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NUMERICAL CALCULATION OF TEMPERATURE DISTRIBUTION AROUND A COAXIAL-SLOT ANTENNA AIMING AT TREATMENT OF BRAIN TUMOR

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1. Introduction

In recent years, various types of medical applications of microwaves have widely been investigated and reported [1]. In particular, minimally invasive microwave thermal therapies using thin coaxial antennas are of a great interest. They are interstitial microwave hyperthermia [2] and microwave coagulation therapy (MCT) [3] for medical treatment of cancer, cardiac catheter ablation for ventricular arrhythmia treatment [4], thermal treatment of BPH (Benign Prostatic Hypertrophy) [5], etc. Up to now, the authors have been studying such thin coaxial antennas for the interstitial microwave hyperthermia.

Hyperthermia is one of the modalities for cancer treatment, utilizing the difference of thermal sensitivity between tumor and normal tissue. In this treatment, the tumor is heated up to the therapeutic temperature between 42 and 45 °C without overheating the surrounding normal tissues. We can enhance the treatment effect of other cancer treatments such as radiotherapy and chemotherapy by using them together with the hyperthermia.

There are a few methods for heating the cancer cells inside the body. Especially, the authors have been studying the coaxial-slot antenna [6], which is one of the thin microwave antennas, for the interstitial microwave hyperthermia. As a result of these investigations, some cases of actual treatments could be realized by use of our developed antenna and the effectiveness of the treatments could be confirmed.

In this paper, we describe the numerical calculation of the temperature distribution around the coaxial-slot antenna for the treatment of brain tumor. It is considered that the interstitial hyperthermia is effective for the treatment of brain tumor, because it is difficult to treat such a tumor by surgical operation, radiotherapy, etc. Basically, the technique of the interstitial hyperthermia for brain tumor is the same as the treatment for the other portion of the human body. However, the temperature control during the treatment is more important than the other cases. Therefore, in this paper, the temperature distribution around the coaxial-slot antenna placed in a brain tumor is calculated by use of realistic human head model.

2. Structure of the antenna

Figure 1 shows the basic structure of the coaxial-slot antenna. Here, the operating frequency is 2.45 GHz, which is one of the ISM (Industrial, Scientific, and Medical) frequencies. The coaxial-slot antenna is composed of a thin semi-rigid coaxial cable. Some ring slots are cut on the outer conductor of a thin coaxial cable and the tip of the cable is short-circuited. Here, L_{ts} is the length from the tip to the center of the slot close to the feeding point, and L_{ls} is the length from the tip to the center of the slot close to the tip. We confirmed the possibility of generating a localized heating pattern by employing two slots, especially when L_{ts} and L_{ls} are set to 20 mm and 10 mm respectively. In addition, we also confirmed that the heating pattern of this coaxial-slot antenna is independent of the antenna insertion depth [7].

3. Numerical calculation -procedure and model-

Figure 2 shows the procedure of calculation. In the calculation, first, we analyze the electric field around the antenna by the FDTD method and calculate the SAR (Specific Absorption Rate) from the following equation:

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$$\mathrm{SAR} = \frac{\sigma}{\rho} E^2 \qquad \text{[W/kg]} \tag{1}$$

where σ is the conductivity of the tissue [S/m], ρ is the density of the tissue [kg/m^3], and E is the electric field (rms) [V/m]. The SAR takes a value proportional to the square of the electric field generated around the antennas and is equivalent to the heating source created by the electric field in the tissue. The SAR distribution is one of the most important characteristics of antennas for heating.

Next, we calculate the temperature distribution around the antenna. In order to obtain the temperature distribution in the tissue, we numerically analyze the bioheat transfer equation [8] including the obtained SAR values using the FDM (Finite Difference Method). The bioheat transfer equation is given by

$$\rho c \frac{\partial T}{\partial t} = \kappa \nabla^2 T - \rho \rho_b c_b F \left(T - T_b\right) + \rho \cdot \mathrm{SAR} \tag{2}$$

where T is the temperature [°C], t is the time [s], ρ is the density [kg/m^3], c is the specific heat [J/kg·K], κ is the thermal conductivity [W/m·K], ρ_b is the density of the blood [kg/m^3], c_b is the specific heat of the blood [J/kg·K], T_b is the temperature of the blood [°C], and F is the blood flow rate [m^3/kg·s].

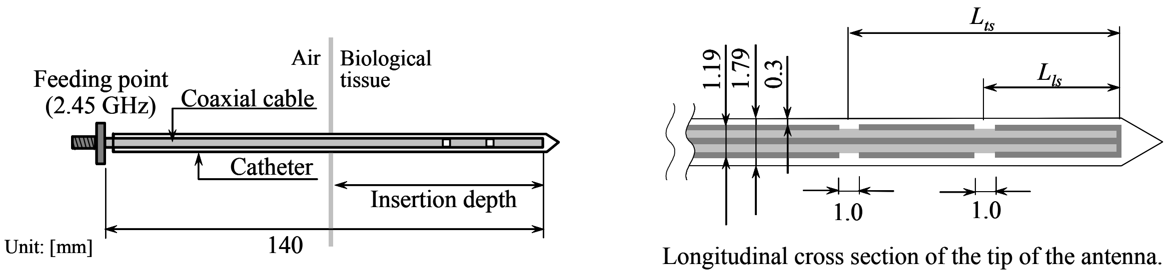

Fig. 1 Basic structure of the coaxial-slot antenna.

