Design of Coaxial Sensor for Dielectric Measurement of Biological Tissues Below 100 MHz Frequency Range

Yuto Shimizu, Kensuke Sasaki, and Tomoaki Nagaoka

Abstract – The objective of this study is to design a coaxial sensor for the dielectric measurement of biological tissues below 100 MHz with reasonable uncertainty. To do this, the dimensions of the coaxial sensor were determined by estimating the measurement uncertainty on the basis of sensitivity analysis and adopting the specifications of the measurement equipment as the sources of uncertainty. A fabricated sensor was used for the dielectric measurement of porcine muscle, and the results of the uncertainty analysis demonstrated that the measurement can be conducted within a standard uncertainty of 1% from 1 to 100 MHz.

1. Introduction

The dielectric properties of biological tissues are fundamental parameters for the electromagnetic modeling of the human body, and are used in the field of radiation protection from electromagnetic fields and in medical applications. Although many dielectric measurements have been conducted to date, studies that focus on frequencies below 100 MHz are rarely carried out [1].

The objective of this study was to develop a coaxial sensor for measurements of biological tissue over 1 MHz, which is a representative technique for the dielectric measurement of biological tissues based on reflection measurement. Some biological tissues have high relative permittivity and dielectric loss. To the best of our knowledge, there are few measurement systems specialized to measure such biological tissues. Generally, numerical simulation is used to design the coaxial sensor [2]; however, depending on the frequency, the design of the sensor may be difficult because of the large calculation cost. For this reason, we tried to apply the design procedure to the dimensions of the coaxial sensor, which are determined in terms of the uncertainty estimated by sensitivity analysis and the specifications of the measurement equipment. The designed sensor was used to measure the dielectric properties, as well as to estimate the uncertainty of the dielectric measurement, of biological tissues.

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2. Method

2.1 Analytical Expression of Electromagnetic Response at Aperture of a Coaxial Sensor

A coaxial sensor, often referred to as a coaxial probe, is used for the dielectric measurement of materials as well as biological tissues by allowing the sensor aperture to come into contact with the sample. The dielectric properties of the sample are converted from the measurand—e.g., the reflection coefficient by a vector network analyzer or the admittance by an impedance analyzer. Assuming only the main transverse electromagnetic mode of transmission into the coaxial line, the relationship between the admittance and the dielectric property (relative complex permittivity) of the sample, $\varepsilon_M\ \left(=\varepsilon'_M - j\varepsilon''_M\right)$, is represented by the following formula [3, 4]:

$$\frac{Y}{Y_0} = \frac{k_0\varepsilon_M/\sqrt{\varepsilon_t}}{\ln(b/a)}\int_0^\infty \frac{\{J_0(a\xi) - J_0(b\xi)\}^2}{\xi\sqrt{\varepsilon_M k_0^2 - \xi^2}}\,d\xi \qquad (1)$$

where Y, Y_0, k_0, ε_t, and J_0 denote, respectively, the input admittance of the coaxial line, the characteristic admittance of the coaxial line, the wave number in vacuum, the relative complex permittivity of the coaxial line (insulator), and the Bessel function of the first kind; and a and b are the radius of the inner conductor and the outer radius of the insulator, respectively. The equation is valid under the condition of an infinite flange and generally valid when the flange size becomes a few times the diameter of the outer conductor [5].

2.2 Sensitivity Analysis

In this study, the dimensions of the coaxial line (a and b) were determined from the uncertainty estimation by sensitivity analysis. A combined standard uncertainty for the real part of the complex permittivity, $u_c(\varepsilon'_M)$, can be derived under the assumption of the law of propagation of uncertainty:

$$u_c^2\left(\varepsilon'_M\right) = \sum_{i=1}^{N} u_i^2\left(\varepsilon'_M\right) \qquad (2)$$

$$u_i\left(\varepsilon'_M\right) \equiv \left|\partial\varepsilon'_M/\partial x_i\right| u(x_i) \qquad (3)$$

where $u_i\left(\varepsilon'_M\right)$ implies the standard uncertainty from the ith source of uncertainty $(u(x_i))$ to ε'_M and N is the

Table 1. Dimensions of coaxial line for coaxial sensor

Name	Diameter of inner conductor $2a$ (mm)	Outer diameter of insulator $2b$ (mm)	Insulator
2.8 mm coaxial	0.93	2.75	PTFE*
5.3 mm coaxial	1.76	5.31	PTFE*
7 mm air line	3.0	7.0	Air

* polytetrafluoroethylene, $\varepsilon_r = 2.2$.

number of sources of uncertainties. Note that the combined standard uncertainty for the imaginary part of the relative complex permittivity can be derived in a similar manner by substituting ε''_M into (2) and (3) instead of ε'_M.

