Dry Phantom Composed of Ceramics and Its Application to SAR Estimation

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***Abstract*— A dry phantom material having the same electric properties in the UHF band as biological tissues is developed. The new composite material is composed of microwave ceramic powder, graphite powder, and bonding resin. This material overcomes the various problems inherent in the conventional jelly phantom material, such as dehydration and deterioration due to invasion of bacteria or mold. This innovation of the phantom material makes it possible to accomplish highly reliable and precise estimation of specific absorption rate (SAR) in biological systems. Dry phantom models of spheres and human heads are fabricated. Experiments are performed to estimate the SAR of human heads exposed to microwave sources by using the thermography method. Since this material removes the necessity of the phantom shell indispensable with the conventional jelly material, the surface SAR distribution can be readily obtained.**

I. Introduction

One of the most important problems in studying the effects of electromagnetic fields on biological systems is quantifying the specific absorption rate (SAR) of the exposed system. Although numerous theoretical methods have been developed for dosimetry, it is essential to verify the theoretical data experimentally. Furthermore, experimental methods afford the viable means for estimating the SAR under complex exposure environments that exceed the capabilities of existing theoretical methods.

Among the experimental SAR estimation methods using phantom models, the thermographic method offers a very useful and practical means to provide the SAR distribution on any arbitrary section of a phantom model [1]. With respect to the phantom material, both the relative permittivity (ε) and the loss tangent (τ) have to be fairly high, for example, typically $\varepsilon = 50$ and $\tau = 0.5$ at 1 GHz, to simulate biological tissues of high water content, such as muscles and the brain [2]. The complex permittivity of these high water content tissues can be closely simulated by a moist jelly material consisting of saline water, polyethylene powder, and a jelling agent [1]. While this jelly material has been widely used so far [1], [3], some intrinsic problems exist. First, a rigid shell is necessary to contain and shape the material, and hence it is difficult to estimate directly the SAR distribution on the surface of the phantom. Next, dehydration and deterioration due to invasion of bacteria or mold often make it difficult to maintain the integrity of the jelly. The jelly is not easy to handle. A solid material has been long desired to replace the jelly.

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This paper presents a newly-developed dry phantom material which overcomes the above-mentioned problems. Homogeneous phantom models of spheres and a human head are fabricated to estimate the SAR distribution in human heads irradiated by nearby UHF sources with the thermographic method. The experimentally estimated SAR distribution in a sphere exposed to half-wavelength dipole irradiation is in good accordance with the analytically calculated distribution. This validates the estimation method. The capability of direct estimation of surface SAR distribution is demonstrated using these phantoms. Hot spot generating condition in homogeneous lossy spheres is studied in the Appendix. Kritikos and Schwan [4] obtained the hot spot generating condition by plane-wave irradiation; the condition by near-source irradiation is newly investigated in this paper. For both plane-wave and near-source irradiation no hot spot is produced in the life-size head equivalent sphere at any frequency and thus maximum SAR always occurs on the surface. The direct surface SAR measurement capability is therefore very useful. Some SAR patterns and peak SAR estimations in the sphere- and head-phantoms for nearby UHF source radiation are reported. These estimations have been difficult to attain with the theoretical methods. A safety implication of these SAR estimations is also presented.

II. Dry Phantom Material

The recent progress in microwave ceramic material has enabled relative permittivity (ε) to be controlled over the range from less than ten to over 10 000. However, the loss tangent (τ) of ceramics is generally very small. To solve this difficulty, a composite material composed of ceramic powder was adopted. Since it was presumed that the addition of a conductive material would increase the loss tangent, some preliminary studies were conducted on a composite material composed of ceramic powder, graphite powder, and bonding resin. The ceramic is one of the family of $(Ba,Ca)(Ti,Sn)O_3$ and the typical grain is a few tens of μm in diameter; the graphite powder has a similar size; and the bonding resin and adhesives are polyfluorine resins. The choice of graphite is one of the clues in this technology: graphite fiber chips do not yield consistent results and the shape (sphere) and size of graphite powder are experimentally selected. The complex permittivity was measured using the coaxial-line S-parameter method [5]. The pipe-shape specimens are carved out and their inside and

