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A Dosimetric Study using Best-fit Cole-Cole Parameters of Biological Tissues and Organs in Radio Frequency Band

Kensuke Sasaki #1, Kanako Wake #, Soichi Watanabe #,

Electromagnetic Compatibility Lab., NICT
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 1848795, Japan
1 *k_sasaki@nict.go.jp*

***Abstract*—Best-fit Cole-Cole parameters for biological tissues and organs are proposed in this study. The sensitivity of the energy absorption is evaluated using a Mie series solution as a preliminary study. Numerical dosimetry studies of the energy absorption of the human models following radio frequency exposure were performed using the best-fit Cole-Cole parameters, and the results were compared with the standard Cole-Cole parameters that are normally used.**

I. INTRODUCTION

Wireless communication technology using the radio frequency (RF) band is now widespread. Public exposure to RF electromagnetic fields (RF-EMF) has been rapidly increasing, and evaluation of the health effects of this exposure is an important issue. International guidelines provide measured limits for public and occupational exposure [1][2]. Numerical dosimetry studies have been used as an important part of the exposure assessment for these safety limits. Precise dosimetry with the use of a high resolution human model (such as that in [3]) is useful for the assessment of energy absorption caused by human bodies. The dielectric properties of biological tissues and organs reported in [4] and [5] are used as a de-facto database for these dosimetry studies.

These dielectric properties were obtained from parametric models based on measurement results [6] and on measurement data in the literature [7]. Measurement data for many biological tissues and organs are quite rare, because there are few studies that have gathered measurement data for biological tissues and organs near the temperature of the human body. The measurement uncertainties of these dielectric properties (e.g. the permittivity and the loss factor) are reported to be almost the same as the standard deviation of the mean of repeat measurements when the measurement system is used at over 50 MHz [8]. Therefore, the accuracy of the data was estimated to be ±5%-10% above 100 MHz and ±15-25% below 100 MHz[6] in accordance with the assessment of the measurement uncertainty of these measurement systems. However, the differences in the dielectric properties, particularly in the permittivity and the loss factor, between the measurement data and the values derived from the parametric models which are actually used for the dosimetric studies cannot be ignored when considering the measurement uncertainty of the measurement data.

The main purpose of this study is the development of a best-fit parametric model in the frequency range from 1 MHz to 20 GHz, and the assessment of its effects on the dosimetry. Best fit Cole-Cole parameters were derived by solving a least-squares problem with use of a fitting algorithm based on that proposed in [9]. The energy absorption sensitivity was assessed with the use of a Mie series solution in the preliminary study. Finally, the effects of the energy absorption in dosimetry studies with human models are evaluated by using the proposed parametric model.

A. *Best-fit Cole-Cole parameters*

The quad Cole-Cole model, which is shown in Eq. (1), is used as the parametric model to represent the four dispersions of the biological tissues, i.e. the α, β, γ, and Δ dispersions.

$$\varepsilon(f) = \varepsilon_\infty + \sum_{l=1}^{4} \frac{\Delta_l}{1 + (j\frac{f}{f_{relax,l}})^{(1-\alpha_l)}} - \frac{\sigma_s}{j2\pi f\varepsilon_0} \qquad (1)$$

where, ε_∞ and σ_s are the limits of the permittivity of the sample at infinite and DC conductivities, respectively, and $f_{relax,l}$ and α_l are the relaxation frequency and the distribution parameter [5]. The 14 Cole-Cole parameters in Eq. (2) were determined by manual decisions in the database [5]. Techniques for solving least-square problems are a common approach used to obtain the parameters for the parametric models. In this case, there are difficulties in solving the least-squares problem of the multiple Cole-Cole models with the conventional approach, because the parameters near the best-fit parameters must be set as initial parameter to obtain the fitting parameters.

The best-fit Cole-Cole parameters were derived by applying the Cole-Cole parameter fitting algorithm based on that proposed in [9] to overcome these problems. The root sum square (RSS) values of the relative deviations in the permittivity and the loss factor are used as the values to be minimized for the least-squares problem, and the Levenberg-Marquardt method [10] is used to derive the best-fit Cole-Cole parameters in this study.