3. Results

3.1 Design of Coaxial Sensor

The three types of coaxial and air lines listed in Table 1 were considered for the sensitivity analysis. The dimensions of the 2.8 mm coaxial and 5.3 mm coaxial lines were from the commercially available semirigid cable, and those of the 7 mm air line were based on the dimensions of the coaxial sensor proposed in [6].

As the source of uncertainties for estimating the combined standard uncertainty using (2), the specifications of an impedance analyzer (E4991B, Keysight Technologies, Inc.) were used in this study. Here, the accuracies of the amplitude and phase of admittance in the data sheet [7] were assumed as expanded uncertainties of the 95% confidence interval with a coverage factor of 2. In the estimation, we considered the tolerance of the amplitude and phase during the material measurement, so that the estimated uncertainty is the worst case of the dielectric property measurement using the considered coaxial sensor.

Figures 1a and 1b show the estimated values of the combined standard uncertainty of the real and imaginary parts of the complex permittivity, respectively, for the measurement of muscle. Those dielectric properties reported in [8] were used for the estimation. The figures show that the values of the uncertainty increase with decreasing frequency. In addition, the combined standard uncertainty decreases if coaxial lines with large dimensions are used.

As a requirement of the dielectric measurement of biological tissues, we consider that the dimensions of a coaxial sensor, including the flange, should be as small as possible, because the amount of tissue that can be excised from animals may be limited, such as with eye or brain tissue. In fact, the dielectric properties of 14 types of tissue are reported in [8]; however, the data of 10 types are not reported in the case of low frequencies, because of the restriction on the amount of tissue required for the coaxial sensor. Therefore, the dimensions of the 5.3 mm coaxial line were used for the dielectric measurement of biological tissues in the megahertz frequency domain in this study.

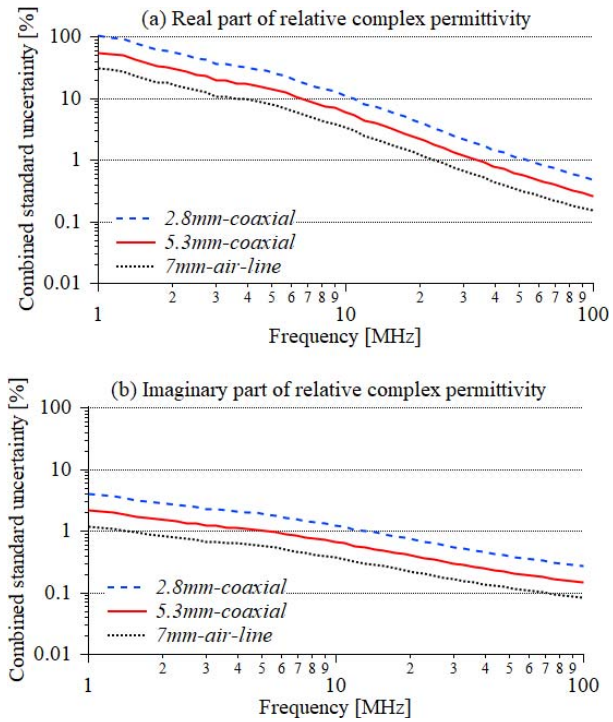

Figure 1. Results of uncertainty estimation.

3.2 Measurement Using the Proposed Sensor

Figure 2 shows the coaxial sensor fabricated on the basis of the probe design in the previous section. The flange diameter was set to 20 mm (around four times the diameter of the outer conductor [5]) and platinum-plated on the metallic area of the sensor

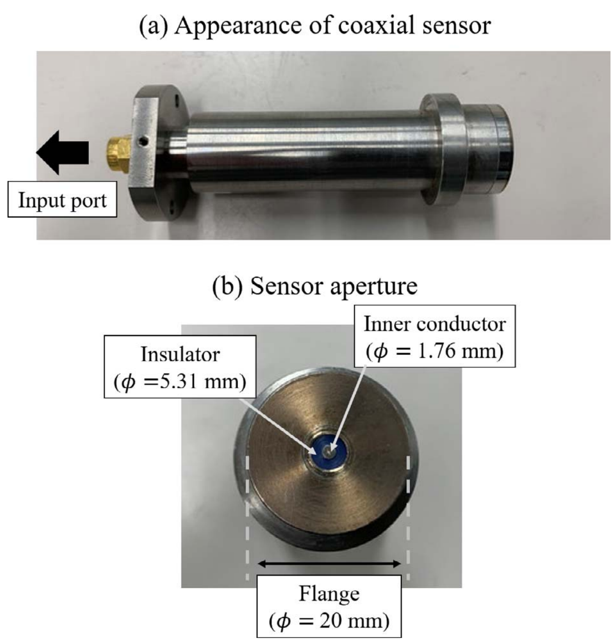

Figure 2. Fabricated coaxial sensor.

