Soft and Dry Phantom Modeling Material Using Silicone Rubber with Carbon Fiber

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***Abstract*— New phantom models that can simulate the effect of electromagnetic waves on human tissues have been developed. These phantom models can be designed to fit a wide range of complex permittivities by using two types of carbon fiber within a silicone rubber base. Tissues with low water content, such as fat and bone, and tissues with high water content, such as skin and muscle, can both be modeled using the phantom models discussed in this paper. When using conventional phantom model materials, care must be taken to prevent decomposition and dehydration during storage. The materials used for these new phantom models do not dry out and can be used repeatedly with reliable results.**

I. INTRODUCTION

IN the past few years, studying the effects of hazardous EM radiation on biological systems has become increasingly important [1], [2]. To study the effects of electromagnetic (EM) fields on biological systems, the development of phantom models has evolved. Phantom models are used to simulate EM wave distributions inside a human body. These models are also useful for the development of RF and microwave hyperthermia equipment used to estimate the specific absorption rate (SAR) in human tissue for the treatment of cancer [3]. In this application, the SAR of a material is measured as an absorption rate, in terms of power per unit mass in a heated medium.

Traditionally, phantom models have been widely used to simulate tissues with high water content [4], [5]. These compounds were generally constructed in one of two ways: the first consisted of a jelly agent, polyethylene powder, sodium chloride and water; and the second consisted of agar, sodium chloride and water. The disadvantage of constructing phantom models using these materials is that the models cannot be used repeatedly since they dry out and decompose over time. To avoid this, nonhydrated phantom models made of ceramic [6] were developed to simulate muscle tissue. However, these models required the use of a special adhesive made with ceramic powder whose function was to remove any air gaps between adjacent pieces of ceramic. Unfortunately, the adhesive was difficult to use and the hard ceramic material could not be cut or reshaped easily.

In order to overcome the shortcomings of traditional phantom models, flexible nonhydrated phantom models have been developed. These new models are made of materials composed of silicone rubber and carbon fiber compounds. The complex permittivity of the phantom models developed using these materials can be controlled by adjusting the composition ratio to simulate high water and low water content of various human tissues.

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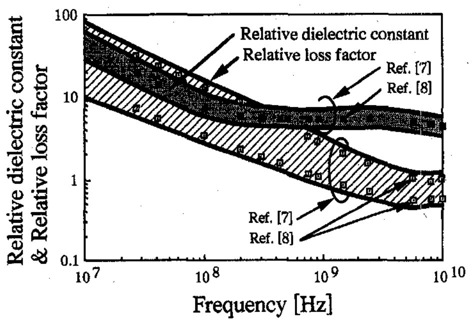

Fig. 1. The relative dielectric constant and the loss factor versus frequency of the tissues of low water content by referring [7] and [8].

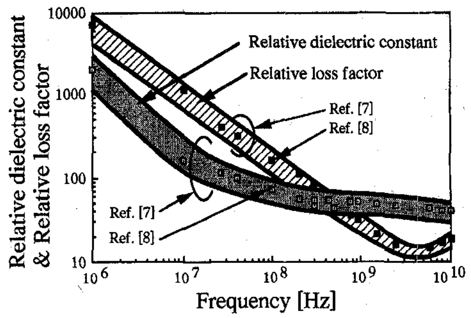

Fig. 2. The relative dielectric constant and the loss factor versus frequency of the tissues of high water content by referring [7] and [8].

II. PHANTOM MODELS

The dielectric properties of biological substances is shown in [7] and [8]. Human tissues are categorized as one of two types depending on their water content. Skin and muscle have a high water content, where as fat and bone have a lower water content. As a result, each tissue has a different relative dielectric constant and loss factor as shown in Figs. 1 and 2. The upper and the lower bands represent the maximum and the minimum values tabulated from [7]. The open and closed squares represent the raw data points given for low and high water content as specified in [8]. Figs. 1 and 2 indicate that the permittivity of tissues with a high water content is about ten times greater than that of tissues with a low water content. This

TABLE I
THE CHARACTERISTICS OF THE CARBON FIBERS

fiber type	length	diameter	DC resistance
A	3.0 mm	9 μm	1.5×10^{-3} Ω·cm
B	0.7 mm	13 μm	1.0×10^{-6} Ω·cm

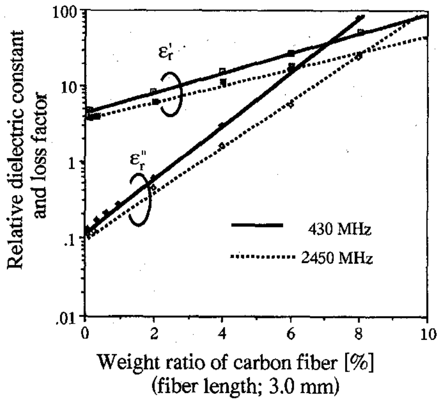

Fig. 3. Complex permittivity versus weight ratio of carbon fiber type A in silicone rubber.

