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Dielectric study on distribution of water in human skin

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We performed dielectric measurements for human skin at various parts of a body by using a time domain reflectometry(TDR) method with flat-ended coaxial electrodes. In order to determine the penetration depth of electric field to skin, we measured also a model double-layer system consisting of upper- and lower- layers of water and Teflon, respectively. Dielectric constant obtained for the model system measurements showed an exponential behavior against the distance between Teflon and the flat-ended coaxial electrode that was let into the water layer. A characteristic penetration depth could be defined as 0.17mm for an electrode with an outer diameter of outer conductor of- 2.2mm. In the skin measurements, we examined how free water contributes to the relaxation strength and estimated the water distribution in both various parts of a human body and depth of skin. Larger values of the relaxation strength were observed on parts where thickness of epidermis is thinner. Larger values were also obtained by using electrode with larger diameter. It is reasonable because the penetration depth increases with size of electrode and the water content increases with the depth in epidermis. The dielectric measurements by electrodes with different penetration depths are effective to clarify the water distribution in depth of skin.
Key words: dielectric relaxation, water distribution, human skin, Penetration depth

1. INTRODUCTION

Human skin is composed of three layers of epidermis, dermis, and subcutaneous tissue sequentially from the surface layer. Water content of epidermis is lower than dermis, and it even decreases toward upper layer of epidermis [1,2]. The water content of skin is closely related to properties and functions of skin and is important for evaluation of the condition of skin to check effectiveness of cosmetics and medical supplies [3].

Though impedance measurements in MHz region can be used to determine conditions of human skin from estimation of the water content of skin, water is not directly observed by this method [4]. Various factors, especially, ionic behaviors related to the electrolyte concentration and the mobility besides water are reflected in MHz region used in the impedance measurements. Higher frequency measurements have been also applied to human skin in recent dielectric studies, where contributions of ionic behaviors are less than the lower frequency region. Dielectric properties of skin obtained by measurements at more than 100MHz [5,6] can reflect water structures. Furthermore dielectric measurements in the frequency range of 500MHz-110GHz [7] indicated that dielectric constant of wrist skin is higher than a palm flat of a hand, because the different thickness of epidermis. However water structures and the relaxation mechanism has not been directly treated even in these studies. On the other hand, time domain reflectometry (TDR) method [8,9] has been employed to argue water structures from the direct measurement of water dynamics in GHz frequency region [10-12] so far. Molecules with permanent electric dipoles reorient following applied electric field. Therefore, dielectric relaxation measurements in GHz frequency region offer information of the mobility (the relaxation time) and the density (the relaxation strength) of free water molecules. Indeed, the relaxation of free water molecules is the dominant dielectric response in this frequency range and other biological molecules show much larger characteristic times. Therefore, scarce arguments about water structure of skin have been reported [3,11,12].

Thus free water can be distinguished from other molecules in biological tissue by the dielectric measurements in GHz region. In addition, TDR measurements require no damage in contact of the flat-ended coaxial electrode with skin [13]. In our previous work, we examined a change of free water content through a drying process of human finger skin after soaking in 37°C water and also monitored healing processes of skin burns due to hydrofluoric acid or heat by the TDR measurements [10]. It was confirmed that the free water content can be a good indicator to evaluate the skin health. We also investigated migration of water within the living body before and after exercises [14]. Furthermore water content of stratum corneum (the top layer of epidermis), which have important functions to prevent water loss from the skin and an invasion of a toxin from the outside, was determined by the same experimental technique [3,15]. Above dielectric studies indicate that electromagnetic wave aquametry is effective to study the properties and functions of skin. However parts of body examined so far have been limited, and the depth dependence of the dielectric properties haven't been clarified yet. Dielectric studies for various parts of body and the depth must be very important to evaluate the condition of the human skin exactly.

In the present study, we performed dielectric measurements for a model double-layer in order to analyze the penetration depth of electric field by the coaxial electrode with outer diameter of the outer conductor, 2.2mm. The double-layer of dielectrics was set up as the upper layer of water and the lower layer of Teflon. We also examined how free water contributes to the relaxation strength in order to estimate the water distribution in both various parts of a human body and the depth of skin by TDR measurement, using the electrode with the outer diameter of outer conductor, 2.2mm. We chose 11 parts of human body with different thickness of epidermis. In addition, dielectric measurements of forearm flexor were performed with three electrodes with different outer diameters to examine the depth dependence of water content.

