Collaboration Projects

Biological Tissue-Equivalent Phantoms Usable in Broadband Frequency Range

Phantoms, which are models simulating various electrical constants of biological tissues, are used to evaluate antenna characteristics of mobile terminals as well as measure amounts of absorbed electromagnetic energy. We developed phantoms that can be used in the range from 3 to 10 GHz as well as broadband. This research was conducted jointly with the Ito laboratory (Professor Koichi Ito) at the Research Center for Frontier Medical Engineering, Chiba University.

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1. Introduction

Since mobile terminals are normally used in the vicinity of human bodies, the electromagnetic waves radiated from the mobile terminals interact with the human body. The electromagnetic energy of electromagnetic waves radiated from a mobile terminal absorbed by a given volume of the human body is expressed as the Specific Absorption Rate (SAR). The influences of a human body on antenna characteristics include changes in the input impedance, the radiation directivity and the radiation efficiency, and low deterioration of antenna characteristics is desired when using the mobile terminal near a human body compared to in free space. However, it is nearly impossible to measure the energy absorbed in an actual human body; the measurements fluctuate due to individual differences such as body types, and there are several problems in reproducibility. In order to eliminate such problems, simulated human bodies, called biological tissue-equivalent phantoms, are used [1]. They simulate various electrical constants of biological tissues (e.g., the relative permittivity and the conductivity) and come in various shapes, from simple ones such as spheres and cubes to shapes closely resembling human bodies; different shapes are used according to the purpose. Phantoms can be classified into numerical phantoms, which are used for computer simulation, and experimental phantoms, which are used for experiments. This article discusses experimental phantoms.

There are two types of biological-tissue equivalent phantoms: liquid and solid phantoms. A liquid phantom requires a container to hold the fluid, but since the E-field probe scan can be easily carried out in liquid, the liquid phantom has been adopted in the SAR measurement method of mobile terminals [2]. A solid phantom does not allow scanning with a probe inside the phantom, but can be manufactured in arbitrary shapes that do not require containers once the molds are created. Such phantoms have been developed for each of the frequency bands below 3 GHz (e.g., 1950 MHz), which are mostly used in mobile terminals [3] [4].

On the other hand, wireless LAN systems operated at 5.2 GHz band have been used, and 5 to 6 GHz band and below have been investigated for the fourth generation mobile communication. Moreover, Ultra WideBand (UWB) communication technologies using the 3.1 to 10.6 GHz band have been developed. Observing this trend, it is highly likely that wireless communication using frequencies of 3 GHz or above, as well as broadband will be put to practical use, and that such mobile terminals will be used in the vicinity of human bodies in the future. For this reason, phantoms with higher frequency or broadband frequency characteristics are required in order to evaluate the amount of absorbed electromagnetic energy and antenna characteristics.

This article describes the composition and electric constants of the developed broadband biological tissue-equivalent solid phantoms as well as the effects of deviations between the electrical constants of the phantoms and biological tissues on the antenna characteristics.

2. Solid Biological Tissue-Equivalent Phantoms

Solid biological tissue-equivalent phantoms include agar-based phantoms solidified mainly with agar, and dry phantoms created from ceramics [1]. Phantoms made by solidifying liquid materials with agar are widely used due to the ease of material acquisition and production. It has also been reported that it is easy to simulate the electrical constants equivalent to brain tissues at frequencies from 800 to 2500 MHz [3]. Dry phantoms, on the other hand, do not contain water and are thus excellent for maintaining relatively constant characteristics over time. However, since the electrical constants are controlled using carbon or high-dielectric materials instead of water, it is difficult to obtain good broadband frequency charateristics. For this reason, as we focused on broadband frequency characteristics in this research, we investigated agar-based phantoms. This type of phantoms have the following features.

- They maintain their shapes by themselves (no need for containers).
- Ingredients are easy to acquire.
- The manufacturing is easy.
- It is possible to manufacture arbitrary shapes and multi-layered.
- It is possible to simulate tissues with high-water content (e.g., brain and muscles).

