole model can be a good empirical representation for the observed impedance, the physical nature of the frequency-dependent component remains to be resolved. Recent work on skin impedance measurements has revealed that the impedance and its frequency effects are largely due to dielectric relaxation processes of the epidermal stratum corneum (Yamamoto and Yamamoto, 1976a). To understand the formative mechanisms governing the relaxation, the structural parameters (i.e., resistivity and dielectric constant) of the skin sheath dielectric must be determined. Previous data for the structural parameters at various depths of the stratum corneum, using skin-stripping technique (Tregear and Dirnhuber, 1962), were limited to measurements of the resistivity or the capacitive component at a given frequency (Tregear, 1966; Lawler et al., 1960). Since the measured impedance represents the total effect of the entire skin sheath under the electrode, the profile of the dielectric constant is not directly evident from such data. In another study, Yamamoto and Yamamoto (1976b) obtained a rough estimation of the profile by calculating the average resistivity and dielectric constant of a sheath of keratin layers removed by stripping. However, as the method did not provide sufficient resolution in thickness, it was difficult to interpret their results and no definite conclusion was reached either on the structural profiles or the corresponding effects on the observed impedance.

In this report we attempt to formulate a structural model for human skin impedance with respect to the structural relaxation process (see the following section) due to morphological variations of the horny cells. First, the profiles of the resistivity and dielectric constant are deduced from observation of the changes in the components of the Cole-Cole model at different stripping levels. Based on these results, the theoretical expression for the skin impedance is derived and is shown to agree well with the observed circular-arc behavior. The existence of a constant-phase, frequency-dependent component is also demonstrated.

STRUCTURAL RELAXATION OF EPIDERMAL CELL LAMINAE

The epidermis is a mosaic in which layers of laminated, inhomogeneous cell structure pile up on top of one another. Each cell structure is characterized by its resistivity ρ and dielectric constant ϵ. Due to dielectric relaxation of the cell, ϵ is a complex quantity and is given as (Schwan, 1957):

$$\epsilon = \epsilon' - j; \qquad \epsilon'' = \epsilon_\infty + (\epsilon_0 - \epsilon_\infty) \int \frac{f(T)}{1 + j\omega T} \, dT, \qquad (2)$$

where ϵ_0 and ϵ_∞ are the boundary values of the effective dielectric constant ϵ' at zero and infinite frequencies, respectively, and $f(T)$ is the distribution function of the relaxation time T. Note that ϵ is a function of the frequency ω, but to simplify notation the dependence of ϵ on ω is not explicitly denoted.

As the cell laminae slowly migrate toward the surface, each cell in turn undergoes definite morphological changes, and hence structurally there is always a successive, gradual variation in the parameters ρ and ϵ across the thickness of the epidermis. This nonuniform variation of the electrical parameters gives rise to another relaxation effect known as structural relaxation

(Yamamoto and Yamamoto, 1976b), which is to be distinguished from the dielectric relaxation of the cellular structure. Thus the electrical impedance characteristics of the skin are determined by the dispersion characteristics of the cell, as well as the variations of the electrical parameters across the epidermis. To simplify our analysis, it is assumed that ρ and ϵ, denoted as $\rho(x)$ and $\epsilon(x)$, respectively, are uniform within the same cell lamina and vary with distance x towards the deep tissues from the surface. It is further assumed that the epidermal stratum corneum is made up of many cell laminae, so that the variations of $\rho(x)$ and $\epsilon(x)$ can be considered continuous. Using the Maxwell-Wagner theory of structural relaxation, the impedance of the skin per unit area is given as (Yamamoto and Yamamoto, 1976b)

$$Z = Z_d + \int_0^d \frac{\rho'(x)}{1 + j\omega\epsilon'(x)\,\rho'(x)}\,dx \tag{3}$$

where

$$\rho'(x) = \frac{\rho(x)/\omega\epsilon''(x)}{\rho(x) + 1/\omega\epsilon''(x)} = \text{effective resistivity.} \tag{4}$$