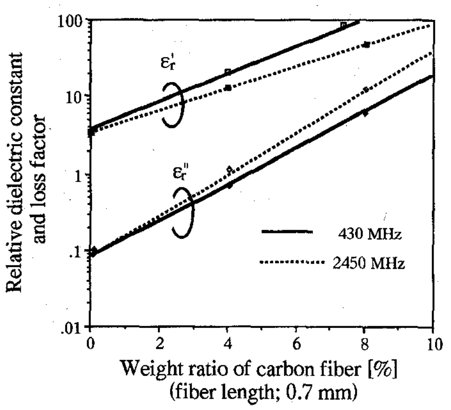

Fig. 4. Complex permittivity versus weight ratio of carbon fiber type B in silicone rubber.

characteristic makes it difficult to develop phantom models for various human tissues that are to be tested at many different frequencies.

To realize a wide range of permittivities in a phantom modeling material, this paper examines the use of two types of carbon fiber material dispersed in a silicone rubber base. For simplicity, the characteristics of the carbon fibers are referred to as type A and type B, as shown in Table I.

To make this type of phantom model, raw silicone rubber is first mixed with two types of carbon fiber and a curing agent. Physical samples are then shaped after degassing. The complex permittivity of the sample is then measured by using the reflection method [9], [10]. This process consists of inserting a troidal-shaped sample into the open end of the coaxial probe. The reflection coefficient of the sample is then measured using a network analyzer, such as the HP8752A. To check the

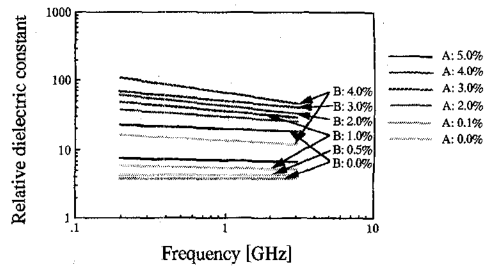

Fig. 5. Relative dielectric constant of the compounded material as a function of the frequency with the weight ratio of the carbon fiber of type A and B taken as the parameter.

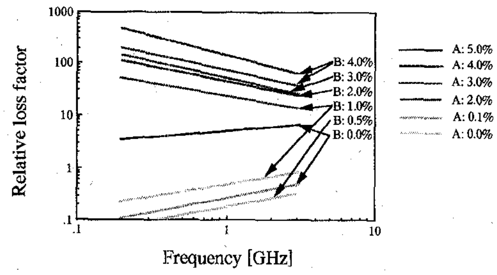

Fig. 6. Relative loss factor of the compounded material as a function of the frequency with the weight ratio of the carbon fiber of type A and B taken as the parameter.

accuracy of the reflection method, the HP85070A dielectric probe was used. Both results agreed within an error of ±5%.

Figs. 3 and 4 show the dielectric constant and the loss factor as a function of the weight ratio of the carbon fiber for both the type A and type B compounds at 430 MHz and 2450 MHz. From this data, it is seen that the relative dielectric constant and loss factor increase linearly as a function of carbon fiber weight ratio for both carbon fiber types. Noting this, it is reasoned that a wide range of dielectric constants and loss factors can be obtained by choosing the proper weight ratios for type A and type B in a silicone rubber base.

III. EXPERIMENTAL RESULTS

Figs. 5 and 6 show measured relative dielectric constants and loss factors of the compound materials versus frequency, for various weight ratios. The temperature of the medium was 25.0°C. The experimental results demonstrated that materials with a wide range of complex dielectric constants could be realized by controlling the weight ratios of the two carbon fiber materials.

Figs. 7 and 8 show the loss tangents as a function of relative dielectric constant, at various weight ratios of carbon fiber at 430 MHz and 2450 MHz. From Figs. 5–8, it is derived that a composite material containing 0.5% carbon fiber type A and 0.5% carbon fiber type B by weight is optimum for modeling tissues with a low water content. Using this information, a dry phantom model was constructed for the low water content case. The measured and experimental results of the relative dielectric constant and loss factor are shown in Fig. 9.