We proposed best-fit Cole-Cole parameters for 41 tissues and organs using the measurement data given in [6] and

[4] from 1 MHz to 20 GHz. A number of these best-fit Cole-Cole parameters are listed in Table I. The best-fit Cole-Cole parameters are obtained with double or triple Cole-Cole parameters. The relaxation frequency of the α dispersion is estimated as approximately 10 Hz from the database [5] . For these reasons, the effects of the α dispersion on the dielectric properties are assumed to be small at frequencies over 1 MHz.

TABLE I
EXAMPLES OF BEST-FIT COLE-COLE MODEL PARAMETERS.

Tissue	ε_∞	σ_s	$f_{relax,1}$ [GHz]	Δ_1	α_1	$f_{relax,2}$ [MHz]	Δ_2	α_2	$f_{relax,3}$ [kHz]	Δ_3	α_3
Blood	11.8	0.996	15.8	41.4	0.015				947	7930	0.092
CSF	18.6	2.22	16.7	49.4	0.046	220	6.20	-0.211			
Fat	2.90	0.025	13.2	1.38	-0.232	34.5	4.53	-2.40	1360	26.9	0.428
Grey Matter	12.7	0.173	18.7	32.2	0.075	2.36	1170	0.315			
Muscle	10.3	0.496	15.5	41.4	0.023	3.85	273	0.447	1130	2440	-0.041
Skin (Dry)	5.01	0.005	19.9	31.4	0.066	6.77	830	0.139			
Skin (Wet)	-4.97	0.135	23.1	54.5	0.253	1.60	3450	0.087			

The deviations of the permittivity and loss factor from the parametric models are listed in Table II. The average and maximum values over the frequency range from 1 MHz to 20 GHz are shown in the table. Improvements in the deviations are observed for the proposed parametric model in all tissues where the average deviations are smaller than the measurement uncertainties of the data used.

TABLE II
AVERAGE AND MAXIMUM DEVIATIONS [%] OF THE PERMITTIVITY AND LOSS FACTOR BECAUSE OF THE COLE-COLE PARAMETERS FROM MEASUREMENT DATA.

Tissue	Permittivity		Loss Factor	
	Gabriel[4]	Proposed	Gabriel[4]	Proposed
	Ave.(Max.)	Ave.(Max.)	Ave.(Max.)	Ave.(Max.)
Blood	9(22)	2(5)	18(34)	2(6)
CSF	3(16)	1(2)	7(21)	1(4)
Fat	14(25)	4(10)	11(31)	4(9)
Grey Matter	8(27)	8(16)	11(28)	7(14)
Muscle	9(21)	1(4)	14(25)	1(3)
Skin (Dry)	11(25)	4(15)	13(29)	4(14)
Skin (Wet)	8(42)	2(21)	8(18)	4(21)

II. PRELIMINARY STUDY: ENERGY ABSORPTION SENSITIVITY FROM THE DIELECTRIC PROPERTIES

A. *Monte-Carlo simulation*

The Mie series solution is used to evaluate the effects of the energy absorption by considering the uncertainty of the dielectric properties. The sphere diameter is set at 20 cm, and the specific absorption rates (SARs), which are defined in Eq. (2), were evaluated.

$$\mathrm{SAR} = \sigma \frac{|\mathrm{E}|^2}{2\rho}, \tag{2}$$

where σ, $|\mathrm{E}|$, and ρ are the conductivity, the amplitude of the electric field, and the density, respectively.

The dielectric properties of the inhomogeneous sphere are set as those of the muscle given in [4]. Figure 1 shows the frequency dependence of the average SAR ($\mathrm{SAR_{ave}}$) relative to the sphere model. The peak value of $\mathrm{SAR_{ave}}$ is obtained at approximately 400 MHz, which indicates the resonance frequency in this model. The sensitivity of $\mathrm{SAR_{ave}}$ in terms of the dielectric properties is evaluated at 30 MHz, 228 MHz, and 6 GHz, for which the loss tangents are 4, 1, and 0.4, respectively.

B. *Monte-Carlo simulation results*

The sensitivity of $\mathrm{SAR_{ave}}$ in terms of the dielectric properties is evaluated by performing a Monte-Carlo simulation at each frequency. Each of the input quantities, which are permittivity ε' and loss factor ε'', are randomly sampled from the normal distribution with a 25 % relative standard deviation of each dielectric property. Table III gives the Monte-Carlo simulation results. The results show that the value of $\mathrm{SAR_{ave}}$ increases with decreasing frequency or with increasing loss tangent.

