Dielectric Characterization of Limited Volume of Human Blood by Open-Ended Coaxial Measurement Probe

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Abstract. *To evaluate the quality of hemodialysis from the limited volume of human blood using a commercially available open-ended coaxial probe, we used pure water in lieu of blood to measure the complex relative permittivity in the frequency range from 200 MHz to 6 GHz with respect to its measured liquid volume. We then obtained the measurement errors relative to the calculated values from an empirical formula Udo developed for water permittivity. As a result, we found that 0.9 ml water in a beaker with a diameter of 24 mm and a depth of 2 mm gives a variation within ±0.5% for the real part and ±7% for the imaginary part. Taking into account the finding for water, we measured for normal healthy subjects the dielectric properties of 2.5 ml whole blood with a temperature of 25℃ in a syringe with a diameter of 20 mm and a depth of 8 mm. There was an agreement between the measurement and the data Gabriel reported for human blood with a temperature of 37℃.*

Keywords: Open-Ended Coaxial Probe, Pure Water, Human Blood, Limited Liquid Volume, Complex Relative Permittivity

1. Introduction

An open-ended coaxial probe has often been used to measure dielectric properties in combination with a network-analyzer [1], though it can be applied to semi-infinite homogeneous materials. For thickness and size of materials to be measured, on the other hand, the probe response on measurement accuracy has not been well examined [2]. With such an open-ended coaxial probe, we seek to determine the dielectric characterization of dialysis fluid in order to show the possibility for evaluating the quality of hemodialysis. Due to the limited volume of human blood, therefore, it is essential to learn how small an amount of blood may provide measurement data with acceptable accuracy. In this study, using a commercially available open-ended coaxial probe, we first measured the complex relative permittivity of pure water in lieu of blood in the frequency range from 200 MHz to 6 GHz with respect to the measured water volume, and investigated relative measurement errors in relation to the calculated values from an empirical formula [3] Udo developed for water permittivity to find out the minimum volume of water providing acceptable measurement accuracy. In view of the finding obtained for water, the complex relative permittivity of a limited amount of whole blood for healthy subjects was measured to compare with the data Gabriel [4][5] reported for human blood.

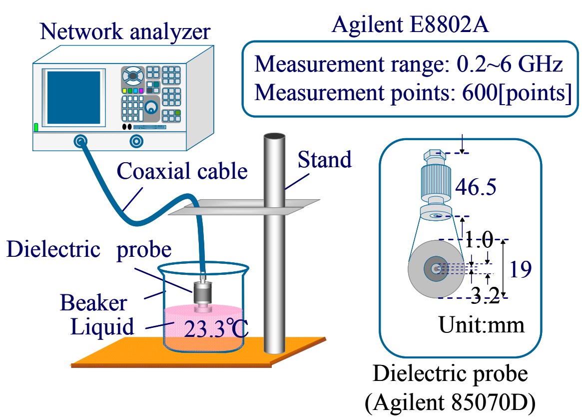

Fig. 1. Measurement setup and open-ended coaxial probe.

2. Method

Figure 1 shows a setup for measuring complex permittivity with a network analyzer (Agilent E8802A) and an open-ended coaxial probe called dielectric probe (Agilent 85070D). Also shown in the same figure are the appearance and dimensions of the probe. Due to the limited availability of human blood, we alternatively used pure water with a temperature of 23.3 ℃ in a beaker with a diameter of 62 mm. Measurement was conducted in the following way. With the dielectric probe connected to a network analyzer as shown in Figure 1, we measured complex relative permittivity of pure water in the beaker with respect to the water volume in the frequency range from 200 MHz to 6 GHz, when changing the distance from the probe face to the beaker bottom. In order to validate the measured results, we compared them with those calculated from an empirical formula Udo proposed for complex relative permittivity ε_r of pure water with temperature of T [℃], which can be expressed as in [3]:

$$\left.\begin{aligned} &\varepsilon_r(j\omega) = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r(\infty) + \frac{\varepsilon_r(0) - \varepsilon_r(\infty)}{1 + j\omega\tau} \\ &\varepsilon_r(0) = 10^{1.94404 - 1.991\times10^{-3}\times T} \\ &\varepsilon_r(\infty) = 5.77\text{-}0.0274\times T \\ &\tau[\mathrm{ps}] = 3.745\times10^{-3}\times\left\{1+0.7\times\left[\frac{T\text{-}27.5}{100}\right]^2\right\}\times e^{\frac{2.2957\times10^3}{T+273.15}} \end{aligned}\right\} \qquad (1)$$

where $\varepsilon_r(0)$ is the DC relative permittivity, $\varepsilon_r(\infty)$ is the relative permittivity at infinite frequency, and τ is the relaxation time constant. In this study, considering the calculated results from (1) as the true values of complex relative permittivity for pure water, we evaluated relative measurement errors with respect to the water volume.