Z_d is the impedance of the tissues underneath the stratum corneum of thickness d and is small compared with the impedance of the stratum corneum given by the integral expression. Alternatively, the impedance Z can be expressed in terms of the distribution function $G(\tau)$ of the time constant τ of the structural relaxation process:

$$Z = Z_d + R_0 \int_{\tau_0}^{\tau_d} \frac{G(\tau)}{1 + j\omega\tau}\,d\tau, \tag{5}$$

where

$$\tau = \epsilon'(x)\rho'(x)$$

$$R_0 = \int_0^d \rho'(x)\,dx$$

$$G(\tau) = (dx/d\tau)\rho'[h(\tau)]/R_0, \qquad \int_{\tau_0}^{\tau_d} G(\tau)\,d\tau = 1.$$

$$h(\tau) = x$$

τ_0 and τ_d are the time constants of the boundary cell layers of the epidermis at $x = 0$ and $x = d$, respectively. In general, τ is also frequency-dependent, as $\epsilon(x)$ may undergo frequency dispersion. To relate the above formulation for the impedance to the observed circular-arc impedance characteristics, i.e., Eq. 1, the dependence of $\epsilon'(x)$ and $\rho'(x)$ (or, equivalently, $G[\tau]$) on ω and x must be determined. However, these quantities are generally difficult to obtain because of the nonuniform distributions with respect to x. In the following two sections we describe a method whereby these functional relationships could be deduced. The method involves successive stripping of the skin followed by subsequent measurement of the residual impedance. Using these data, the theoretical skin impedance characteristics can be obtained by direct evaluation of Eqs. 3 or 5. In Structural Model for Skin Impedance (below) we show that the theoretical skin impedance agrees closely with circular-arc behavior.

SKIN IMPEDANCE MEASUREMENTS WITH SUCCESSIVE STRIPPINGS

The impedance of the skin on the ventral side of the forearm, referred to as the active skin site, was measured. The experimental set-up was like that described by Poon and Choy (1978). Possible errors due to the electrode system at the active skin site were checked by using two types of electrodes applied to separate skin sites on the forearm: a 9-mm-ϕ paste-filled Ag/AgCl electrode and a 15-mm-ϕ brass-plate electrode. The electrode paste used was standard electrolytic gel for ECG applications (Spectra 360; Parker Laboratories, Inc., Orange, N.J.). The effects of hydration and electrolyte diffusion through the skin, which could be a source of uncertainty for the paste-filled electrode, and the relatively large impedance and imperfect interfacing of the dry electrode, could be simultaneously corrected by comparing the two measured impedances. The impedance of the Ag/AgCl electrode was further minimized by treatment with Kodak D-19 photographic developer (Eastman Kodak Co., Rochester, N.Y.), a method described by Getzel and Webster (1976). The brass-plate electrode was polished to shininess each time before application so as to eliminate surface dirt and irregularity, thus facilitating electrode contact.

The experiment was carried out in a quiet room where the temperature was kept fairly steady at ~22°C and the relative humidity at ~80%. At the beginning of the experiment the skin sites for electrode attachment were cleaned with rubbing alcohol and left to dry completely. After electrode attachment a stabilization period of ~30 min was allowed before measurements were taken. The transient response of the impedance at each active skin site was determined in turn and the corresponding parameters for the Cole–Cole equivalent model were determined (Poon and Choy, 1978). In brief, the measured transient response was fitted in a least-square sense to a set of theoretical transient response curves calculated from Eq. 1, each of which corresponded to different values of the parameter α. The optimal estimate for α was then given by the best-fitted response curve, and the characteristic frequency of the Cole–Cole impedance function was calculated by noting the time constant of the transient response.

After each measurement at both active skin sites, the skin was stripped with ordinary cellulose adhesive tape (3M Co., St. Paul, Minn.), removing some surface cell layers of the skin (Tregear and Dirnhuber, 1962), and the impedance of the remaining tissue was again measured. The process of stripping and measuring was repeated until nearly all the keratin layers were removed, so that little difference in the impedance was observed by further stripping. From previous studies with frequency domain measurements (Yamamoto and Yamamoto, 1976a,b), it has been shown that the same circular-arc law could apply for the intact as well as the stripped skin. Furthermore, the transient response technique required much less time for the measurement, thus reducing errors due to possible changes in the skin cellular structure after stripping.

EXPERIMENTAL RESULTS AND ANALYSIS

A total of 11 skin-strippings were performed on the forearm. At each stripping level the impedance characteristic was closely approximated by the Cole-Cole equivalent model. The corresponding parameters (α, ω_0, R_n, where the subscript n denotes number of strippings) characterizing the impedance function were estimated from the best-fitted response curve. The variations of these parameters with respect to successive strippings are shown in Fig. 1. From these data the structural properties of the epidermal stratum corneum can be deduced.