2. EXPERIMENTAL

2-1 Water-Teflon system

A flat Teflon sheet (the static permittivity ε_t=2.1, thickness: 10mm) was purchased from FLON INDUSTRY. Distilled and de-ionized water (the static permittivity ε_w=78.3 at 25°C [16]) was prepared by Milli-Q-Lab. The glass bottle was filled with water, and Teflon was placed at the bottom of the bottle (Water-Teflon double-layer system) was used as a model system to analyze the penetration depth of electric field by the electrode [15]. Dielectric measurements were performed by TDR in the frequency range of 100MHz-10GHz at room temperature (25±1°C) with the electrode of the outer diameter of outer conductor, 2.2mm. The end of electrode was immersed in water. The position of electrode just touched with the Teflon was defined as zero-position of distance between the surfaces of Teflon and the electrode in water. After setting the zero-position, the distance between surfaces of Teflon and the electrode was changed gradually by a jack in order to measure dielectric constant. The distance was determined by a digimatic indicator (Mitutoyo ID-C 112A).

2-2 Various parts of a human body

Various parts of human body (male, 25 years old), with different thickness of epidermis, such as lip, cheek, forearm flexor, elbow, upper arm flexor, flat of a hand, back of the hand, knee, calf, ham, feet bottom were chosen for our measurements. The skin of parts for measurements were wiped with Kimwipe before measurements. Dielectric measurements were performed by TDR with the same electrode used for the water-Teflon system at room temperature, (24.7±0.2°C) and constant humidity, (52.5±1%) [13]. Good contact of the end of electrode and the skin surface is required in dielectric measurements. A silicon stopper was then put around the electrode to enlarge the contact area and to stabilize the contact.

2-3 Depth dependence on forearm flexor

Forearm flexor (intermediate thickness of epidermis among the present study) was chosen to examine the depth dependence of water content. Outer diameters of outer conductor of the electrodes used here were 1.2mm, 2.2mm and 3.6mm, respectively.

3. RESULTS AND DISCUSSION

3-1 Determination of the penetration depth of electric field

Figure 1 shows a relationship of static dielectric constant, ε_s, and the distance, l, between surfaces of Teflon and the electrode with the outer diameter, 2.2mm. $\varepsilon_s(l)$ drastically increased with increase of l and came to the steady value of pure water. Similar measurements were performed five times. Although $\varepsilon_s(0)$ was larger value than ε_t=2.1 due to imperfect contact between the electrode and Teflon at l=0, this would not affect our estimation of the penetration depth as discussed follows. The single logarithmic plot of ε_w-$\varepsilon_s(l)$, against l exhibited

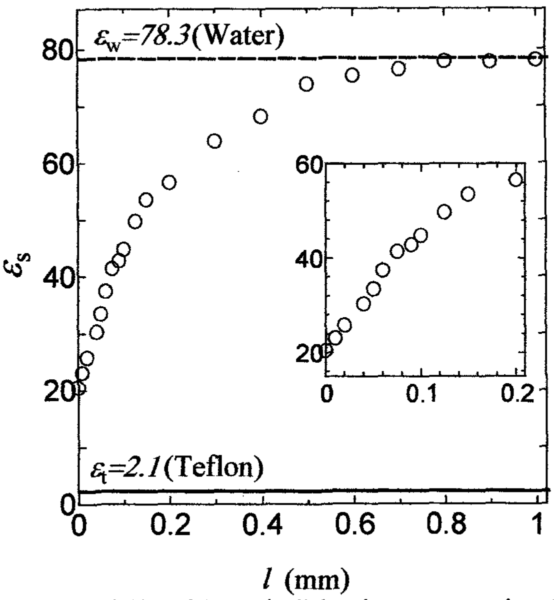

Fig.1 Plot of the static dielectric constant against the distance between surfaces of Teflon and electrode.

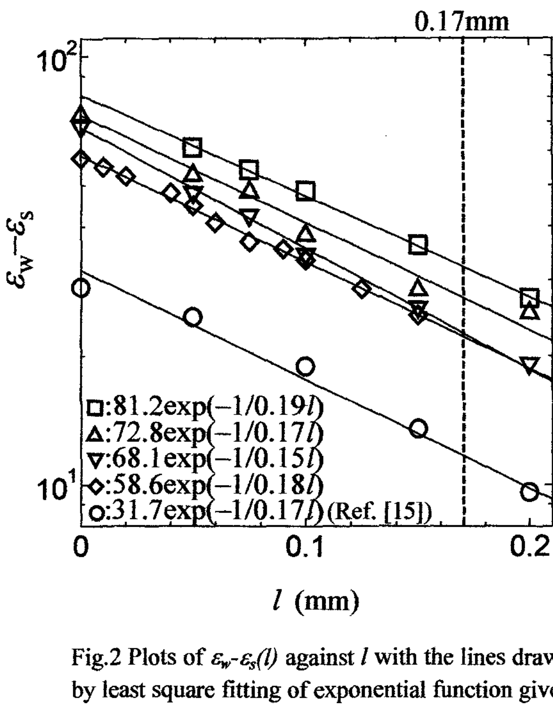

Fig.2 Plots of ε_w-$\varepsilon_s(l)$ against l with the lines drawn by least square fitting of exponential function given by eq.(2). The measurements were performed five times.

