Dielectric Property Measurements of Biological Tissues: Recent Activityies for Development of a Novel Database

Kensuke Sasaki[1], Kanako Wake[1], Soichi Watanabe[1], Maya Mizuno[1], Kaori Fukunaga[1], Kentaro Katayama[2], and Hiroetsu Suzuki[2]*

[1]National Institute of Information and Communications Technology, Nukuikiramachi, Koganei, Tokyo, 184--8795, Japan, k_sasaki@nict.go.jp

[2]Nippon Veterinary and Life Science University, Kyonancho, Musasino, Tokyo, 180--8602, Japan.

Abstract

The dielectric property values of biological tissues are used for the safety analysis and development of medical applications. A previous study conducted by Gabriel et al. has provided reference dielectric databases. To the best of our knowledge, no other databases have been constructed that allow a comprehensive measurement to be conducted with such a large number of tissues and organs. To this end, we present the development of a novel database for adaptation to recent research, permitting the validation of measured dataset by Gabriel et al. In this paper, we introduce measurement systems for further developing the database and summarize our findings with a discussion on the remaining challenges.

1. Introduction

In recent decades, dielectric properties of body tissues have been used for the assessment of radiation safety by electromagnetic wave propagation and in biomedical applications such as hyperthermia and non-invasive diagnosis technologies. Therefore, a database reference of dielectric properties has been developed [1]-[3] and is currently in use. The vast data sets have been obtained by Gabriel's study [4]-[7], with measurements of 43 tissues using three independent systems [5], and further development of parametric models [6].

High-resolution human models constructed with millimeter and smaller voxels were developed and used for the assessment of safety by electromagnetic fields [8] [9] [10]. A large number of tissues and organs are categorized in these human models. For example, the Japanese human models, Taro and Hanako, are constructed with a total of 58 tissues [8]. The tissue counts are larger than those recorded by Gabriel et al. Hence, to overcome this issue, the dielectric properties having similar constitution are replaced for the tissues that have not been adapted in a previous database. Despite this database modification, precise dosimetry validation remains a challenge.

We are now working to develop a novel database of biological tissues and organs. The main aim of this study is to allow expansion of the frequency range and numbers of tissues used in determining the dielectric property and compare the collected data to tissues from previous directories. Also, the validation of the previous database is examined by comparison of the same measured data with different systems. In this paper, we describe a measurement system for further developing the present database and summarize our findings with a critical discussion on remaining challenges.

2. Method

The measurement systems are constructed with several components for dielectric property analysis and temperature control units. Three measurement methods were employed for the determination of dielectric properties between 1 Hz and 110 GHz.

A two-terminal (parallel-plate) and four-terminal method was employed for the detection range of 1 Hz–10 MHz. Figure 1 (a) illustrates the cell unit compositions used for this purpose. The four-terminal cell was designed as proposed by Schwan et al [11]. An impedance analyzer (SI 1260, Solartron) was used to directly access the impedance features of the tissue and a temperature and humidity cabinet was employed (LH-113, Espec) to control the atmospheric conditions in the measurement cell, when the biological tissues are examined. Figure 2 shows a typical measurement conducted for a porcine blood sample at a constant temperature of 37 °C. For comparison, the measured data by Gabriel et. al. [5] is

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also plotted. We observe that results obtained from our two– and four–terminal methods are in good agreement for the loss factor from 100 Hz to 100 kHz. Below the 100 Hz threshold, the difference between the methods becomes more apparent with decreasing frequencies. This change can be attributed to the error factor of dielectric polarization at the boundary of each parallel-plate in the 2-terminal method. Above 100 kHz, the two-terminal probe method gives comparable data, with additional enhanced continuity to the coaxial probe method (further details provided in subsection 3). No significant effect is seen using the 4-terminal method. However, this variation can be associated to the error term of the cell. We find that the loss factor of biological tissue within this frequency band is linear; the value decreases as a function of f^{-1} (where f is frequency), indicating that conductivity is approximately constant. In contrast, when evaluating the methods for permittivity, we observe differing trends.