DC Resistance

For the initial few strippings, the DC resistance, R_n, decreased almost exponentially as the horny cells were progressively removed (Fig. 1 a). The actual profile of the resistance variation with distance x is more difficult to obtain because the thickness of cell layers
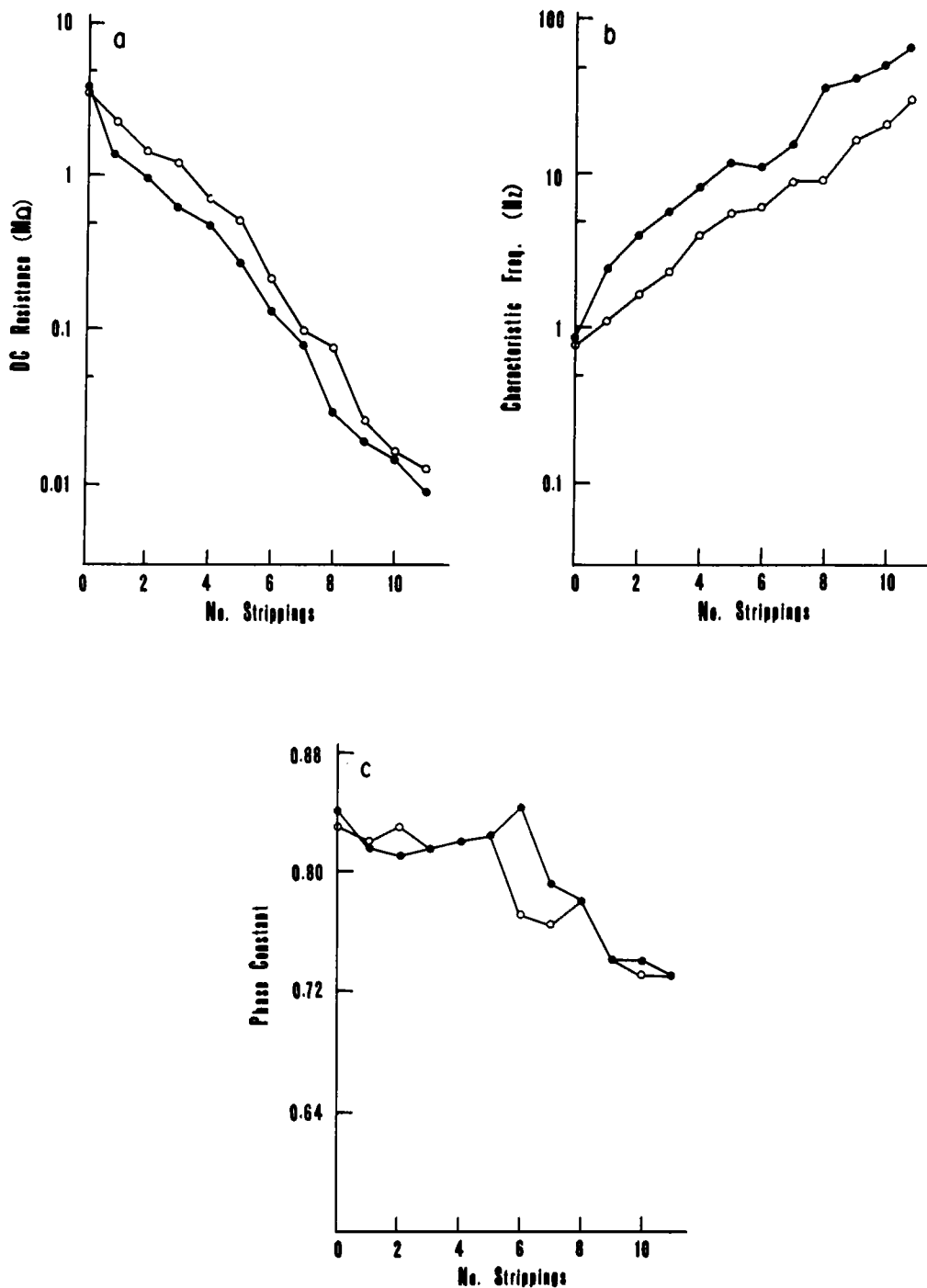
FIGURE 1   Variation of model parameters with number of strippings n. Ordinates: (a) DC resistance R_n; (b) characteristic frequency, $\omega_0/2\pi$; (c) phase constant, α. Parameter values shown are those for a 9-mm-ϕ Ag/AgCl electrode (closed circles) and a 15-mm-ϕ brass-plate electrode (open circles), respectively.

removed per stripping is not readily determined. To a first approximation, however, we will simply assume that the thickness of tissues removed in the initial strippings were uniform, and the resistance R_n was also an exponential function of x (i.e., $R_n = R_0 e^{-kx}$). This consideration is also suggested by previous findings (Tregear, 1966; Yamamoto and Yamamoto, 1976a). However, it is recognized that such condition does not necessarily obtain in general, and the effects of possible departure from this will be discussed in the last section and the appendix. Accordingly, it can be shown easily that for $x_n \ll d$ the resistivity $\rho(x)$ is also an exponential function of x. That is,

$$\rho(x) = \rho_0 \, e^{-kx}$$

$$R_n = \int_{x_n}^{d} \rho_0 \, e^{-kx} \, \mathrm{d}x \simeq (\rho_0/k) \, e^{-kx} n, \tag{6}$$

where ρ_0 is the surface resistivity of the intact skin and x_n is the total thickness of the removed keratin layers after the nth stripping. After about five strippings the value of R_n has dropped by almost tenfold and continues to decrease exponentially as stripping proceeds (Fig. 1 a). These results agree with the findings of Tregear (1966) and Yamamoto and Yamamoto (1976a).