Similarly, a composite containing 3.0% carbon fiber type A and 2.0% carbon fiber type B may be ideal to simulate tissues

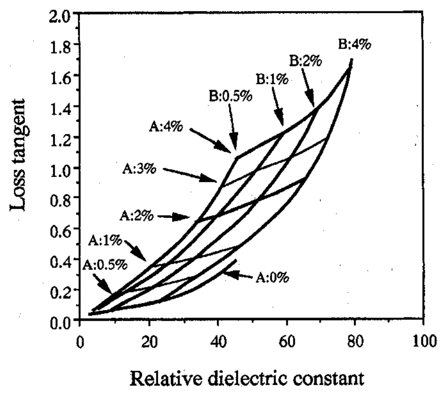

Fig. 7. Loss tangent versus relative dielectric constant of dry phantom model as a parameter of weight ratio of carbon fiber (430 MHz, 25°C).

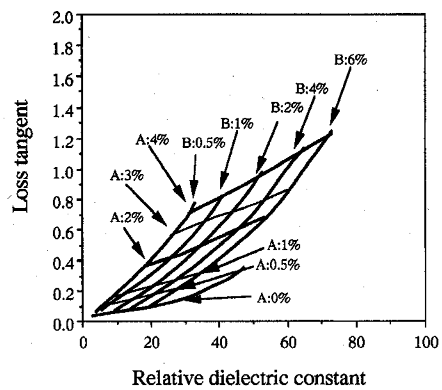

Fig. 8. Losstangent versus relative dielectric constant of dry phantom model as a parameter of weight ratio of carbon fiber (2450 MHz, 25°C).

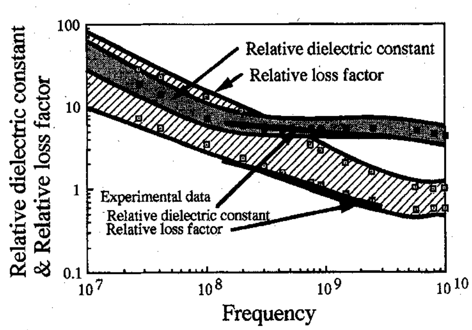

Fig. 9. Experimental value of the relative dielectric constant and the loss factor versus frequency of the dry phantom model with the reported value (model of low water content).

with a high water content. The measured relative dielectric constant and loss factor for this case is shown in Fig. 10.

Using the dry phantom models, the specific absorption rate (SAR) was obtained and compared to a simulated value. The simulated SAR distribution was calculated using the finite difference time domain (FDTD) method [11]–[13] for a TE_{10} waveguide mode at 430 MHz. The test setup for measuring the SAR distribution is shown in Fig. 11. The waveguide applicator is filled with water, with a relative dielectric constant of 78 at 430 MHz. The size of the rectangular waveguide is 100×50 mm^2. To ensure that only the TE_{10} mode is generated

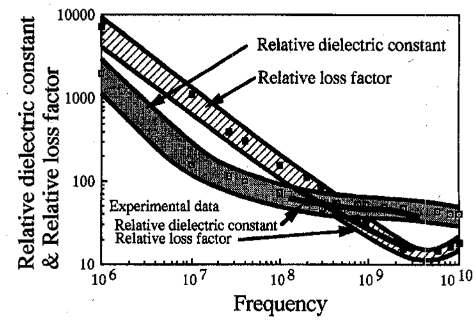

Fig. 10. Experimental value of the relative dielectric constant and the loss factor versus frequency of the dry phantom model with the reported value (model of high water content).

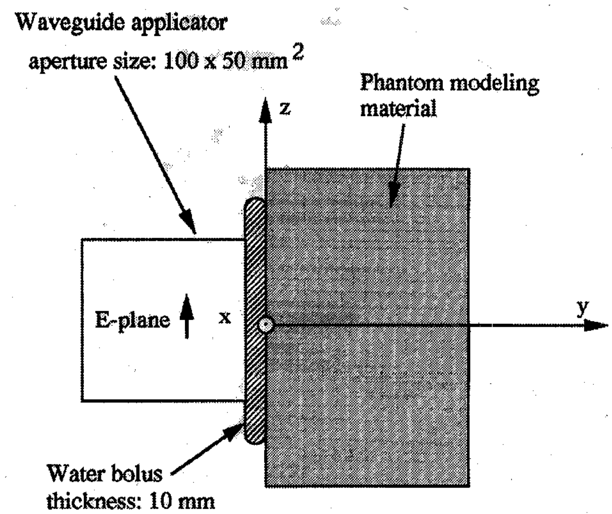

Fig. 11. A coordinate system used to calculated SAR distribution.

at this frequency, a mode-reject filter is inserted in the aperture of the applicator [14]. The applicator is then attached to a 10 mm-thick water bolus. The purpose of the water bolus between the aperture and the model is to provide impedance matching. Additionally the extra length of the bolus allows us to neglect any evanescent moding that may occur in the model near the aperture phantom model interface. Fig. 12 shows the experimental and simulated results of the SAR distribution for the dry phantom model with a high water content. Fig. 13 shows the results for a bilayered tissue model consisting of fat and muscle. In this case, the SAR distribution is obtained using a thermograph camera after 5 minutes of heating at 430 MHz. The results shown in Figs. 12 and 13 show a close agreement between simulated and experimental results. The slight discrepancy in SAR values is probably due to a small amount of heat conduction in the dry phantom model.

