110 GHz Broadband Measurement of Permittivity on Human Epidermis Using 1mm Coaxial Probe

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Abstract — **In this work, we have characterized permittivity of human epidermis (the epidermis: the outer skin layer) using microwave up to 110GHz. A one mm-diameter coaxial probe was adopted to increase measuring bandwidth as well as to enhance the spatial resolution. Pork was used to discriminate the permittivities between muscle tissues and fat tissues. The influence of the sample thickness was also studied. Considering several factors, the permittivity was measured on epidermis of the human palm and the wrist. In addition, a relaxation phenomenon observed in the wrist skin, revealed by Cole-Cole parameters, suggested that it originated from high water content beneath thin epidermis of the wrist skin. A relaxation phenomenon revealed by Cole-Cole parameters was observed in the wrist skin. This explains that high water content cells exist beneath thin epidermis of the wrist skin.**

I. INTRODUCTION

As the frequency increases, the permittivity of biological tissues decreases because of dielectric relaxation. In lower frequency ranges below 1 GHz, α and β relaxations are expressed and it is known to be due to the cell membrane and boundaries. Another high frequency relaxation (approximately 20 GHz) is called γ-relaxation due to bound water.[1] To express the relaxation properties of biological tissues, a Cole-Cole equation that expresses the complex permittivity as a function of frequency is widely used.[2] In the Cole-Cole equation, 5 parameters should be determined from the measured permittivity empirically.

This study aims to find the characteristics of permittivity of human skin tissues by utilizing Cole-Cole parameters in a wide band frequency range of 0.5 – 110GHz. Measurement up to 110 GHz was possible by adopting a 1 mm-diameter (inner diameter of outer conductor) coaxial probe. Coaxial probes are widely accepted in measuring material specific permittivity at high frequency regions. Especially in the field of life

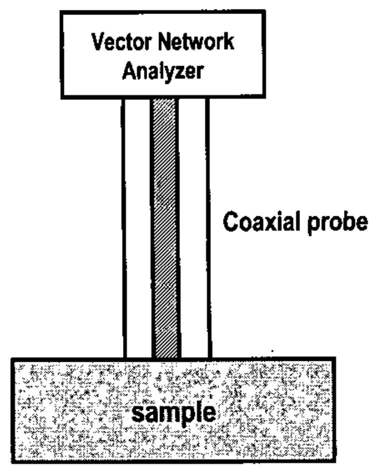

Fig. 1. Experiment setup

sciences, it is beneficial because coaxial probes can provide ways to measure the electric properties of the biological tissues without damages.[3] Coaxial probes of 3 mm-diameter cannot be used above 44 GHz, due to the excitation of higher order mode. Therefore, a 1 mm diameter coaxial probe was used in this study to cover higher frequency ranges up to 110 GHz.

There have been reports on the effect of sample thickness on the permittivity at discrete frequencies or narrow band frequencies.[4, 5] However, this effect has not been established on broadband microwaves. In this study, we observe the effect in broadband frequency range.

II. EXPERIMENT

A. Experiment setup

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Vector Network-Analyzers (HP 8510C & HP8510XF) were set up for 1 port measurements to obtain reflection coefficient as shown in Fig. 1 Measurement system was calibrated based on the cross-ratio transformation using three standard materials that were distilled water, methanol and air before unknown permittivity was measured.[6] All experiments were performed at room temperature(approximately 25±1°C). A frequency range for 1 mm probe measurements was from 500MHz to 110GHz and for 3 mm probe measurements, 500 MHz to 30 GHz.

B. Permittivity of saline

To show the validity of the experiments, we first measured the saline. Another purpose of the experiment is to see if a probe size could influence permittivity measurements. Physiological saline (50 ml, 0.9% NaCl) in a beaker was measured with both 1 mm and 3 mm coaxial probes at room temperature. The measured complex dielectric constants are compared in Fig.2. The results shows that there was no difference in permittivity up to 30 GHz, thus showed that probe sizes used in this study did not influence permittivity measurements on large homogenous material.

C. Pork fat and muscle permittivity

Using a piece of pork, muscle and fat permittivities were measured. Each measured sample was more than 3 mm in thickness and repeated several times to ensure the repeatability of the measurement. Figure 3 shows the measured complex dielectric constants.

D. Effect of thickness

Since the coaxial prove measurement basically uses the fringing capacitance at the open end of the probe, the thickness of the sample can influence on the measurement. Ideally, the measurement should be performed with a very thick homogeneous sample to ensure the accuracy. However, this condition cannot be satisfied in certain cases, especially in biological case. Therefore, the experiment was performed to find the proper thickness of sample that can be reliably measured with a 1mm coaxial probe. As is shown in Fig. 4, muscle and fat samples were prepared with various thicknesses. In experiment, upper layer thickness d is controlled and lower layer has enough thickness. We could confirm that once the thickness(d in Fig.4) of samples were more than 1 mm, the sample thickness was no longer influencing permittivity measurements. In the same manner, a 3mm probe was tested and it was found that measurements were not affected once the thickness of a sample was thicker than 3 mm. These results agree with our expectation because the fringing field will spread over in a similar manner of parallel capacitor.