Characteristic Frequency

In general, the dielectric constant of a cellular structure undergoes frequency dispersion and hence is a function of the frequency. Also, owing to the morphological variations associated with the epidermal flow, the value of ϵ is likely to vary during the different phases of the displacement. Therefore, we have $\epsilon = \epsilon(\omega, x)$, and the skin impedance will be subject to both the cellular relaxation and the morphological variations across the epidermis. To see the effects of these processes on the value and the distribution of the dielectric constant, we obtain the characteristic frequency of the equivalent impedance function of the skin after each stripping. From Fig. 1 b, we see that the characteristic frequency of the skin impedance varies in the range of ~1–50 Hz, a value which is even below the low-frequency relaxation range (α-dispersions) of most biological tissues (Schwan, 1957). For the analysis of the skin impedance, therefore, frequency dispersion effects due to the relaxation of the cellular structure, namely Eq. 2, will be relatively insignificant. In other words, the observed frequency effects of the skin impedance will be largely due to the structural relaxation mechanism arising from the nonuniform composition of the epidermis. Hence, ignoring the frequency-dependent dielectric loss term ϵ'', we have $\epsilon = \epsilon(x) = \epsilon'(x)$, and Eq. 4 simply becomes $\rho'(x) = \rho(x)$, i.e., the resistance is dominated by the ionic term.

Next, the effect of the morphological variation on the value of ϵ is investigated. From Fig. 1 b we see that as more keratin layers are removed from the skin the characteristic frequency of the impedance function increases exponentially with the number of strippings. Fig. 2 shows that a reciprocal relationship exists between R_n and ω_0. Referring to Eq. 6, we see that $R_n \propto \rho(x)$ and hence the characteristic frequency ω_0 can be empirically related to the resistivity as $\omega_0 \propto 1/\rho(x)$. In general, ω_0 is a function of both the resistivity and the dielectric constant (i.e., $\omega_0 = f[\rho\epsilon]$); the reciprocal relationship between ρ and ω_0 suggests that the dielectric constant should be fairly uniform within the stratum corneum. It will be shown below that the above
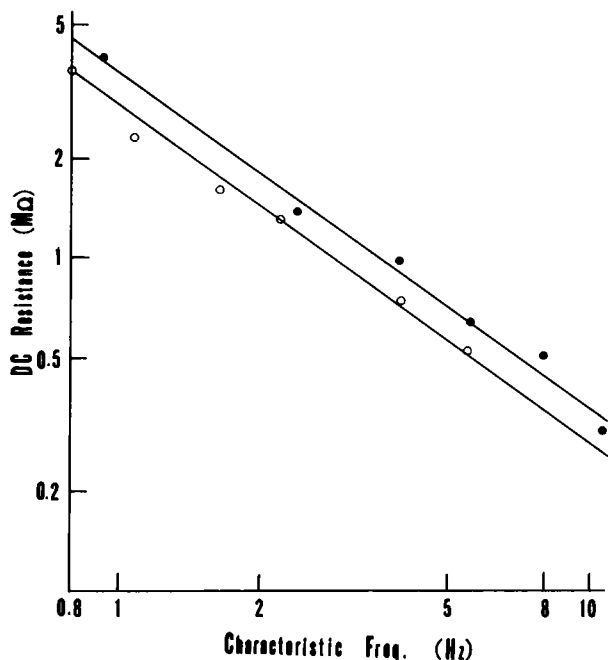
FIGURE 2 Reciprocal relationship between R_n and ω_0. Slope for each straight line shown is -1.

relationship can be satisfied by a model of the epidermis in which the dielectric constant is uniform throughout.