For validation of the complex relative permittivity of human blood, our measured results, which will be described in the next chapter, were compared with those calculated from the multiple Cole-Cole dispersion formula Gabriel developed for human biological tissues [4]:

$$\varepsilon_r(j\omega) = \varepsilon_r(\infty) + \sum_{k=1}^{4} \frac{\Delta\varepsilon_k}{1+(j\omega\tau_k)^{1-\alpha_k}} + \frac{\sigma}{j\omega\varepsilon_0} \qquad (2)$$

where α_k is the distribution index or a measure of the broadening of dispersion, σ is the conductivity and $\Delta\varepsilon_k = \varepsilon_{rk}(0) - \varepsilon_{rk}(\infty)$. Gabriel also derived these parameters for human blood [4] based on experimental data, which were used for calculation.

3. Results and Discussion

Figures 2(a) and 2(b) show the measured frequency characteristics of complex relative permittivity for pure water and

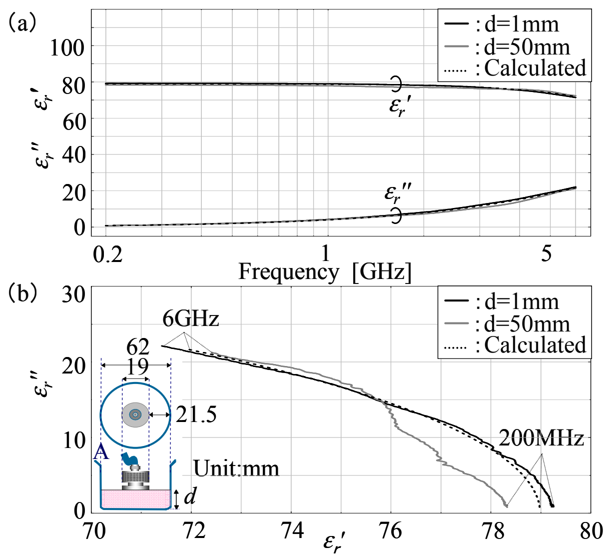

Fig. 2. Measured results of complex relative permittivity when changing distance d from probe face to bottom of beaker: (a) frequency characteristics and (b) Cole-Cole plots.

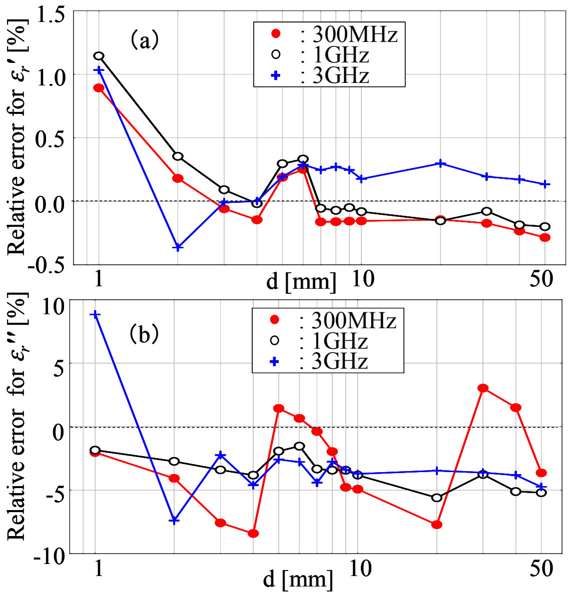

Fig. 3. Relative errors to calculated values of complex relative permittivity when changing distance d from probe face to bottom of beaker.

Table 1. Subjects and their sex, age and blood temperature.

Subject	Sex	Age [year]	Blood temperature [℃]
A	Male	52	25.1
B	Male	53	25.1
C	Female	23	25.1
D	Female	37	25.1

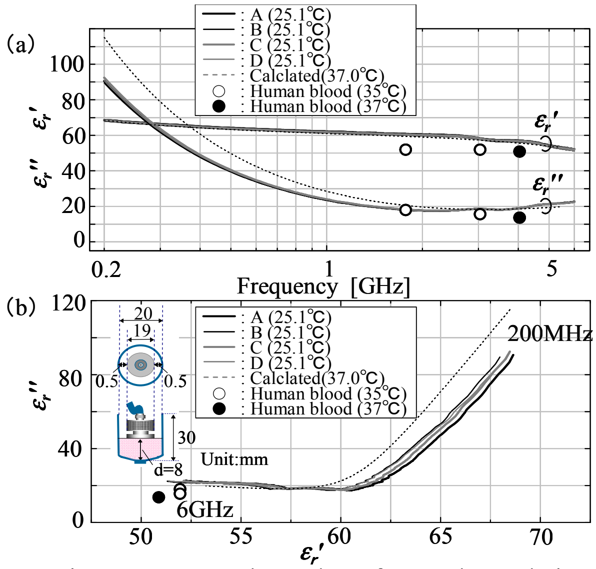

Fig. 4. Measured results of complex relative permittivity of blood for four healthy subjects. (a) frequency characteristics and (b) Cole-Cole plots.