a straight line as shown in Figure 2, that leads a relation between $\varepsilon_s(l)$ and l as,

$$\varepsilon_s(l) = \varepsilon_t + (\varepsilon_w - \varepsilon_t)\left(1 - A\exp\left(-\frac{l}{l_0}\right)\right), \quad (1)$$

where A is correction parameter for imperfect contact between the electrode and Teflon at l=0, and l_0 is defined as penetration depth of electric field by the electrode. Eq.(1) can be rewritten as

$$\varepsilon_w - \varepsilon_s(l) = A(\varepsilon_w - \varepsilon_t)\exp\left(-\frac{l}{l_0}\right). \quad (2)$$

Using eq.(2), we can determine the penetration depth of electric field from a slope of the straight line obtained from the least-square method. This definition means that 63.2% of observed dielectric constant results from the depth of 0 to l_0. Although the parameter A obtained from each measurement showed any deviation, it does not affect the estimation of l_0. Indeed, the slopes in Figure 2 did not deviate so much. An average value of l_0 is obtained as 0.17mm for the electrode with the outer diameter of-2.2mm.

3-2 Various parts of skin on a human body

Dielectric dispersion and absorption observed by TDR for human skin of various parts were shown in Figure 3. It was found that dielectric dispersion and absorption were significantly dependent on the parts of skin. These dielectric spectra in the present frequency range could be described by the summation of two Cole-Cole equations as [17]

$$\varepsilon^* = \varepsilon_\infty + \frac{\Delta\varepsilon_h}{1+(j\omega\tau_h)^{\beta_h}} + \frac{\Delta\varepsilon_l}{1+(j\omega\tau_l)^{\beta_l}}, \quad (3)$$

where $\Delta\varepsilon$ is the relaxation strength, τ is the relaxation time, β is the symmetric broadening parameter, ω is the angular frequency, j is the imaginary unit, ε_∞ is the limiting high frequency dielectric constant, and h and l indicate the higher and lower relaxation processes, respectively. Figure 4 shows a typical fitting result for forearm flexor. It is reasonable to consider that the h process results from the reorientation of free water molecules and the l process results from a superposition of multiple factors, such as interfacial polarization, bound water, and chain motion of macromolecules [10] [18]. Figure 5 shows relationship between the relaxation strength of free water and thickness of epidermis [19]. Larger values of the relaxation strength were observed on parts where thickness of epidermis is thinner. The plots in Figure 5 show average values obtained from four measurements at different measuring spots. The error bar shows the standard deviation. The error is from both contact failure between the electrode and skin surface and a difference in the condition of skin. However, larger values of the relaxation strength were clearly observed on parts where thickness of epidermis is thinner. The contribution of a dermis with high water content to the dielectric constant increases with decreasing thickness of epidermis. Since the penetration depth was estimated as 0.17mm, observed dielectric response were sensitive to epidermis and also a part of dermis in skin of various parts of a human body.

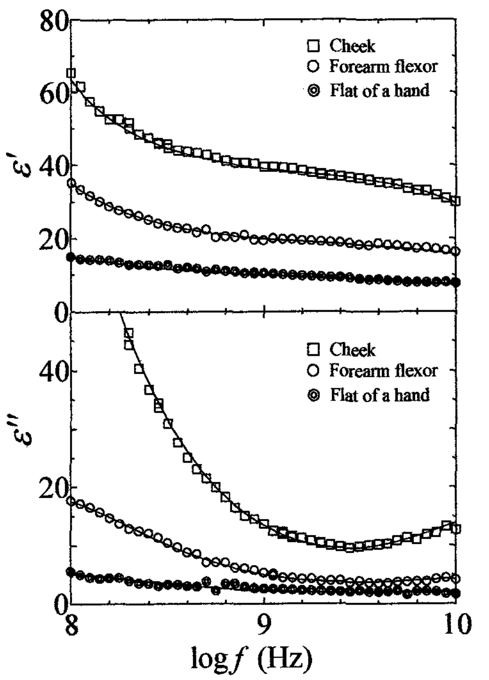

Fig.3 Dielectric dispersion and absorption for human skin of various parts.