STRUCTURAL MODEL FOR SKIN IMPEDANCE

In view of the foregoing results we consider the simple model for skin impedance in relation to the structural relaxation process, assuming that the resistivity has an exponential profile and the dielectric constant is both uniform and independent of the frequency. The impedance Z_n after the nth stripping is, from Eqs. 3 and 5,

$$Z_n = Z_d + \int_{x_n}^{d} \frac{\rho_0 e^{-kx}}{1 + j\omega\tau}\, dx. \tag{7}$$

As for the distribution function for the relaxation times, we have $dx = -(1/k\tau)d\tau$, so that, from Eq. 5, the distribution function becomes

$$G(\tau) = -1/k\epsilon R_n.$$

Eq. 7 then becomes

$$Z_n = Z_d + \int_{\tau_d}^{\tau_n} \frac{1/k\epsilon}{1 + j\omega\tau}\, d\tau, \tag{8}$$

where τ_n denotes the boundary value after the nth stripping. Eq. 8 shows that the relaxation time, τ, is uniformly distributed over the range (τ_d, τ_n).

To show further how the present model relates to the equivalent impedance function of Cole and Cole, the integral of Eq. 8 is evaluated so that

$$Z_n = Z_d + \frac{R_n}{j\omega\tau_n} \left[\ln \sqrt{1 + (\omega\tau)^2} + j \tan^{-1} \omega\tau\right]_{\tau_d}^{\tau_n}.$$

For the upper portion of the epidermis the condition $\tau_d \ll \tau_n$ is satisfied. Hence we have

$$Z_n = Z_d + R_n \left\{\frac{\tan^{-1}\omega\tau_n}{\omega\tau_n} + \frac{\ln \sqrt{1 + (\omega\tau_n)^2}}{j\omega\tau_n}\right\}. \tag{9}$$

Eq. 9 can be written as

$$Z_n = Z_d + \frac{R_n}{1 + \left\{\left[\left(\dfrac{\tan^{-1}\omega\tau_n}{\omega\tau_n F}\right) - 1\right] + j\left(\dfrac{\ln \sqrt{1 + (\omega\tau_n)^2}}{\omega\tau_n F}\right)\right\}}$$
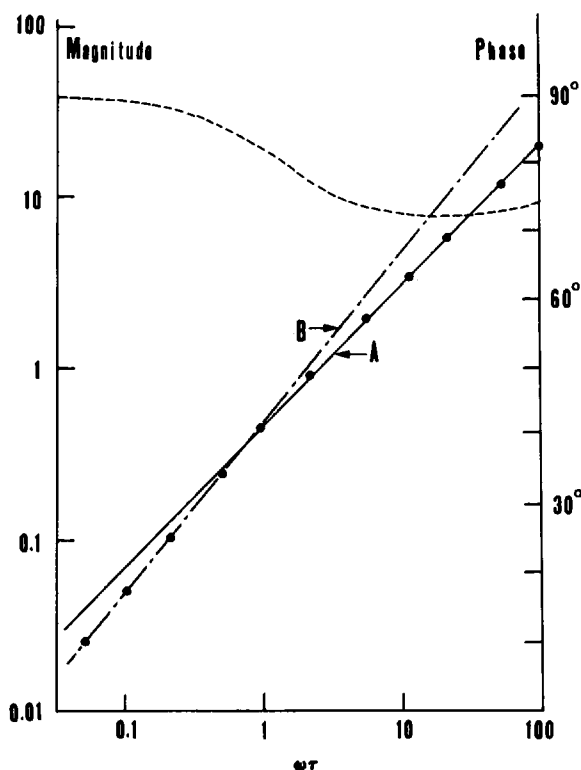
$$= Z_d + \frac{R_n}{1 + Y(\omega\tau_n)} \tag{10}$$

FIGURE 3 Frequency characteristics of $Y(\omega\tau)$. The magnitude plot (closed circles) can be closely approximated by two distinct straight lines with a corner at approximately $\omega\tau - 1$. Slope is ≈ 0.82 for straight line A and ≈ 1 for straight line B. In the phase plot (dashed), the phase angle θ approaches a constant value of $\sim 74°$ at high frequencies ($\omega\tau > 1$).

where

$$F = \left(\frac{\tan^{-1}\omega\tau_n}{\omega\tau_n}\right)^2 + \left(\frac{\ln\sqrt{1 + (\omega\tau_n)^2}}{\omega\tau_n}\right)^2 .$$