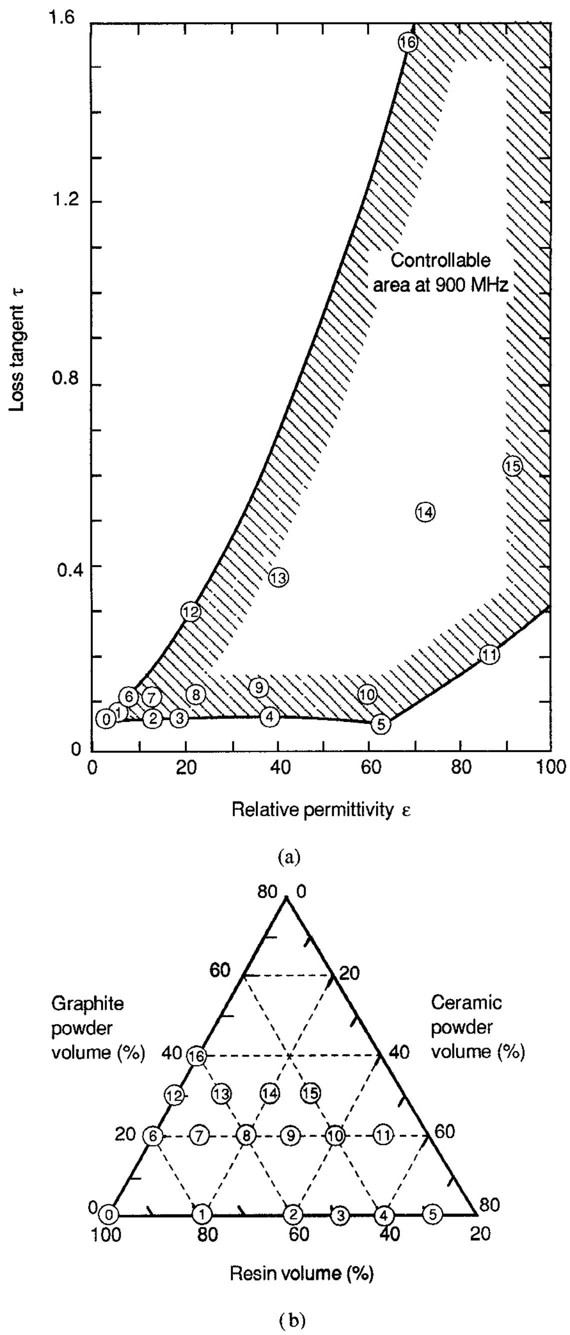


Fig. 1. (a) Relative permittivity and loss tangent at 900 MHz of composite phantom material. Circled figures represent measured specimens. (b) Constituent ratios of the specimens presented in (a).

outside walls are silver-pasted to ensure the electric contact to the coaxial air line.

Measured results show that a wide range of ε and τ values can be satisfactorily synthesized, as shown in Fig. 1, by changing the constituent ratio. In Fig. 1(a), the hatched area depicts the achievable permittivity at 900 MHz. At this frequency the relative permittivity and the tangent loss of high water content biological tissues are typically 50 and 0.5. Thus this composite can be readily used as a phantom material in electromagnetic exposure simulation experiments.

In the thermographic method, the observed temperature rise due to RF irradiation is ideally the product of the specific heat and the SAR, as explained in Section IV. Considering the dynamic range limitation of the available thermographic systems, the specific heat of the phantom material should be small because this can substantially reduce the output power required of the radiation source. The specific heat of this new material is 0.8×10^3 J/kg · K, which is acceptably small.

III. Phantom Models

Homogeneous phantom models of spheres and of a human head shape were fabricated using the new material. The main purpose of these models was to study SAR distribution in a human head irradiated by near UHF sources, such as portable radios.

The fabricating process is as follows: First, raw materials were mixed and kneaded into small pellets. Next, these pellets were injection-molded into planar sectors 6-mm thick. A number of sectors were stacked and bonded altogether using epoxy adhesives mixed with ceramic powder. Finally, the stack was carved into the desired shape by a numerically-controlled machine. This process is essential because injection-molding of a large mass often generates cracks due to heat stress. It was experimentally confirmed that the molding process does not cause anisotropy in the dielectric properties of the material, and that stacking only slightly affects the microwave properties of the models.