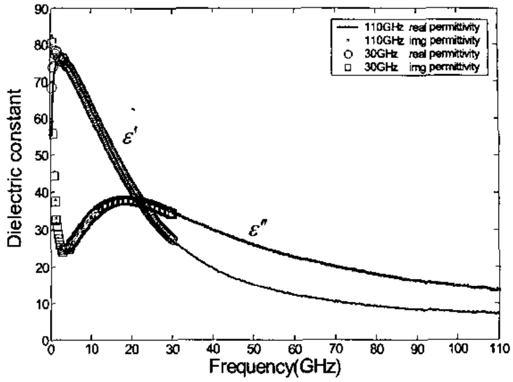

Fig. 2. saline(0.9% NaCl) complex permittivity

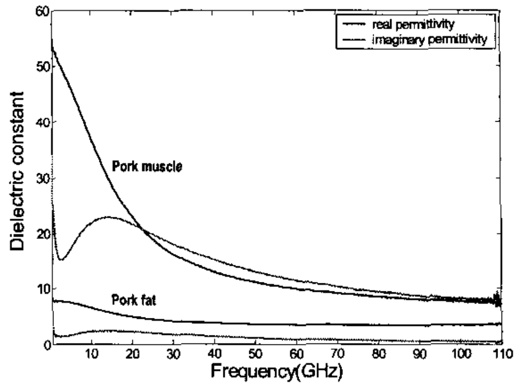

Fig. 3. pork muscle and fat complex permittivity

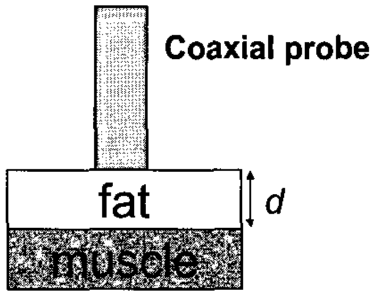

Fig. 4. thickness experiment

E. Palm and wrist skin permittivity

Considering the results obtained from experiments described above, a 1mm coaxial probe is expected to detect the permittivity of human palm epidermis accurately. Skin is composed of dermis and epidermis. Epidermis denotes external skin surface and the dermis is the inner skin layer. Human palm epidermis is known to

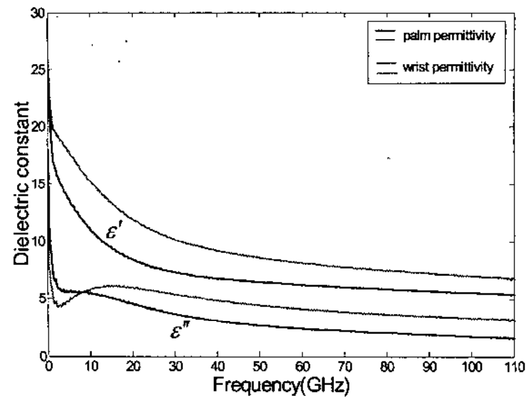

Fig. 5(a). Permittivities of palm and wrist skins measured up to 110 GHz using 1mm probes