their Cole-Cole plots, respectively, when changing distance d from the probe face to the bottom of the beaker. Thick and thin solid lines indicate the measured results for d =1 mm and d =50 mm, respectively. Dotted lines indicate the calculated results from (1). Figure 2(a) shows good agreement between the measured and calculated results regardless of the distance d, while Figure 2(b) shows some discrepancies between the measured results particularly for d =1 mm and the calculated result. Figures 3(a) and 3(b) show measurement errors relative to the calculated values of real and imaginary parts, respectively, for complex relative permittivity measured at frequencies of 300 MHz, 1 GHz and 3 GHz, which reveal that the water volume in a beaker with a depth of over d =2 mm gives the variations within ±0.5% for a real part and ±7% for an imaginary part. Furthermore, we measured the complex relative permittivity when changing the distance between the sides of the probe and the beaker, which showed that the side distance has almost no effect on the measured results, and gives the variations within ±0.3% for the real part and -5.5% for the imaginary parts.

Again, according to Gabriel [4], on the other hand, the dielectric properties of human blood show that in comparison with those of water the permittivity is smaller, while the conductivity is larger. This suggests that the same amount of blood as water should provide measurement data with more acceptable accuracy due to the larger loss angle or dissipation factor. In view of the finding obtained for water, therefore, to measure the complex relative permittivity of human blood, we used 2.5 ml of whole blood in a syringe with a diameter of 20 mm and a depth of 8 mm for four healthy subjects, which are summarized along with their sex, age and blood temperature (25.1℃) in Table 1. For all blood samples used, ethylenediaminetetraacetic acid was added for anti-coagulant, which hardly affects the dielectric properties [6].

Figures 4(a) and 4(b) show the measured frequency characteristics of complex relative permittivity of whole blood for four subjects and their Cole-Cole plots, respectively. Also shown in the figure is a setup for measurement. It should be noted that different blood samples give almost the same results. Dashed lines in these figures indicate the calculated results from (2) for whole blood with a temperature of 37℃. Open and closed circles are the data cited in [5] for human blood with 35℃ and 37℃, respectively. Figure 4 shows that the measured real parts agree well with the calculated results and cited data despite different blood temperatures, while the imaginary measured parts are 20% smaller at most than the calculated ones at frequencies less than 1 GHz despite good agreement between them at over 1 GHz.

4. Conclusions

Using an open-ended coaxial probe in combination with a network-analyzer, we seek to measure the dielectric properties of dialysis fluid in order to evaluate the conditions and quality of hemodialysis. Due to the limited availability of human blood, however, it is essential to grasp how small an amount of blood may provide measurement data with acceptable accuracy. In this study, with a commercially available open-ended coaxial probe, in lieu of blood, we measured the complex relative permittivity of pure water in the frequency range from 200 MHz to 6 GHz with respect to its measured volume to obtain the measured errors relative to the calculated values from an empirical formula Udo proposed for water permittivity. Results showed that 0.9 ml water in a beaker with a diameter of 24 mm and a depth of 2 mm gives the variation within ±0.5% for the real part and ±7% for the imaginary part. Taking into account the finding, we measured the dielectric properties of 2.5 ml blood with a temperature of 25 ℃ in normal healthy subjects in a syringe with a diameter of 20 mm and a depth of 8 mm to reveal agreement between the measurement and the data Gabriel reported for human blood with a temperature of 37℃.

In a future study, we will measure the dielectric properties of blood and plasma for subjects with kidney disease before/after dialyses.

References

[1] Delanghe P., Martens L. and Zutter D. De: Design rules for an experimental setup using an open-ended coaxial probe based on theoretical modeling. *IEEE Transactions on Instrumentation and Measurement*, 43: 810-817, 1994.

[2] Hagl D. M., Popovic D., Hagness S. C., Booske J. H., and Okoniewski M.: Sensing volume of open-ended coaxial probes for dielectric characterization of breast tissue at microwave frequencies., *IEEE Transactions on Microwave Theory & Techniques*, 51(4): 1194-1206, 2003.

[3] Kaatze U.: Complex permittivity of water as a function of frequency and temperature. *Journal of Chemical and Engineering Data*: 34: 371-374, 1989.

[4] Gabriel C.: The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Physics in Medicine and Biolog*y, 41: 2271–2293, 1996.

[5] Gabriel C.: The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20. *Physics in Medicine and Biolog*y, 41: 2251–2269, 1996.

[6] Wakatsuchi H., Hanazawa M, Watanabe S., Nishikata A., Kouzai M., Kojima M., Yamashiro Y., Sasaki K. and Hashimoto O.: The measurements of the complex permittivities of blood samples in quasi-millimeter and millimeter wave bands, *IECE Transactions on Communications*, E90-B(6): 1357-1359, 2007.