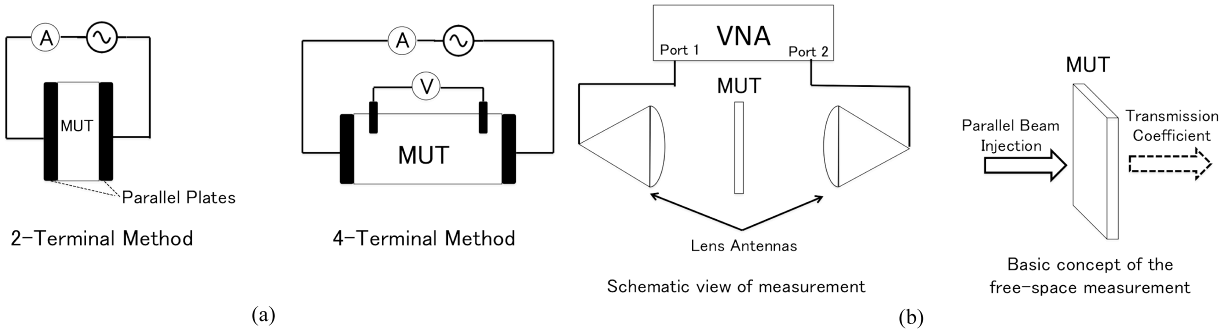

Fig 1. Systems for the dielectric property measurement of biological samples. (a) Extremely low frequency (ELF) to intermediate frequency (IF) bands. (b) Extremely high frequency (EHF) band.

The coaxial probe method [12] is the most effective technique for the measurement of dielectric properties of biological tissues, as it is a non-destructive process and there is a lower limitation of reforming tissues compared with other present methods. For our studies, commercial measurement systems employing the dielectric probe technique were used from 10 to 500 MHz (DAK-12, Schmid & Partner Engineering AG) and from 500 MHz to 50 GHz (Performance Probe 85070E, Agilent Technologies). In this case, each dielectric probe was connected to a vector network analyzer (E8364B or E8364C, Agilent Technologies) and water baths (MATS-OTOR-MJ, Tokai Hit) were used to control the temperature of biological tissues used in the dielectric probe. We observed an ideal continuity for the blood sample, between the two sets of dielectric probes at 500 MHz (as shown in Fig. 2).

The free-space method with a spot-focus-type lens antenna was applied for dielectric property measurements from 50 to 110 GHz [13] (Fig. 1(b)). For this purpose, two lens antennas (KLA-002, Kanto Electronic Application and Development Inc.) were directly connected to a vector network analyzer (E8361A, Agilent Technologies) through a MMW frequency extender (N5260A, Agilent Technologies). Subsequently, a localized air conditioner (PAU-AZ1800SE, Apiste) was integrated to control the temperature during these specific measurements. The final measured data from the blood sample is displayed in Fig. 2. The result with our free-space model system is shown to be in fair agreement with relation to the data attained with the coaxial probe method (at 50 GHz) [13].

For the measurement of biological tissues, the value of the measured data varies widely with repeat measurement especially for the coaxial probe method. It may arise from the uncertainty of correct alignment and connection in the set-up; the presence of an air gap, which have previously been reported in conventional coaxial probe methods. Furthermore, biological tissues are inhomogeneous in most cases and errors can arise due to this significant inconsistency, as reported previously by Gabriel et al [14]. To achieve reliable data, measurements were repeated many times. We determined the validity of our results by taking into account the continuity of the data between different measurement systems and its correlation to previously reported data [5] [7].

3. Measurement Activities of Biological Tissues

For the measurement of biological tissue activities, *in vitro* measurements were conducted, where animal models including pigs, rabbits, and cattle were examined. Experiments were performed up to 48 h after the animal had been sacrificed. For each organism, enucleated tissues were precisely fractionated into sample tissues for measurement. Assessment was conducted on more than 70 independent tissue samples.

Figures 3(a)–(c) presents the measured results at the VHF–EHF bands at temperature of 34±3 °C. The relaxation frequency of γ dispersion was obtained within 20–30 GHz. The γ dispersion exhibited dielectric properties due to the presence of water molecules, whereas the relaxation frequency alternated between 21 and 25 GHz, upon adjustment of the temperature from 30–37 °C [15]. This implied that our measured results were consistent with the typical dispersion characteristics of pure water.