Figure 2(a) to (c) indicate the sensitivity of $\mathrm{SAR_{ave}}$ in terms of each input quantity, which are the absolute value of the complex permittivity $|\varepsilon|$, the permittivity, and the conductivity. Here, the x and y-axes are the relative deviations of the input quantities and those of the average SAR ($\Delta\mathrm{SAR_{ave}}$), respectively. The effect of the conductivity is dominant at 30 MHz, because a large effect on $\Delta\mathrm{SAR_{ave}}$ caused by $\Delta\varepsilon''$, rather than by $\Delta\varepsilon'$, is observed. In the case at 228 MHz, where the loss tangent is 1, $\Delta\mathrm{SAR_{ave}}$ is affected by both ε' and ε''; however, the degree of the effect on $\Delta\mathrm{SAR_{ave}}$ caused by ε'' is larger than that caused by ε'. The value of $\Delta\mathrm{SAR_{ave}}$ at 6 GHz depends on that of ε'. For these reasons, it is expected that the $\Delta\mathrm{SAR_{ave}}$ characteristics relative to $\Delta|\varepsilon|$ (Fig. 2(a)) agree with the characteristics in which the input quantities are dominant at each frequency, i.e. the $\Delta\mathrm{SAR_{ave}}$ characteristics for $\Delta|\varepsilon|$ (Fig. 2(a)) agree with those for $\Delta\varepsilon$ (Fig. 2(c)) at 30 MHz and 228 MHz, and they agree with the $\Delta\mathrm{SAR_{ave}}$ characteristics for $\Delta\varepsilon'$(Fig. 2(b)) at 6 GHz.

It was found that the value of $\mathrm{SAR_{ave}}$ was sensitively affected by the value of the loss factor when the loss tangent is large or near 1 in the low frequency region from 30 MHz to 6 GHz. In the case where the loss tangent is small, $\mathrm{SAR_{ave}}$ is affected by the permittivity; however, the degree of this effect is small.

TABLE III
RESULTS OF THE MONTE-CARLO SIMULATIONS.

	30 MHz	228 MHz	6 GHz
ε_r' Standard Deviation	106 25 %	69.1 25 %	48.5 25 %
ε_r'' Standard Deviation	419 25 %	69.1 25 %	19.3 25 %
$\mathrm{SAR_{ave}}$ Standard Deviation	78.7 μW/kg 25 %	3.55 mW/kg 13 %	1.23 mW/kg 8 %

III. DOSIMETRY WITH HUMAN MODELS

The effects of the use of our Cole-Cole parameters are evaluated by performing numerical simulations using male and female human models [3]. The finite difference time-domain method [11] is used, and the perfectly matched layer [12] is applied at all boundaries of the calculation region. The voxel size for the simulation is set at 2 mm, and the exposure conditions used for the simulation are E-polarized transverse electromagnetic (TEM) waves at several frequencies, ranging from 30 MHz to 3000 MHz.

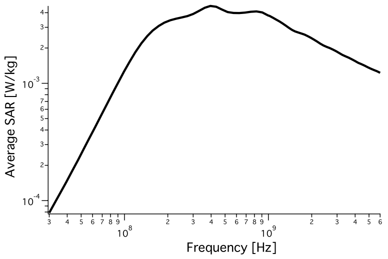

Fig. 1. Frequency dependence of the average SAR.

