Dielectric Modeling of Adipose Tissue as a Function of Water Content From 1 GHz to 100 GHz

Kensuke Sasaki and Tomoaki Nagaoka

Abstract – The dielectric properties of adipose tissue have large variability mainly due to variable water content. In this study, a parametric model of the dielectric properties of adipose tissue that expresses the Cole–Cole parameters as functions of water content was proposed. The model was parameterized on the basis of dielectric measurements of porcine adipose tissues in vitro in the frequency range from 1 GHz to 100 GHz. Our model demonstrated fair agreement with the measurement results. In addition, dielectric properties derived from our model was compared with those derived using the mixing rule to demonstrate the advantage of the proposed model.

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. There have been numerous studies on dielectric measurement since the 1990s, and it is well known that tissue water content is one of the dominant factors determining dielectric properties in the radio frequency domain [1, 2]. In particular, the dielectric properties of adipose tissue, distributed throughout the body, have a large variance with water content; the spread in the values (ratio of the maximum to minimum) are up to 10-fold for permittivity and 30-fold for conductivity [2–4]. In research studies on computational dosimetry for radiation protection from electromagnetic fields, representative data of adipose tissue have been adopted in the electromagnetic modeling of the human body [5]. As a current advancement of the electromagnetic modeling of the human body, biomedical image data have been used for determining the nonuniform distribution of the dielectric properties of each tissue [6]. To enable a precise electromagnetic model of the human body, it is essential to provide the dielectric properties of adipose tissue with respect to water content.

In this study, our objective is to develop a parametric model of the dielectric properties of adipose tissue for water content. First, dielectric measurements of adipose tissue were conducted in vitro using porcine tissue at frequencies from 1 GHz to 100 GHz. The tissue water content was also measured for each tissue sample. Second, a novel parametric model, in which the Cole–Cole model was formulated as function of water content, was proposed and parameterized on the basis of measurement results. The applicability of the parametric model was discussed by comparing the dielectric properties derived from the model with the measurement data. Finally, the effectiveness of the proposed model was discussed in comparison with the mixing rule.

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2. Measurement Methods

2.1 Tissues

Adipose tissues were separated from porcine subcutaneous tissues. The tissues were obtained from the skin at the abdomen in general and also from the back for low-water content (or high-fat content) adipose tissue. The tissue samples were prepared to ensure that they were at least several times larger than the diameter of the contact surface of the sensor for dielectric measurement; the contact surface of the sensor is ϕ9.5 mm [7].

Measurement samples were stored in an incubator to increase the temperature to body temperature (around 35 °C), and relative humidity was controlled to >95% to prevent tissue drying. After the warming process, the samples ($N = 29$) were subjected to dielectric measurements.

2.2 Measurements

A coaxial sensor, often referred to as a *coaxial probe*, was used for the dielectric measurements at frequencies from 1 GHz to 100 GHz [7]. Before starting the measurements, the measurement system was verified using methanol at a room temperature of 20 °C. The same measurement setup as that described in [8] was used for the dielectric measurements. The coaxial sensor is connected to a millimeter wave test head module (N5260A test set, Agilent Technologies, Xxx, XX) via a coaxial cable. Three standard calibration methods were adopted. ?1

The measurement procedure for each sample is as follows. The tissue temperature was measured using a thermocouple thermometer before starting the measurements. For each adipose sample, the measurements were repeated five times by attaching the sensor to different parts of the sample. The tissue temperature was measured and recorded. These processes were repeated for each adipose sample. To minimize the decrease of tissue temperature, the sample was set on a

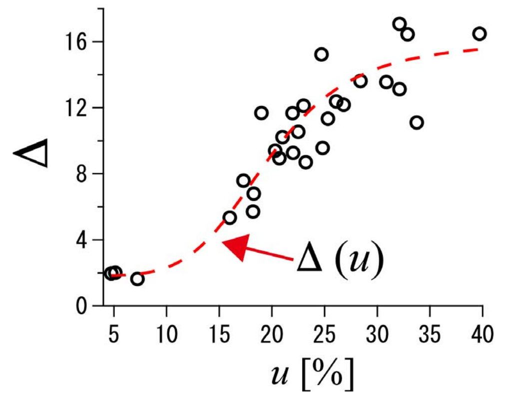

Figure 1. Example of parameterization of the Cole–Cole model.

glass heater (MATS-OTSF-LO, Tokai Hit, Xxxx, XX). Tissue temperatures during the measurement were within the range of 27 °C; to 38 °C, and the mean
?2 tissue temperature was 34 °C.