Fig. 2 shows the fabricated phantom models. They are (a) a 20 cm diameter sphere which approximates a human head and (b) a life-size human head shape model. Some smaller samples were also manufactured. These models can be split into mutually-orthogonal sections in order to observe the internal SAR distribution on the sections as well as on the surface.

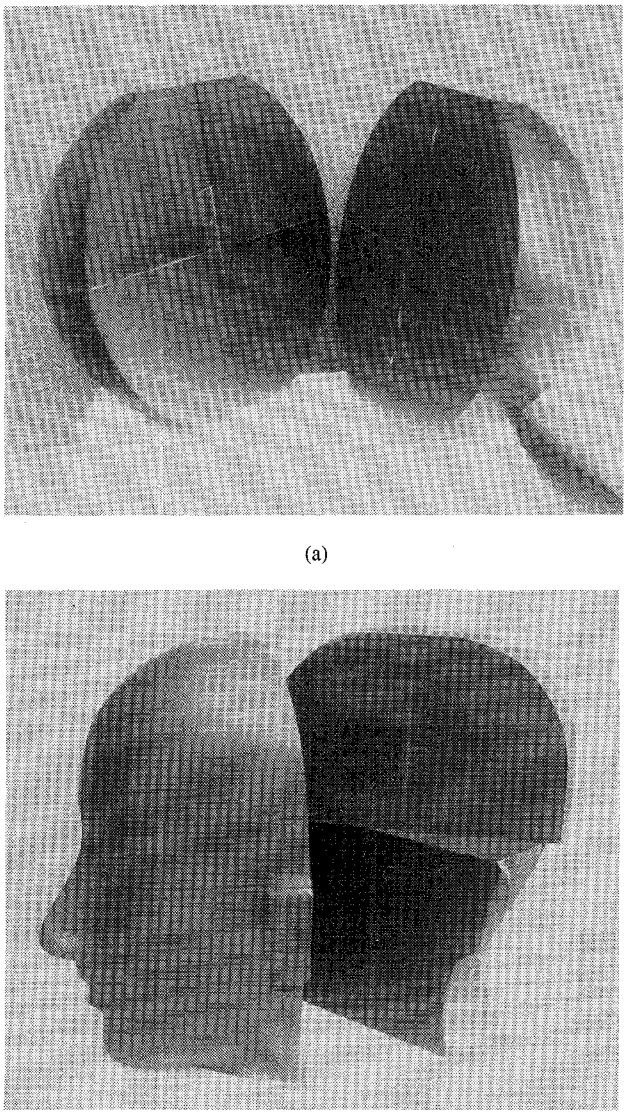
IV. SAR Estimation Experiments

A. Thermographic Method and Its Validation

Thermographic experiments were carried out using the dry phantom models, to estimate the SAR distribution in human heads. The estimation procedure is as follows: First, a phantom with a uniform temperature placed in a radio anechoic chamber was exposed to UHF radio waves radiated by a nearby source for 15 to 180 seconds. The exposure duration is determined to yield a temperature rise of at least 1 K. After the exposure period, the phantom was swiftly placed in front of a thermography camera head, and a thermographic image was immediately taken to map the temperature rise profile on a section or surface of the phantom. If heat diffusion is negligibly small during this procedure, the SAR at an arbitrary point is directly given by

$$\mathrm{SAR} = cT/t \ \mathrm{W/kg} \tag{1}$$

where c (J/kg·K) is the specific heat of the phantom material, T (K) is the temperature rise at the point, and t (second) is the exposure duration. Hence the temperature rise profile is proportional to the SAR distribution on the above assumption. The experimental setup is shown in Fig. 3.



(a) (b)

Fig. 2. Human head phantom models developed. (a) Sphere (20 cm diameter) and (b) life-size human head model.