IV. Conclusion

In this paper, the development and application of dry state phantom models using new compounds has been shown. These new compounds consist of silicone rubber and two types of carbon fiber. By controlling the weight ratios of the carbon fiber materials for a given sample, the electromagnetic response of various human tissues can be accurately simulated.

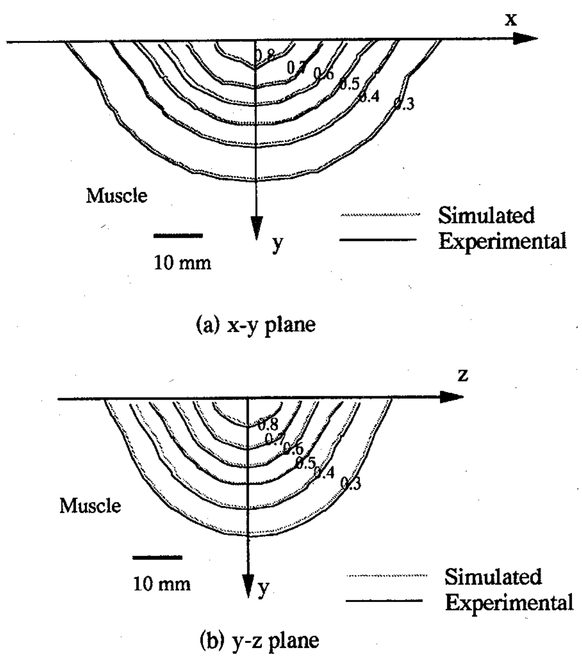

Fig. 12. SAR distribution inside the model of tissues of high water content.

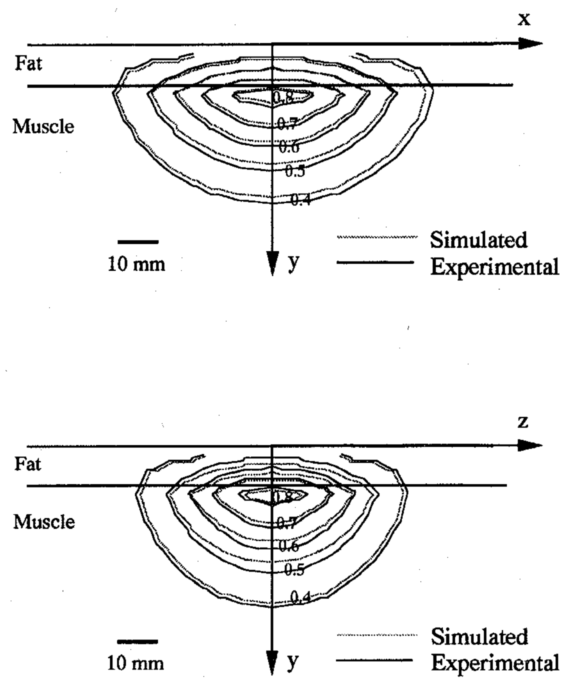

Fig. 13. SAR distribution inside the bilayered tissue model. (Tissue model of low water content of 10 mm thickness is set in between the applicator and the tissue model of high water content.)

In addition, this type of phantom model can be used to accurately simulate any arbitrary tissue or group of tissues by selecting the proper weight ratios of the carbon fibers. By using silicone rubber as the base material of the dry phantom model, it is easy to form or change the shape of the model by simply cutting the material. Also, it is easy to determine the SAR distribution at an arbitrary position inside the model by cutting and then heating the sample. Since the material is soft, any gap between the sample and probe can be removed by slightly reshaping the sample. Also in the case of inhomogeneous materials, this type of phantom model is better suited to easily remove any air gap between numerous material interfaces. Since the model contains no water, it is very stable over time and requires no special care or maintenance.

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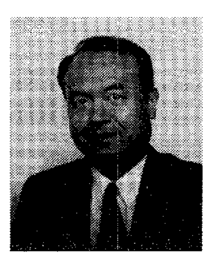

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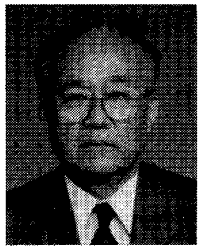

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