In Eq. 10, $Y(\omega\tau_n)$ is a dimensionless function of $\omega\tau_n$ corresponding to the constant-phase, frequency-dependent component of Eq. 1. To establish this relationship, one must show that $Y(\omega\tau_n)$ is of the form $(\omega/\omega_0)^\alpha e^{j\alpha_\phi\pi/2}$, with $\alpha_m \simeq \alpha \simeq \alpha_\phi$. From Fig. 3, which shows the frequency characteristics of $Y(\omega\tau_n)$, we note that for $\omega\tau_n > 1$, (a) the magnitude of $Y(\omega\tau_n)$ varies with the frequency according to a power law ω^{α_m}, with $\alpha_m \simeq 0.82$; (b) the phase angle of $Y(\omega\tau_n)$ is apprxoimately constant ($\sim 74°$) with $\alpha_\phi \simeq 0.82$. Clearly, at high frequencies the complex function $Y(\omega\tau_n)$ is almost equivalent to a constant phase, frequency-dependent component. The phase constant $\alpha \simeq 0.82$ for both the magnitude plot and the phase plot also agrees with the experimental results for the skin impedance corresponding to the initial few strippings (Fig. 1 c). It is expected that at deeper stripping levels the condition of $\tau_d \ll \tau_n$ will not be satisfied and Eq. 9 will no longer be applicable. As seen in Fig. 1 c, the value of α is fairly constant at ~ 0.82, except after the sixth stripping or so, when the value starts to decrease slightly.

At lower frequencies ($\omega\tau_n < 1$) the phase angle of $Y(\omega\tau_n)$ gradually approaches 90° and the magnitude response is given by a power law with $\alpha_m = 1$. Thus, in the low-frequency range the frequency dispersion effect is not prominent and $Y(\omega\tau_n)$ is more like a pure capacitive component.

Next we obtain the complex impedance plot of Eq. 10. As shown in Fig. 4, the locus of the impedance function approximates closely to the ideal circular-arc plot. Only at the extreme low frequency end is the theoretical value of Z_n slightly lower than the expected value. The phase angle of the equivalent Cole-Cole impedance function (obtained empirically) is $\sim 72°$,
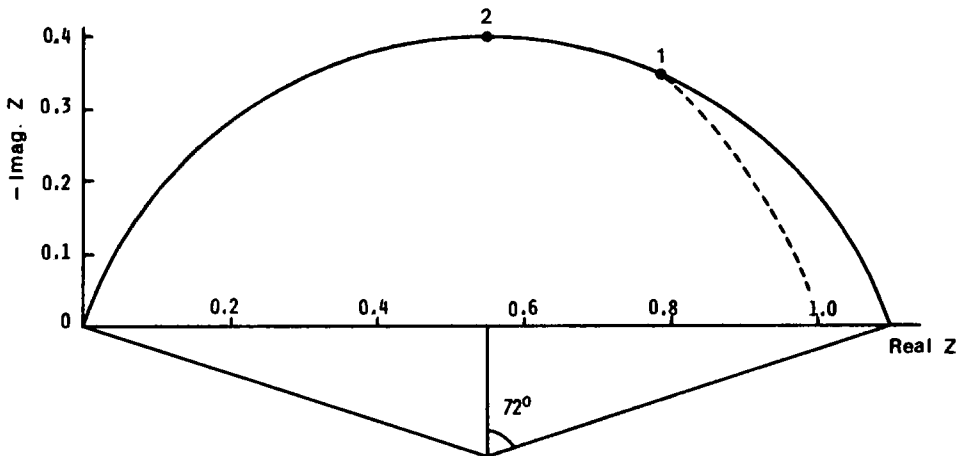

FIGURE 4 Impedance locus from structural skin model (dashed) as approximated by an ideal circular arc (solid). The former locus is obtained from Eq. 10 with $R_n = 1$ (normalized) and $Z_d = 0$. At high frequencies ($\omega\tau > 1$) the two loci are almost identical. Ordinate, imaginary part of $-Z$; abscissa, real part of Z. Numerals shown on curve are values of $\omega\tau$.

compared to the value of 74° derived from the structural model. Furthermore, the theoretical impedance Z_n has a maximum reactance at $\sim \omega \tau_n = 2$. Hence the characteristic frequency of the equivalent impedance function is related to τ_n by

$$\omega_0 = 2/\tau_n = 2/\rho(x_n)\epsilon(x_n). \tag{11}$$

Since ϵ is assumed to be constant in the model, we see that $\omega_0 \infty R_n^{-1}$, and the reciprocal relationship of Fig. 2 is justified.

CONCLUSION AND DISCUSSION

In this report we have shown that the anomalous constant-phase, frequency-dependent component of the equivalent model for skin impedance can be explained in terms of structural relaxation mechanism occurring in the epidermal laminae. From analysis of the changes in the parameters of the equivalent model after stripping, profiles of the electrical parameters ρ and ϵ have been deduced and shown to be equivalent to a rectangular distribution of the relaxation time. Based on these findings, a structural model for skin impedance is proposed which gives an expression for the impedance characteristics that is like the Cole-Cole equivalent model. The impedance locus calculated from the structural model gives an almost ideal circular arc (except at extremely low-frequency end) with $\alpha = 0.82$, which also agrees with the data. As most circular plots are extrapolated from high frequencies, the discrepancies at low frequencies do not seriously affect the present analysis. Obviously, with more accurate determination of ρ and ϵ, such discrepancies can be further reduced. In view of the possible variabilities of ρ and ϵ it is more appropriate to regard Eq. 9 as an approximate and practical formula for evaluating the skin impedance.