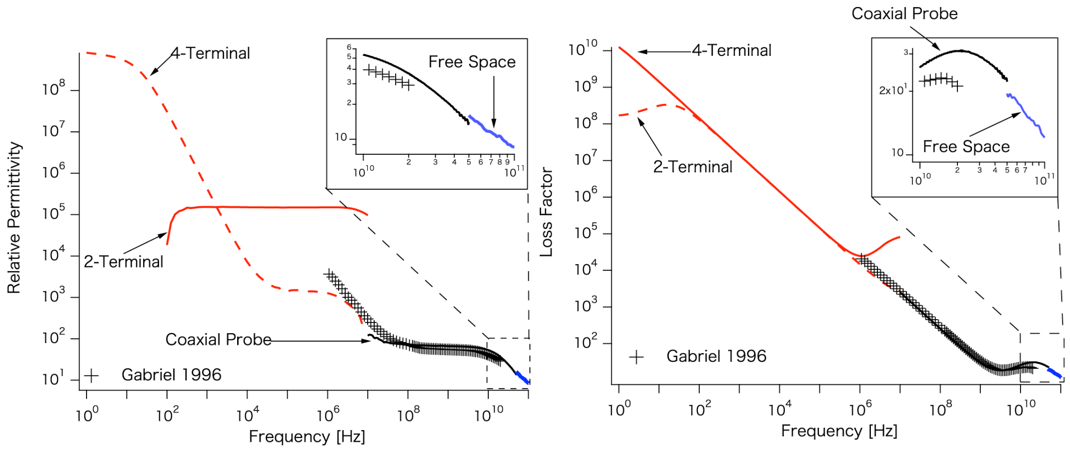

Fig 2. Relative complex permittivity and loss factor of the blood sample (porcine).

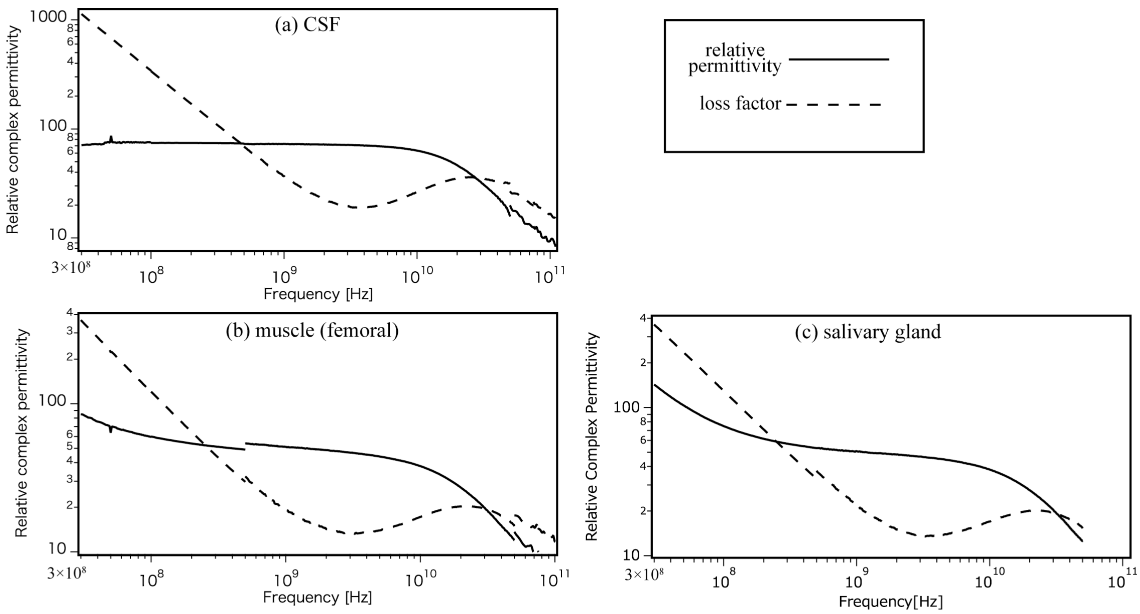

Fig 3. Measurement results for (a) CSF, (b) Muscle (femoral) and (c) Salivary gland.

Consequently, the conductivities of the ELF–IF bands were also investigated. Table 1 lists the conductivities of several tissue types including muscle, salivary gland, and fat. The measured data with open-ended coaxial probes by Gabriel et al. [7] is also included for comparison. We find that both data values are in considerable agreement.

Table 1. Conductivities [S/m] of examined tissues.

	blood	CSF	muscle (femoral)	salivary gland	fat
Our study	0.79	1.4	0.28	0.078	0.02
Gabriel et al. [7]	0.7	2	0.28	N/D	0.04

There are two challenges remaining in our study. First, the crucial requirement for advances in the present system, as presently, the permittivity measurement remains a difficult task when studying ELF to IF bands. Furthermore, measurable tissues are limited by their amount, such case for salivary gland at EHF band in Fig. 3(d). Most importantly, a viable approach is necessary to allow bone tissue, as the isolation and forming steps are extremely arduous. The second challenge is the development of parametric models to interpolate the measured data such as proposed by Gabriel et al. [6] [7].

4. Conclusion

In this study, we have focused on the development of a novel database for biological tissues and organs. We introduce measurement systems and results obtained by *in vitro* experiments. Two potential applications are discussed that may provide insight into further development of measurement processes and parametric models.

5. Acknowledgments

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