Photo 1 shows an upper body phantom created based on the average values of Japanese adult men as an example. Unlike liquid phantoms, these phantoms can be easily manufactured once molds are prepared and do not require containers to hold the phantoms.

Photo 1 Upper body phantom (Provided by the Ito laboratory, Chiba university)

3. Composition and Electrical Constants of Solid Biological Tissue-Equivalent Phantoms

3.1 Adjustment of the Electrical Constants

Table 1 shows an example of composition for the agar-based phantoms used in this research. Agar is used to maintain the shape of the phantoms by preventing separation of water contents. TX-151 is used as thickener and sodium dehydroacetate is used as preservative.

Figure 1 shows the relationship between electrical constants and composition of the phantoms at 5.2 GHz, where the horizontal and vertical axes represent the relative permittivity and the conductivity of the phantoms, respectively. Each square

Table 1 Example of agar-based phantom composition

Ingredient	Weight [g]
Deionized water	3375.0
Agar	104.6
Sodium chloride (NaCl)	21.5
Sodium dehydroacetate	2.0
TX-151	57.1
Polyethylene powder (PEP)	548.1

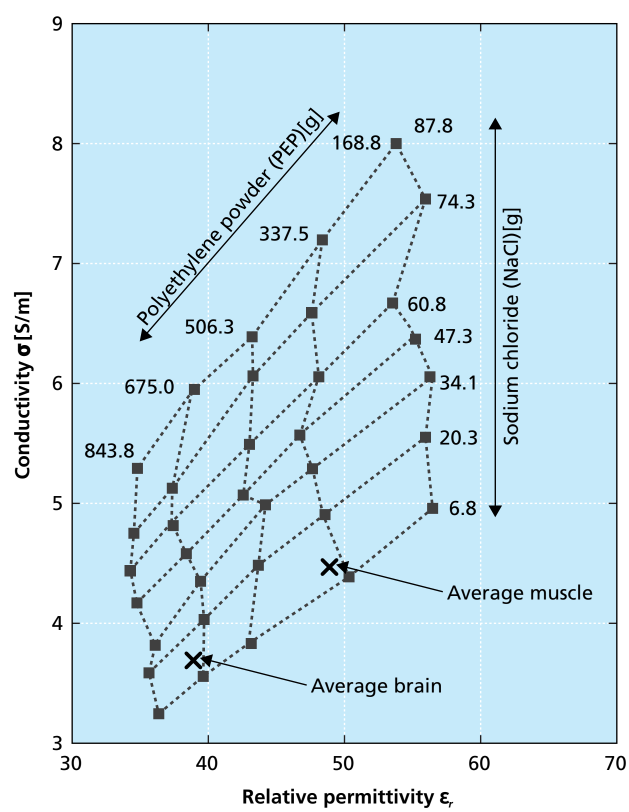

Figure 1 Relationship between phantom electrical constants and composition at 5.2 GHz

in the graph represents the electrical constants for each phantom with different amounts of polyethylene powder (PEP) and sodium chloride (NaCl). As can clearly be seen from the figure, the relative permittivity and the conductivity depends on the amounts of PEP while the relative permittivity only depends on NaCl. Thus, it is possible to obtain desired electrical constants by adjusting the amount of PEP and NaCl. For the sake of comparison with biological electrical constants, average values for brain and muscle tissues [5] are shown. These values are within the allowable ranges shown on the figure and it is concluded that it is possible to manufacture solid biological tissue-equivalent phantoms at 5.2 GHz by adjusting the amounts of PEP and NaCl. It is also possible to manufacture desired phantoms by adjusting the amounts of PEP and NaCl at other frequencies as well [6].