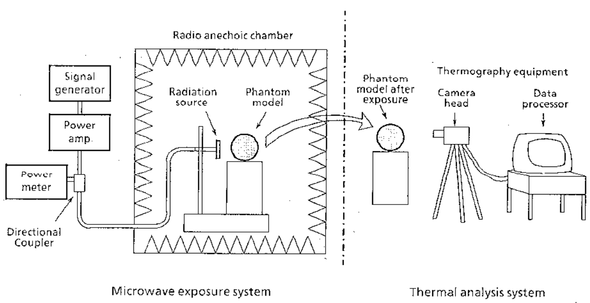
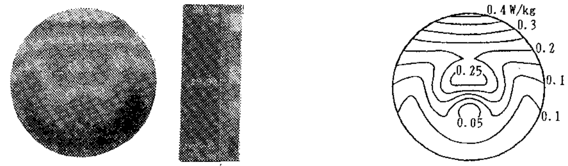


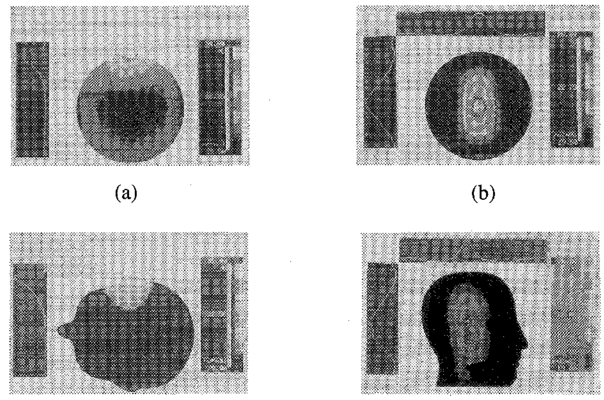
Fig. 3. Experimental setup for SAR estimation.

This procedure was initially applied to a small (10-cm ϕ) spherical phantom to validate the estimation method of SAR distribution. The smaller sphere gives more complicated SAR pattern and thus is more suitable for comparison between experimental and calculated data than a 20-cm ϕ sphere. The 10-cm ϕ spherical phantom was irradiated by a 900-MHz half-wavelength dipole installed at a distance of 10 cm from the phantom. The thermographic image on the H plane is shown in Fig. 4(a). An analytical method [6] yielded an SAR distribution on the H plane given the same exposure parameters, as shown in Fig. 4(b). These independently-derived distributions correspond with each other in every detail; it can therefore be stated this method is valid.



(a) (b)

Fig. 4. SAR distribution on H plane of 10-cm ϕ spherical phantom. (a) Experimentally-obtained thermographic image and (b) analytically derived contour map.



(a) (b) (c) (d)

Fig. 5. Thermographic images of phantom models exposed to 900-MHz half-wavelength dipole irradiation. (a) H plane and (b) surface of 20-cm ϕ sphere. (c) H plane (horizontal section) and (d) surface of real-size human head model.

B. Life-Size Human Head and Its Equivalent Sphere Phantom Experiment

The SAR of the 20-cm ϕ sphere and the human head model were then measured using irradiation sources of a half-wavelength dipole and a portable radio model equipped with a quarter-wavelength whip antenna at 900 MHz. Maximum antenna output power available in our facility was about 200 W. The measured thermographic images are shown Fig. 5. The surface distributions such as Fig. 5(b) and (d) are newly available because of the dry material. The oval isotherms show the difference of E- and H-plane SAR patterns. Maximum SAR is always located at the front surface point nearest to the source antenna.

Kritikos and Schwan [4] showed a radius-frequency diagram to describe the generation of hot spots inside lossy spheres by plane-wave irradiation. They suggest that no internal hot spot is generated in a 20-cm ϕ sphere at any frequency. The analytical method given in [6] leads to a similar result for hot-spot generation by half-wavelength dipole near-field irradiation (see the Appendix), and no hot spot is generated in

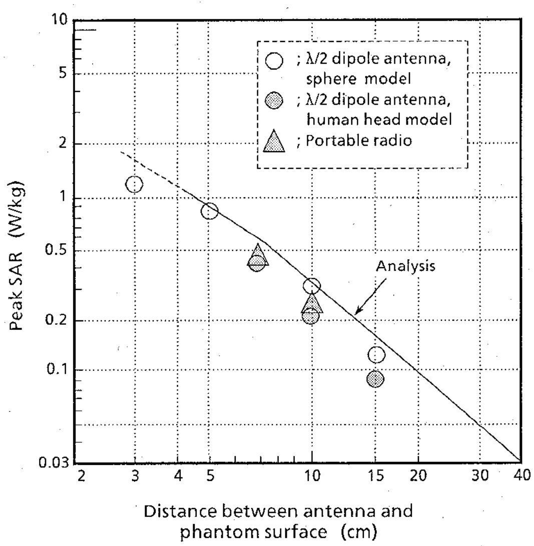


Fig. 6. SAR estimation results at 900 MHz with thermography method. Antenna input power is normalized to 1 W.

a 20-cm ϕ sphere. Therefore, maximum SAR always occurs on the top surface of a human-head sized sphere irradiated by plane-waves or near-field radiation so that the direct surface measurement capability of these dry phantoms is very useful.