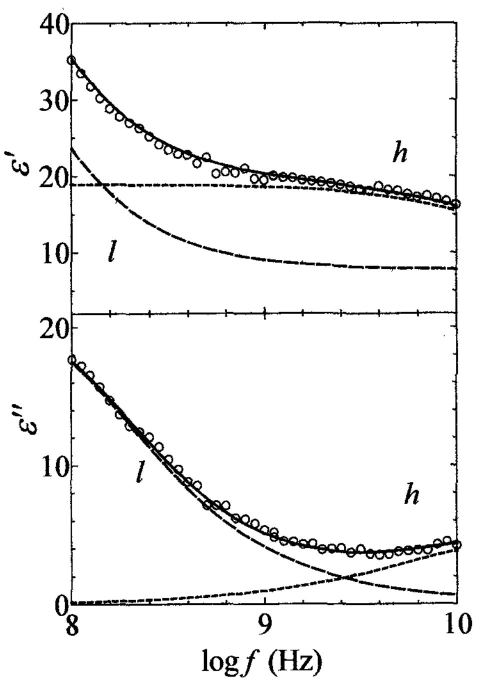

Fig.4 Dielectric dispersion and absorption for forearm flexor.

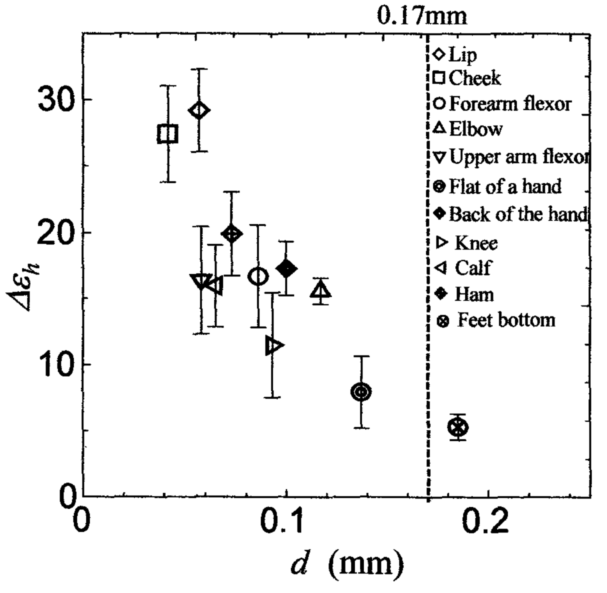

Fig.5 Plot of the relaxation strength for free water against thickness of epidermis.

3-3 Forearm flexor

Figure 6 shows a relationship of the relaxation strength of free water at forearm flexor and the outer diameters of outer conductor of electrodes. Larger values of the relaxation strength were observed for electrode with the larger outer diameters. Generally the penetration depth of electric field increases with increasing outer diameter of an electrode [15]. Though the penetration depth for the electrodes with the outer diameters of 1.2mm and 3.6mm haven't been estimated yet, it is found that the larger electrode reflects more contribution of higher

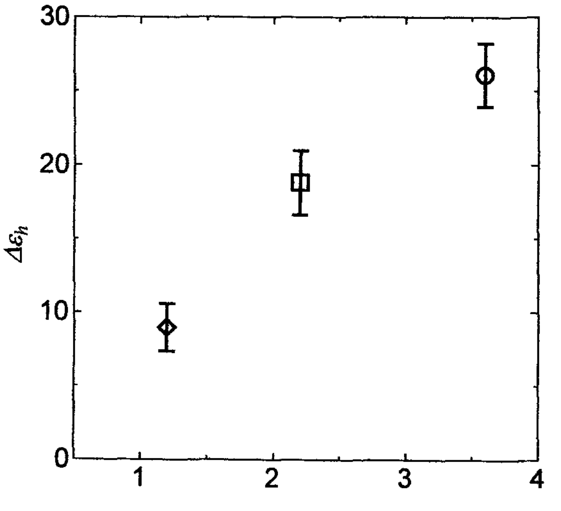

Fig.6 Plot of the relaxation strength for free water at forearm flexor against the outer diameters of outer conductor of electrodes.

water content in dermis. The dielectric measurements by electrodes with different penetration depths are effective to clarify the water distribution in depth for skin.

The present work reports a method to estimate the penetration depth of applied electric field for TDR measurements. The water distribution in both the various parts of a human body and the depth of skin were discussed. Further quantitative analysis will be performed, in future, with determination of the penetration depth for various sizes of electrodes.

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