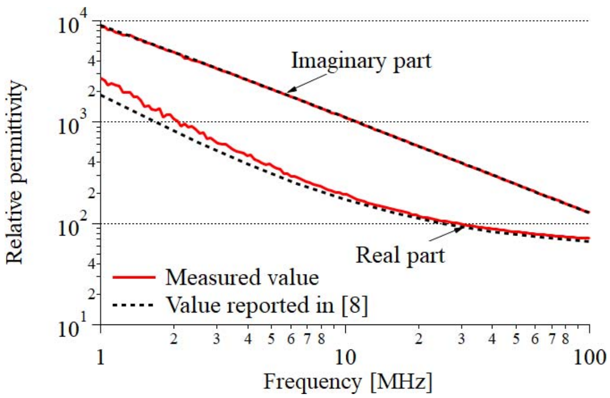

Figure 3. Measured complex relative permittivity of porcine muscle.

aperture to suppress the electrode polarization effect [9]. Dielectric measurements of excised porcine muscle were conducted. Before starting each measurement, the probe was calibrated by the three-standard method using short, air, and water. Fresh tissue samples of porcine muscle were separated into sample sizes larger than 20 mm square, which allows sufficient contact of the sensor with the sample. After separation, the temperature of the sample was controlled to approximately 37°C using an incubator. Note that the tissues were stored at a humidity of 95% to avoid tissue drying. Measurement was completed by 24 hours after death. Figure 3 shows the measurement results of porcine muscle at a tissue temperature of 37°C. The values of complex relative permittivities reported in [8] are also shown as reference.

The combined uncertainties of measured dielectric properties are shown in Figure 4. Note that the sources of uncertainty due to tissue variability have not been considered in the assessment of the measurement uncertainty in this study, whereas those due to the measurement system—e.g., calibration—have been. The combined uncertainties of the real and imaginary parts of complex permittivity were 1% and 0.2% at maximum, respectively, as shown in Figure 4. These values are smaller than the estimated ones; the estimation approach of the combined standard uncertainty using catalog specifications can overestimate the uncertainty. Conversely, by designing to reduce the uncertainty using catalog specifications, it is possible to design a high-performance probe in actual use.

Furthermore, the combined standard uncertainty of 1% is smaller than those of the relative standard variation through multiple measurements of 25%, which was reported in [8]. Therefore, since our designed probe has less uncertainty than the variation of the dielectric property between the tissue samples, it is possible to measure the dielectric property considering the difference of samples.

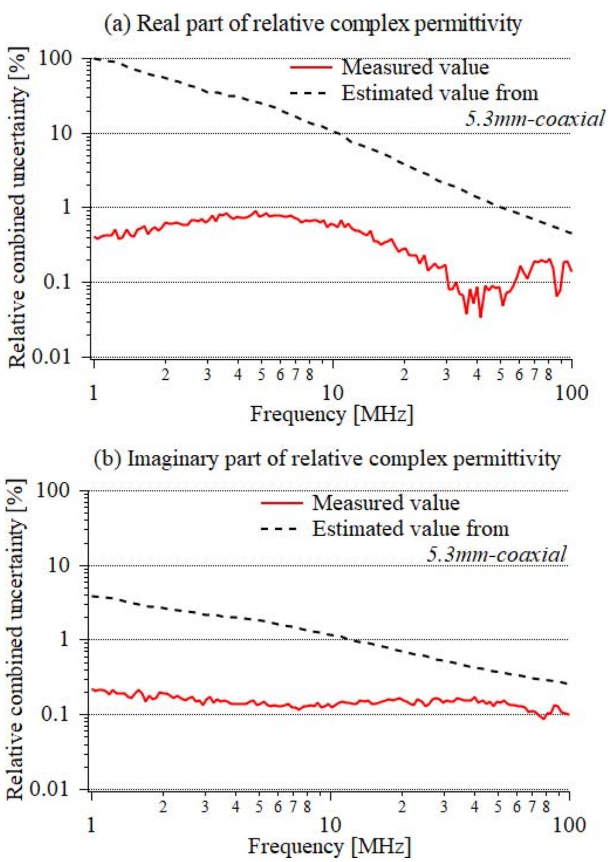

Figure 4. Measurement uncertainties of fabricated sensor.

4. Conclusion

In this study, we developed a coaxial sensor for measuring dielectric properties in the megahertz frequency range. The dimensions of the coaxial sensor were determined by estimating the combined standard uncertainty from the analytical representation of the electromagnetic response at the aperture of the sensor and from the source of uncertainties of the measurement equipment in the data sheet. The designed sensor was used for the dielectric measurement of porcine muscle, and the measurement uncertainty was also evaluated. We demonstrated the applicability of the design approach of the coaxial sensor based on the uncertainty estimation, and also validated the designed sensor in actual measurement of biological tissue.

5. References

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