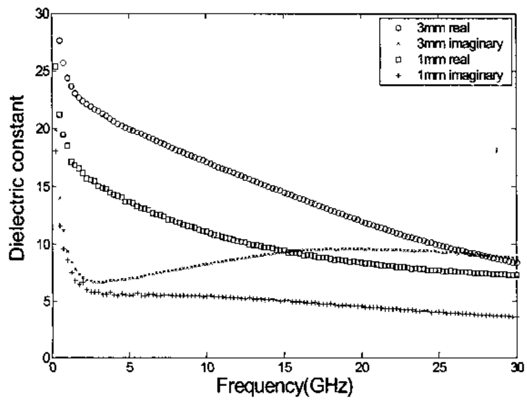

Fig. 5(b). Palm skin permittivity measured by 1mm, 3mm probe

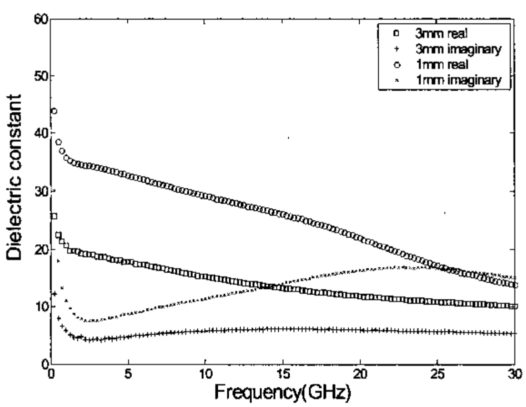

Fig. 5(c). Wrist skin permittivity measured by 1mm, 3mm probe

be the thickest (approximately 1.5 mm), thus it was assumed that our 1 mm probe measurements could obtain reliable permittivity of epidermis. In this experiment human palm and wrist skin were assessed for the permittivity. Both parts of skin were completely dried for the measurements and total 10 measurements per each type of probe were performed to yield mean values. First, palm skin was measured for permittivity with both probes (1mm, 3mm probe). Figure 5(a) shows the complex dielectric constants measured with 1 mm probe up to 110GHz. Figure 5(b) shows the comparison of dielectric constants measured with 1 mm and 3 mm probes. The figure shows that the real part measured with a 3mm probe is higher than that with a 1mm probe at frequency range between 0.5 to 15 GHz, and the difference decrease as frequency increase. On the contrary, an imaginary part showed little difference at lower frequencies but the discrepancy increases as frequency increase. The wrist skin was also measured in the same way, and showed the similar pattern of difference between 1 and 3 mm probes up to 15 GHz. However, overall permittivity values were higher than those of the palm skin as is shown in Fig. 5(c). Plausible reasons for this difference between the two-skin regions are due to thickness of epidermis and its interaction with probe diameter. Thickness of the wrist skin is known to be 0.1 ~ 1.0 mm, and the dermis (3 mm-thick inner skin) contains blood vessels. Therefore, even a 1mm probe may see the region beyond the epidermis of wrist, thus the permittivity could have been influenced by blood vessels that have higher permittivity.[7] Therefore it is considered that higher permittivity obtained from the wrist skin was due to the influence of high water containing inner skin (the dermis). This influence should be more pronounced in measurements with a 3 mm probe since the detection depth is higher. It could have also caused bigger difference of permittivity between 1 and 3 mm probe measurements of the wrist skin than those of the palm skin.

III. COLE-COLE PARAMETER

The permittivity obtained from epidermis experiments was utilized to yield optimized Cole-Cole parameters as shown in table I. The Cole-Cole equation is given as (1)

$$\begin{aligned} \varepsilon^* &= \varepsilon' - j\varepsilon'' \\ &= \varepsilon'_\infty - \frac{j\sigma_s}{2\pi f \varepsilon_0} + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + (jf/f_c)^{(1-\alpha)}} \end{aligned} \qquad (1)$$

where f , f_c denote measured and relaxation frequency and ε_s , ε_∞ mean the permittivity at low and high frequency. The spread in relaxation time is characterized by an empirical parameter α . As expected, saline relaxation frequency (f_c) was 20GHz and for the other materials f_c were found to be below 20GHz which appeared to be affected by the relaxation frequency of

TABLE I
COLE–COLE PARAMETER

material	ε_s	σ_s	ε_∞	f_c	α
Saline	73.38	2.457	5.105	20.02	$1.342e^{-2}$
Pork muscle	49.86	$8.330e^{-1}$	5.714	14.08	$8.099e^{-2}$
Pork fat	5.840	$8.699e^{-2}$	2.938	12.26	$8.913e^{-7}$
Palm epidermis	19.73	$2.870e^{-1}$	4.596	7.223	$2.531e^{-1}$
Wrist skin	21.86	$1.895e^{-1}$	4.581	15.54	$2.672e^{-1}$

TABLE II
COLE–COLE PARAMETER VARING WATER CONTENTS

material	ε_s	σ_s	ε_∞	f_c	α
Ethanol treated muscle	28.01	$2.677e^{-1}$	$7.980e^{-1}$	12.53	$2.736e^{-2}$
Saline treated muscle	52.93	1.260	$1.466e^{-1}$	19.70	$3.791e^{-3}$

water, and alpha values were close to 0. Values of the rest 3 parameters depend on the kind of a material.

In order to confirm that observed Cole-Cole parameter values are mainly affected by the water molecules relaxation, an additional experiment was conducted by altering water content of pork muscle tissues. By immersing a slice of muscle tissues into the 99.9% ethanol for 45 ~ 60 minutes, water can be eliminated from the tissues since the ethanol expels water. Then, permittivities were measured again after removing excessive ethanol from the surface. Water elimination reduced permittivity significantly, and a reversed phenomenon was also demonstrated by introducing the same tissue slice into 0.9% physiological saline for 15 hours as shown table II.

IV. CONCLUSION

This study attempted to find the most proper way to measure the permittivity of the epidermis including the palm and the wrist. Broadband microwave measurement up to 110 GHz was performed using 1mm coaxial probes for this purpose. In order to assure reliable measurements, series of experiments were performed using pork muscle and fat tissues, and the effects of sample thickness, probe size and interaction between them were established. The result revealed that the human wrist skin shows higher permittivity than the skin of the palm. Main reasons for the difference shown between two regions appear to be the water content, and the thickness of the epidermis. Also, main relaxation observed by Cole-Cole parameters at microwave frequencies was confirmed to be due to high water content. Since the permittivity of thin wrist epidermis was influenced by high water content blood vessels beneath, the detection depth of the 1mm coaxial probes could be estimated to be about 1mm. Results also suggest that the smaller probe size is recommended to measure the permittivity of a biological tissue that is thinner than 1 mm.

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