3.2 Frequency Characteristics

Figure 2 shows the results of the measured frequency characteristics (0.9 to 10 GHz) of the phantoms. The target values are set as the values obtained by multiplying the average values of the biological muscle tissue's electrical constants by 2/3 (hereinafter referred to as 2/3-muscle model). This is because the electrical constants of the body estimated from outside are equivalent to nearly 2/3 of the muscle tissue's electrical constants. The error bars show ±10% margins of the target values. As can clearly be seen from the figure, the measurement results of the relative permittivity are within ±10% of the biological values throughout the entire frequency range and the measured values of the conductivity are also within ±10% of the biological values at frequencies of 3 GHz or higher. Although the measured conductivity values deviate from the target values at frequencies lower than 3 GHz, the results show that it is possible to manufacture phantoms with constants that are within ±10% of the target values in the frequency range from 3 to 10 GHz. Similar results were obtained when the average values for brain tissues were set as the target values. Moreover, by adjusting the composition ratios to suit the target values at each frequency, the phantoms can be used in a wide frequency range.

4. Effects of Deviation in Phantom Electrical Constants

It is useful to evaluate the effects of deviations of the phantom electrical constants from the target electrical constants on the SAR and antenna characteristics prior to the measurement. In this article, the effect of the deviation was evaluated using a half-wave length dipole antenna and a cubic phantom with numerical calculations. **Figure 3** shows the evaluation model. The feed point for the dipole antenna was positioned at the center of the opposing phantom surface and the distance between the antenna and the surface of the phantom was set to 10 mm. It is noted that the dipole antenna is assumed to be a perfect conductor and adjusted to be almost half the wave length (0.47 wavelength) at each frequency. The calculation was performed using the measured and target electrical constants of the 2/3-muscle model shown in Fig. 2 with the Finite-Difference Time-Domain (FDTD) method*.

* FDTD method: A finite-difference time-domain method in which the Maxwell equations are differentiated directly and calculated in the time domain. Used for evaluation of SAR and antenna characteristics.

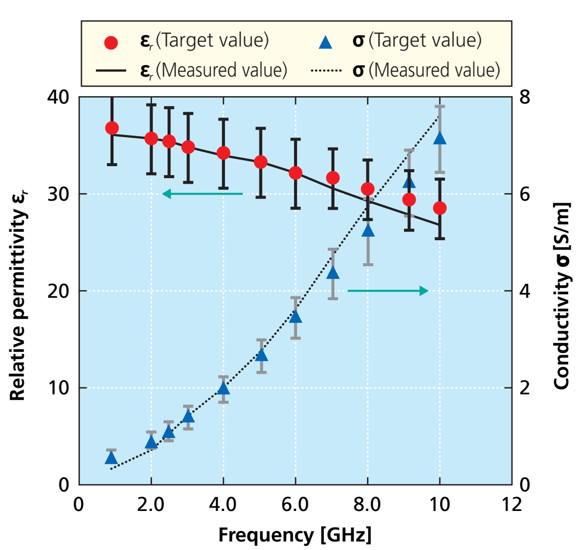

Figure 2 Phantom frequency characteristics

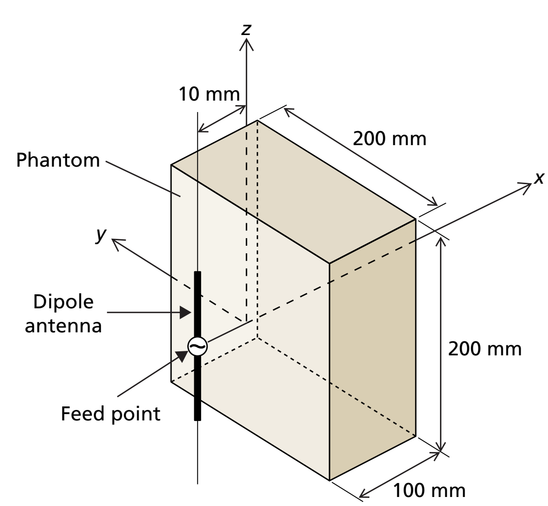

Figure 3 Evaluation model

4.1 SAR

SAR is an index indicating energy absorbed in biological tissues and is given by

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

where σ is the electrical conductivity [S/m], E is the electric field strength (effective value) [V/m] and ρ is the density [kg/m^3] of the biological tissues. **Figure 4** shows the calculated SAR results, where the vertical axis shows how much the SAR calculated using the measured phantom electrical constants deviates from the SAR calculated using the target electrical constants. The SAR values are averaged over a 10-g cubic volume of tissue. As can clearly be seen from the figure, the deviation of the SAR is within approximately 1.5% at frequencies of 3 GHz or higher, which is insignificant for all practical purposes. The deviation is larger at frequencies lower than 3 GHz. It can be considered that the conductivity of the phantom deviates from the target values at lower frequencies.