From a mathematical standpoint, it is possible to construct a number of distribution functions that would give similar circular-arc loci. In particular, it is known that the circular-arc impedance locus can be exactly obtained from a symmetrical, single-humped distribution function of the form (Fuoss and Kirkwood, 1941)

$$G(\tau) = \frac{1}{2\pi\tau} \cdot \frac{\sin(1 - \alpha)\pi}{\cosh\{\alpha \ln \tau / \sqrt{\tau_n \tau_d}\} - \cos(1 - \alpha)\pi}.$$

However, the validity of this kind of elaborate mathematical representation of the relaxation process is hardly justifiable on physical and physiological grounds. Moreover, from our data for the stripping experiment, it is almost impossible that the same distribution law with humps can apply to all levels of stripped skin.

Much of the foregoing analysis tacitly ignores the possible existence of additional electrical pathways that may not be running directly across the epidermis under the recording electrode. For example, a small fraction of the current may be flowing entirely within the epidermis in a direction parallel to the skin surface, and never reaches the more conductive subepidermal and dermal layers. When these lateral shunting effects are prominent, the impedance will become a complicated function of the electrical parameters of the skin, and any conclusions about the

values of these parameters will be invalid. It is thus imperative to see that these shunt components do not contribute significantly to the observed impedance. From the dramatic decrease in the DC resistance after the stripping procedure (Fig. 1 a), it is apparent that the major portion of the current flux must go directly across the epidermis in a direction perpendicular to the surface. After complete removal of the epidermis, the residual resistance R_n is found to be very small and negligible compared with the impedance of the intact skin (Tregear, 1966; Yamamoto and Yamamoto, 1976a). These observations suggest that the measured impedance (or more appropriately, the admittance) must be located in that part of the epidermis that lies directly under the recording electrode. The physical situation is like that of a lossy dielectric material excited by an electric field set up between two parallel conducting surfaces (the electrode and dermis). As the thickness of the epidermis is much smaller than the dimension and spacing of the electrodes, fringe effects at the edge of the electrode can be neglected and hence the flux lines can be assumed to be perpendicular to the electrode surface (Poon, 1979; Yamamoto and Yamamoto, 1976a). Thus the effects of any lateral shunt paths can be neglected without causing significant errors.

The resistance R is due to ionic currents through the epidermis and can be viewed as a leakage pathway in shunt with the dispersive dielectric formed by the horny cells. This includes any ionic paths that flow through the cells or via the intercellular spaces. When the eccrine sweat glands are active, a significant portion of the current is also carried by the sweat ducts, resulting in a remarkable decrease in the resistance (Venables and Martin, 1967). Furthermore, as the resistivity of the epidermal cells is highest near the surface (Tregear, 1966), the measured resistance will be much higher for a thicker skin. These factors, among some others (Poon, 1977), account in part for the large variability in the specific resistance ($0.3 \sim 5$ M$\Omega \cdot$ cm^2 on human arm) observed among different individuals or different skin sites (p. 59 in Tregear, 1966). Despite such variability in the absolute value of the resistance, the resistivity profile of the epidermis reported by various investigators is not much different from a simple exponential. Furthermore, similar results for the impedance characteristics are obtained for different individuals, and these in general conform to the same circular-arc law (Khalafalla et al., 1971; Yamamoto and Yamamoto, 1976a,b; Poon and Choy, 1978). It therefore appears that for the purpose of analysis it is more suitable to consider the normalized form (with respect to R) of the impedance.

One assumption of the method is that the stripping procedure removed layers of keratin cells uniformly from the epidermis. This facilitates our data analysis considerably while necessarily sacrificing desirable accuracy. The exponential profile for the resistivity can be considered as a first approximation to the true profile. This result is also consistent with findings by other workers (Tregear, 1966; Yamamoto and Yamamoto, 1976a). On the other hand, any departure from the ideal condition of uniform stripping will result in similar alterations of the functions $\rho(x)$, $\epsilon(x)$, and $G(\tau)$. In the extreme case, it is possible that the number of horny cells removed in each stripping decreased exponentially and the resistivity profile was uniform. Under this condition, the profile for ϵ will become nonuniform, but the same rectangular distribution function $G(\tau)$ is obtained (see Appendix). Consequently, the model (Eqs. 8–10) is established despite possible errors in ρ and ϵ due to the stripping procedure.