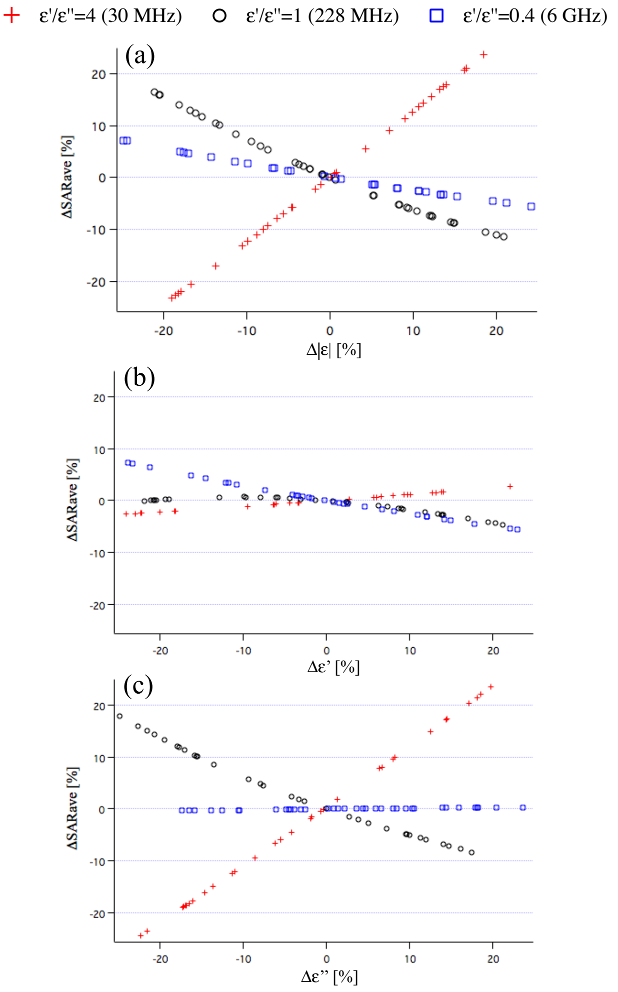

Fig. 2. Deviations of the average SARs as functions of (a) the absolute value of complex permittivity, (b) the permittivity, and (c) the conductivity or the loss factor.

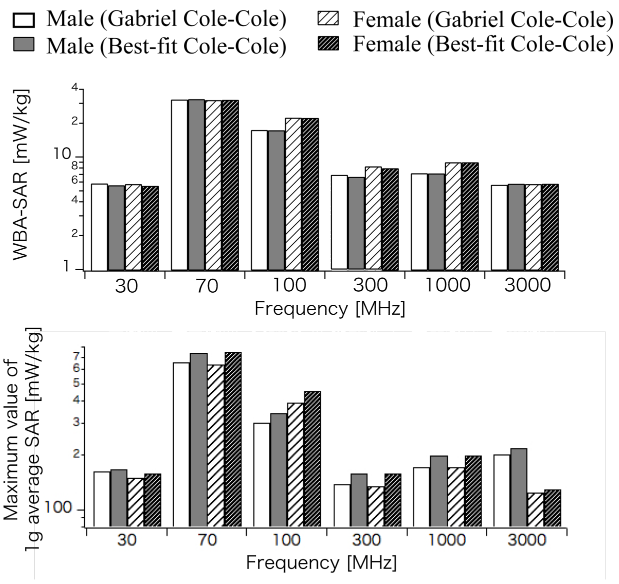

Fig. 3. Whole body average SARs and maximum values of 1 g average SARs obtained from dielectric properties in terms of the Cole-Cole parameters.

Figure 3 indicates the whole body average SAR (WBA-SAR) and the maximum values of the 1 g averaged SAR[13]. The WBA-SARs for each parametric model agreed well, with 5 % deviations at each frequency. This result indicates that the effects on the energy absorption into the whole body when using the best-fit Cole-Cole parameters are small. On the other hand, the deviations of the maximum values of the 1 g averaged SAR are more than 10 % in several cases.

IV. CONCLUSION

Best-fit Cole-Cole parameters for biological tissues and organs are proposed in this study. The deviations from the measurement data were improved by using the proposed Cole-Cole parameters in comparison with those that are conventionally used in the frequency range from 1 MHz to 20 GHz. The energy absorption sensitivity was evaluated using the inhomogeneous sphere model as a preliminary study. The results indicated that the average SAR values are sensitively affected by the loss factor rather than the permittivity when the loss tangent is large at frequencies below the resonant frequency. In the case where the loss tangent becomes small, the dependence on the permittivity is greater than that on the loss factor. However, the degree of sensitivity in the average SAR in the high loss tangent region is smaller than that in the low loss tangent.

Examples of precise dosimetry by plane wave exposure using human models were performed, using the dielectric properties with the best-fit parameters at several frequencies, ranging from 30 MHz to 3000 MHz. The results for the WBA-SARs indicated agreement between the cases in which the proposed best-fit parameters and the conventionally used Cole-Cole parameters are applied. The deviation of the maximum value of the 1 g averaged SAR was larger than 10 % in some cases. However, because the effect on the dosimetry of using the best-fit Cole-Cole parameters is not always large, it is feasible to use these parameters in any case for dosimetric studies in bioelectromagnetics.

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