After the dielectric measurement were conducted for each sample, the samples were stored in a freezer. The water content of each measured sample was estimated from the difference in mass before and after freeze drying. The measured water content ranged from 4.8% to 39.7%; the means ± standard deviations (SD) were 25.8% ± 10.4%.

3. Dielectric Modeling

3.1 Parameterization Method

The dielectric dispersion characteristics of tissues are well represented using the Cole–Cole equation [2]. Therefore, we proposed a dielectric model of adipose tissue by expanding the conventional Cole–Cole model.

$$\varepsilon_r^*(f,u) = \varepsilon_\infty(u) - j\frac{\sigma_s(u)}{2\pi f \varepsilon_0} + \frac{\Delta(u)}{1 + j\left(f/f_r(u)\right)^{1-\alpha(u)}} \quad (1)$$

Here, ε_r^* is the relative complex permittivity, which is a function of frequency f (hertz) and water content u (percentage), and j and ε_0 are a pure imaginary number and permittivity in a vacuum $\approx 8.85 \times 10^{-12}$ (farad per meter), respectively. Also, ε_∞, σ_s, Δ, f_r, and α are the relative permittivity at $f \gg f_r$, dc conductivity (siemens per meter), magnitude of dispersion, relaxation frequency (hertz], and distribution parameter, respectively. These Cole–Cole parameters were as-
?3 sumed as functions of the water content in our model.

The Cole–Cole parameters were functionalized using the procedure for a tissue-equivalent phantom proposed in [9]. Note that the mathematical formulae for the functionalization of each parameter were empirically determined in accordance with the correlation between each parameter and the water content (an
?4 example is shown in Figure 1).

As a result of the parameterization, the Cole–Cole parameters were functionalized as follows:

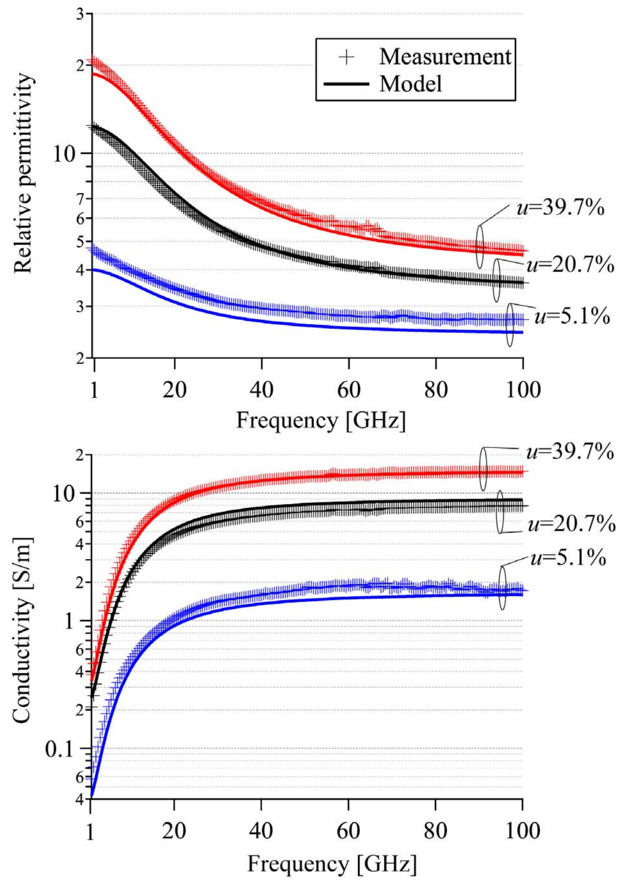

Figure 2. Example of results derived from the model (1) and measurement: relative permittivity (top) and conductivity (siemens per meter; bottom).