APPENDIX

We consider the adverse situation where the data of Fig. 1 had been due to an exponential peeling of the horny cells. When this applies, the resistivity profile will become uniform, and

$$x_n = d(1 - e^{-nk'}) \tag{12}$$

$$R_n = \int_{x_n}^{d} \rho dx = \rho(d - x_n) = \rho d \, e^{-nk'}, \tag{13}$$

Where k' is a constant. From Fig. 1 b and Eq. 12,

$$\omega_0 = r \, e^{nk'} = \frac{rd}{d - x_n}. \tag{14}$$

The constant r denotes the characteristic frequency of the intact skin. Eq. 14 can be satisfied if ϵ is of the form

$$\epsilon(x) = \epsilon'(x) = \epsilon_0(1 - x_n/d) \tag{15}$$

with ϵ_0 − constant. Accordingly, from Eq. 5,

$$\tau_n = \rho\epsilon_0(1 - x_n/d) \tag{16}$$

and

$$G(\tau) = \left(\frac{d\tau_n}{dx_n}\right)^{-1} \rho/R_n = -\frac{d}{R_n \epsilon_0} = \text{constant}.$$

Hence the resulting distribution function is also rectangular. Moreover, referring to Eqs. 13 and 15, we have

$$\frac{d}{\epsilon_0} = \frac{\rho d \, e^{-nk'}}{\rho\epsilon_0 \, e^{-nk'}} = \frac{R_n}{\tau_n},$$

so that Eq. 5 becomes

$$Z_n = Z_d + \int_{\tau_d - 0}^{\tau_n} \frac{R_n/\tau_n}{1 + j\omega\tau} \, d\tau. \tag{17}$$

The last equation is equivalent to Eq. 8. As before, evaluation of the integral of Eq. 17 leads to the same Eqs. 9 and 10. Furthermore, the characteristic frequency is given by Eq. 11 and is

$$\omega_0 = \frac{2 d}{\rho\epsilon_0(d - x_n)}.$$

Hence Eq. 14 is satisfied.

REFERENCES

COLE, K. S., and R. H. COLE. 1941. Dispersion and absorption in dielectrics. I. Alternating current characteristics. *J. Chem. Phys.* 9:341–351.

FUOSS, R. M., and J. G. KIRKWOOD. 1941. Electrical properties of solids. VII: Dipole moments in polyvinyl chloride-diphenyl systems. *J. Am. Chem. Soc.* **63**:385–394.

GETZEL, W. A., and J. G. WEBSTER. 1976. Minimizing silver-silver chloride electrode impedance. *IEEE Trans. Bio-Med. Eng.* **23**:87–88.

KHALAFALLA, A. S., L. TURNER, and D. SPYKER. 1971. An electrical model to simulate skin dielectric dispersion. *Comput. Biomed. Res.* **4**:359–373.

LAWLER, J. C., M. J. DAVIS, and E. C. GRIFFITH. 1960. Electrical characteristics of the skin. *J. Invest. Dermatol.* **34**:301–308.

PLONSEY, R. 1969. Bioelectric Phenomena. McGraw-Hill Book Company, New York. 380 pp.

POON, C. S. 1977. Theoretical and experimental studies of the impedance characteristics of human skin. M. Phil. Thesis, The Chinese University of Hong Kong. 90–103.

POON, C. S. 1979. Comments on Laplace plane analysis of transient impedance between acupuncture points Li-4 and Li-12. *IEEE Trans. Bio-Med. Eng.* **26**:181–182.

POON, C. S., and T. T. C. CHOY. 1978. Transient response studies of biological cell impedance. *Med. Biol. Eng. Comput.* **16**:633–641.

SCHWAN, H. P. 1957. Electrical properties of tissue and cell suspensions. *Adv. Biol. Med. Phys.* **5**:147–209.

TREGEAR, R. T. 1966. Physical Functions of Skin. Academic Press Inc., New York. 53–72.

TREGEAR, R. T., and P. DIRNHUBER. 1962. The mass of keratin removed from the stratum corneum by stripping with adhesive tape. *J. Invest. Dermatol.* **38**:375–381.

VENABLES, P. H., and I. MARTIN. 1967. Skin resistance and skin potential. *In* A Manual of Psychophysiological Research. P. H. Venables and I. Martin, editors. John Wiley & Sons, Inc., New York. 53–102.

YAMAMOTO, T., and Y. YAMAMOTO. 1976a. Electrical properties of epidermal stratum corneum. *Med. Biol. Eng.* **14**:151–158.

YAMAMOTO, T., and Y. YAMAMOTO 1976b. Dielectric constant and resistivity of epidermal stratum corneum. *Med. Biol. Eng.* **14**:494–499.