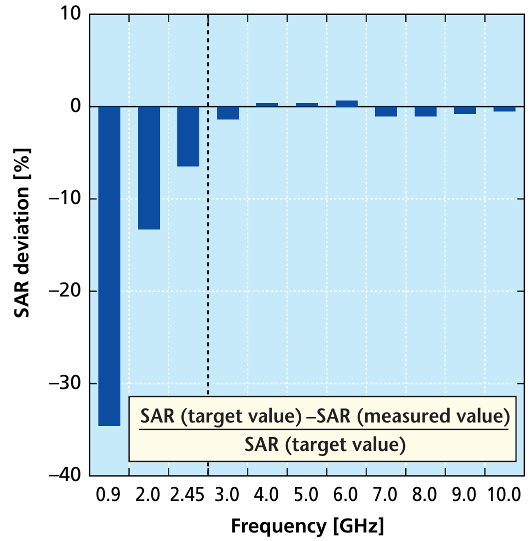

Figure 4 Effects of deviation in electrical constants on the SAR

4.2 Antenna Characteristics

Next, the effects of the deviation of the electrical constants of the phantom from those of biological tissues on the radiation effeciency are evaluated. Since the antenna is assumed to be a perfect conductor, the ratio between radiation power and antenna input power is used as the radiation efficiency. As a result, unlike for the SAR results, the deviation of the phantom electrical constants did not give rise to any significant effects even at frequencies lower than 3 GHz (**Figure 5**). Similar results were obtained for the input impedance and the radiation pattern characteristics as well [7].

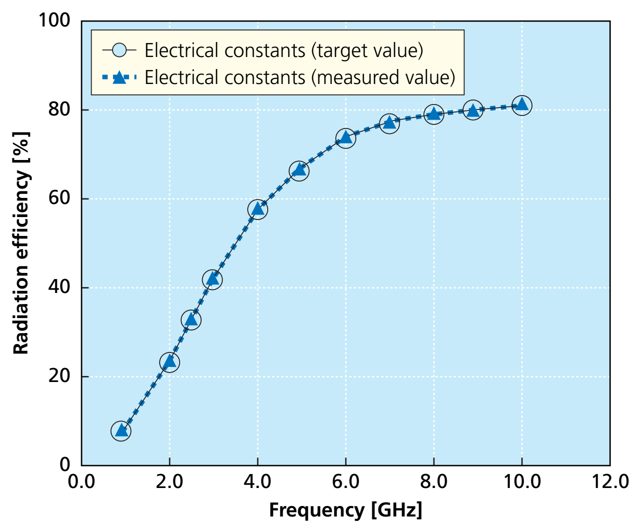

Figure 5 Effects of deviation in electrical constants on radiation efficiency

5. Conclusion

We developed solid biological tissue-equivalent phantoms that can be used for communication systems using several frequency or wider frequency bands, which will be put to practical use in the future. Moreover, we evaluated the effects of deviations of the electrical constants of the phantoms from those of biological tissues on the SAR and antenna characteristics quantitatively. It was shown that it is possible to investigate antenna characteristics using a phantom with the same composition ratios in the range from 0.9 to 10 GHz. As for the SAR, the deviations of the phantom electrical constants from the target values become large at frequencies lower than 3 GHz, but the effects on the SAR is small in the range from 3 to 10 GHz. Therefore, the phantoms can be used mostly without problems. In addition, the phantoms can be used in even wider frequency ranges by adjusting the composition ratios to the target values in each frequency. In the future, we will work on improvement of the storage stability of the phantoms.

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Abbreviations

FDTD: Finite-Difference Time-Domain
SAR: Specific Absorption Rate
UWB: Ultra WideBand