$$\varepsilon_\infty(u) = 5.00 - 3.03\exp(-0.029u) \quad (2)$$

$$\sigma_s(u) = 0.037 + \frac{0.255}{1 + \left(18.1/u\right)^{6.97}} \quad (3)$$

$$\Delta(u) = 1.60 + \frac{13.6}{1 + \left(19.9/u\right)^{4.66}} \quad (4)$$

$$f_r(u) = (17.5 + 0.012u) \times 10^9 \quad (5)$$

$$\alpha(u) = 453\exp(-2.00u) \quad (6)$$

3.2 Results of Dielectric Parameterization

Figure 2 shows the dielectric properties (relative permittivity and conductivity) obtained from the measurement and from our model for water content of 5.1%, 20.7%, and 39.7% as examples. The deviations (mean ± SD) between our model and the measurement results for all data were 10% ± 7% for permittivity and 15% ± 11% for conductivity.

The effects of tissue heterogeneity on the dielectric properties of each adipose sample were estimated to be 9% for permittivity and 17% for conductivity. Note that the effect of tissue heterogeneity was estimated from the SD of the mean of each sample obtained from five repetitions of measurements [10], and the previously mentioned values are the average values over the whole frequency range and all samples. In addition, the standard uncertainties in the measurement system for the measurement of a reference liquid (methanol) were reported to be no larger than 13% for permittivity and 16% for conductivity [8]. Considering the measurement uncertainty for the reference liquid and the tissue heterogeneity for each sample, the discrepancies in the dielectric properties between our model and the measurements were considered to be marginal.

4. Discussion

To discuss the advantage of our model (1), the dielectric properties derived from the model were compared with those from the mixing rule. We focus on a mixing rule referred to as Lichtenecker's exponential law [11], which has been used in the computational dosimetry of human exposure to radio frequency electromagnetic fields [12]. The relative complex permittivities of a mixing material ($\varepsilon^*_{r,\mathrm{mix}}$) were formulated using [12]

$$\varepsilon^*_{r,\mathrm{mix}}(u) = \varepsilon_{r,w}^{\frac{u-u_{\mathrm{ref}}}{100-u_{\mathrm{ref}}}}\varepsilon_{r,\mathrm{ref}}^{\frac{100-u}{100-u_{\mathrm{ref}}}}(1-j\tan\delta) \tag{7}$$

where $\varepsilon_{r,w}$ is the relative permittivity of water, and $\varepsilon_{r,\mathrm{ref}}$ and $\tan\delta$ are the relative permittivity and loss tangent of a reference sample with $u = u_{\mathrm{ref}}$, respectively.

Figure 3 shows the dielectric properties derived from our model (1) and from the mixing rule. To determine the dielectric properties from the mixing rule, we used the dielectric properties of water ($\varepsilon_{r,w}$) at 34 °C using the parametric model by Ellison [13], and $\varepsilon_{r,\mathrm{ref}}$ was derived from our model with $u_{\mathrm{ref}} = 25\%$ (around the mean water content throughout the sample in our measurements).

The dielectric properties derived from the mixing rule were in fair agreement with those derived from the model for a water content of 40%. The deviations in dielectric properties (mean ± SD throughout the frequency range) derived from the mixing rule from those derived from the model were 10% ± 4% for permittivity and 6% ± 5% for conductivity. On the other hand, the deviations were 6% ± 4% for permittivity and 26% ± 3% for conductivity at $u = 20\%$, and they enormously increased for $u = 5\%$.