C. Antenna-Phantom Distance Dependence of SAR and Its Safety Implication

From these and other thermographic measurements, peak SAR's of the head phantom models were derived for several distances as shown in Fig. 6, where the antenna input power is normalized to 1 W. In this figure the calculated SAR variation for 20-cm ϕ spherical models [6] is also plotted and agrees well with the experimental data.

From a radiofrequency radiation safety viewpoint, one important fact is indicated by this figure. As shown in Fig. 6, if the antenna-phantom distance is 5 cm (this is a particularly close distance), the peak SAR is nearly 1 W/kg for the normalized antenna input power. The peak SAR caused by a 7-W portable radio, therefore, is inferred to be less than 8 W/kg at 900 MHz. This SAR of 8 W/kg matches the safety guide value in ANSI C 95. 1-1982 [7] and other guidelines of radiofrequency radiation safety. Therefore, the exclusion of low power radiation sources from these guidelines is reasonable. Similar estimation results have been published [8].

V. Conclusion

A dry phantom material to simulate high water content biological tissues has been presented. The material is a combination of microwave ceramic powder, graphite powder and bonding resin. Human head phantoms were fabricated to estimate SAR's of human heads exposed to radio waves from nearby UHF sources. Surface SAR distributions as well as precise SAR estimations are obtained using the developed phantoms. The electrical and physical properties of the new material are very stable. These phantoms, therefore, are very useful not only for reliable SAR estimation but also for other research areas, such as the development of microwave hyperthermia instruments and performance evaluation of antennas mounted close to the human body.

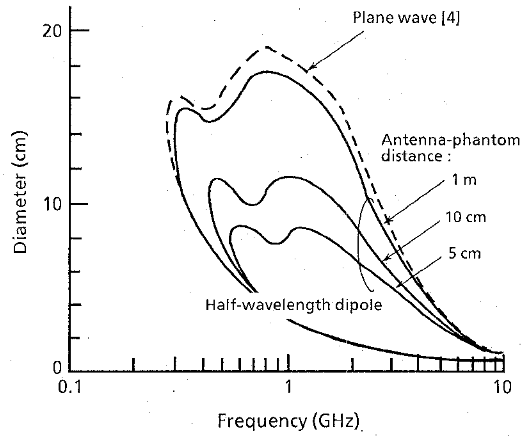


Fig. 7. Hot spot generating condition in a lossy sphere by plane-wave and half-wavelength dipole irradiation. Combination of diameter and frequency inside the curves generates hot spot.

VI. Appendix

SAR distributions within biological systems and phantom models exposed to electromagnetic fields have been studied in numerous contributions. Kritikos and Schwan [4] first proposed the hot-spot generating condition for homogeneous lossy spheres by plane-wave irradiation on a diameter-frequency diagram. This is shown in Fig. 7 by a broken line. A combination of a frequency and a diameter in the region surrounded by the broken line yields a hot spot inside the sphere. Outside the region no hot spot is produced and thus maximum SAR occurs on the surface of the sphere irradiated with a plane wave.

On the other hand, the hot spot generating condition for near-source irradiation has not been examined. Amemiya and Uebayashi [6] studied an analytical method to determine SAR distribution in a lossy sphere with dipole irradiation. They derived the electric and magnetic Herz vectors in a lossy sphere generated by a half-wavelength dipole, and the electric field inside the sphere thereby. The SAR can be readily obtained. With this method the SAR distribution in lossy spheres is calculated, assuming the same dielectric dispersion as Kritikos and Schwan [4]. The hot spot generating condition by half-wavelength dipole irradiation is then obtained by a numerical searching technique. The results are shown in Fig. 7 by solid lines for various antenna-phantom distances. The regions surrounded by the solid lines also yield hot spots.

The hot spot generating conditions depicted by these regions suggest that no hot spot is produced in a human-head size 20-cm ϕ sphere, and hence maximum SAR always occurs on the surface.

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