The applicability of the mixing rule may deteriorate with the increase in $|u - u_{\mathrm{ref}}|$; this tendency has been observed through $u = 20\%$ to 5% in Figure 3, as an example. In the mixing rule, the values of $\varepsilon_{r,\mathrm{ref}}$ and $\varepsilon_{r,w}$ are obtained with $u = u_{\mathrm{ref}}$ and 100%, respectively, according to (7). This implies that the dielectric properties derived from the mixing rule with $u = 40\%$

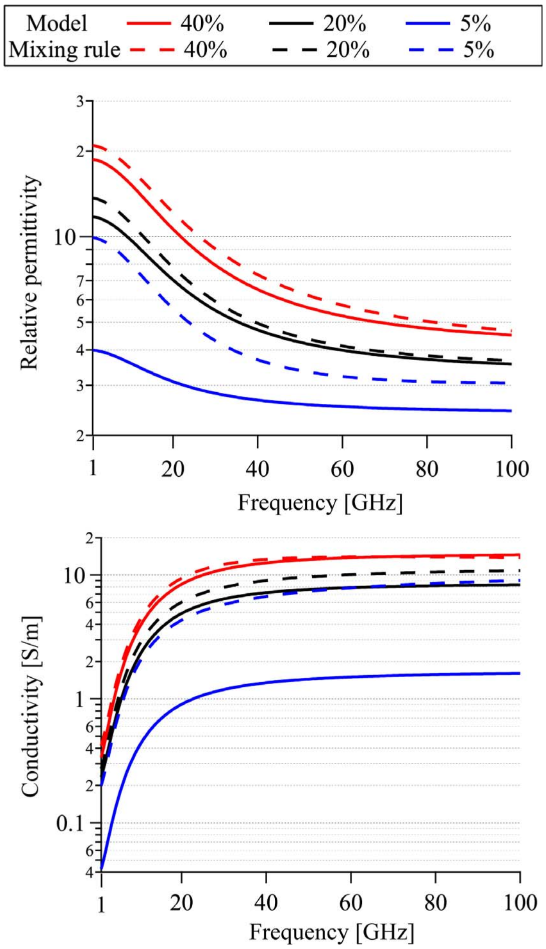

Figure 3. Dielectric properties derived from (1) and from mixing rule: relative permittivity (top) and conductivity (siemens per meter; bottom).

were interpolations between $\varepsilon_{r,w}$ and $\varepsilon_{r,\mathrm{ref}}$, whereas those in the other cases, $u = 5\%$ and 20%, were extrapolations. Because the dielectric properties in the case of $u = 5\%$ derived from the mixing rule are extrapolated values, large differences from the model are expected. On the other hand, the dielectric properties in the case of $u = 40\%$ derived from the mixing rule demonstrated deviations of similar order to those between the model and the measurement, as described in Section 3.2. Note that we also applied the mixing rule with $u_{\mathrm{ref}} = 5\%$ and compared the interpolated dielectric data at $u = 20\%$, 30%, and 40% derived from the mixing rule with those derived from the model. In these cases, large deviations from the previous case ($u_{\mathrm{ref}} = 25\%$) were observed, particularly in conductivity in the range of u from 20% to 40%. In addition, the mixing rule assumes nonvariant in the loss tangent ($\tan\delta$) with water content, as shown in (7). It may also limit applicability of the mixing rule and cause larger deviations in conductivity compared with permittivity. In fact, values of $\tan\delta$ with $u = 5\%$ decrease 50% to 80% from those with $u = 25\%$ (u_{ref}),

and these variances were within 10% from u_{ref} to
?5 $u = 40\%$.

These results demonstrated that the mixing rule from Lichtenecker's exponential law may provide a reasonable agreement with our proposed model in interpolating ($u \geq u_{\mathrm{ref}}$) dielectric properties, if u_{ref} was reasonably selected. On the other hand, our model has the advantage of reasonably being able to determine dielectric properties over a wide range of water content from 5% to 40%, especially at low water content.

5. Conclusion

In this study, we provided the Cole–Cole parameters of adipose tissue, with the parameters determined as functions of water content. The coefficients of the parameters were systematically derived by parameter fitting and using the dielectric data of porcine adipose tissue measured in vitro. Dielectric data derived from our model show fair agreement with the measurement data. In addition, the advantage of our model was demonstrated in comparison with the conventional mixing rule.

The provided model can be used to determine the appropriate dielectric properties of adipose tissue, with a large variance and distribution throughout the body, at frequencies ranging from 1 GHz to 100 GHz.

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