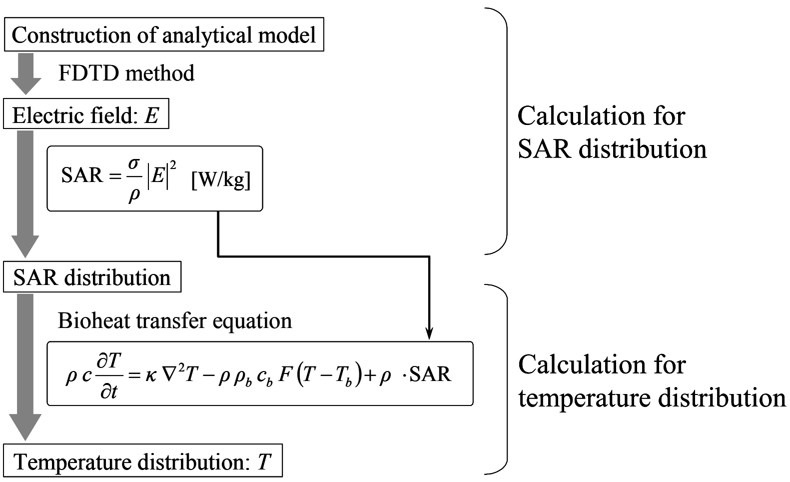

Fig. 2 Procedure of calculation.

Figure 3 shows the calculation model based on the realistic human head model developed at Brooks Air Force Base Laboratories [9]. We embedded a tumorous region around the center of the brain and put the coaxial-slot antenna into this tumor. Then, at the calculation, we picked up a region close to the antenna. Moreover, in the calculation, we employed nonuniform grids and used small-size grids only for the antenna. In addition, at the temperature calculation, we used the same grids as the FDTD calculation and calculated only inside the biological tissue (the region $z \geq 20$ mm). Table 1 shows the physical properties of biological tissues for the calculation.

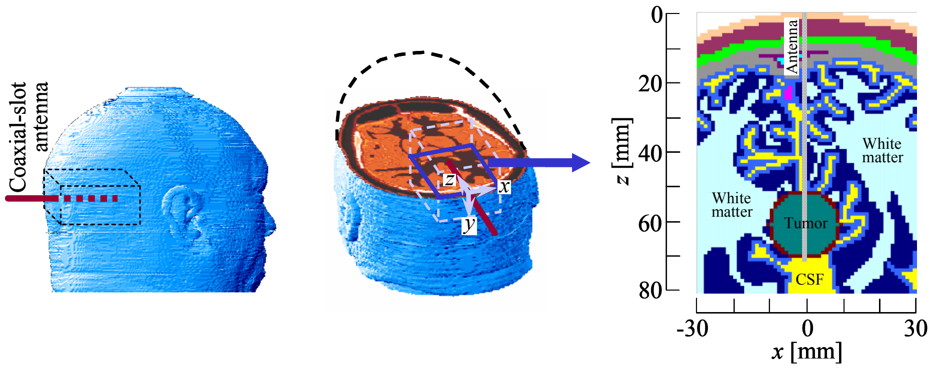

Fig. 3 Calculation model based on the realistic human head model.

4. Calculated results

Figure 4 shows the calculated SAR distribution around the coaxial-slot antenna. The observation plane of the distribution is x-z plane at $y=0$. If the coaxial-slot antenna is inserted into a uniform medium, we observe a relatively uniform and high SAR region only around the tip of the antenna. However, from Fig. 4, we can observe a complex SAR distribution especially at $x=10$ mm, $z=60$ mm because of non uniform electrical properties.

Table 1 Physical properties of biological tissues (e.g. [10]).

	Relative permittivity ε_r	Conductivity σ [S/m]	Density ρ [kg/m^3]	Specific heat c [J/kg·K]	Thermal conductivity κ [W/m·K]	Blood flow rate F [m^3/kg·s]
Tumor(center)	38.0	1.15	1,040	3,900	0.57	0.0
Tumor(periphery)	38.0	1.15	1,040	3,900	0.57	1.67×10^{-5}
Bone cancellous	18.6	0.81	1,920	1,300	0.44	4.20×10^{-7}
Bone marrow	5.3	0.10	1,040	3,960	0.51	4.20×10^{-7}
CSF	66.2	3.46	1,007	4,000	0.60	9.33×10^{-6}
Blood	58.3	2.54	1,058	3,840	0.50	-
Gray matter	48.9	1.80	1,038	3,680	0.57	9.33×10^{-6}
Skin	38.0	1.46	1,125	3,500	0.50	1.67×10^{-5}
Ligamants	43.1	1.68	1,220	3,500	0.60	8.30×10^{-6}
Bone cortical	11.4	0.39	1,990	1,300	0.44	4.20×10^{-7}
Cerebellum	44.8	2.10	1,038	4,200	0.58	9.33×10^{-6}
White matter	36.2	1.21	1,038	3,600	0.50	9.33×10^{-6}
Muscle	52.7	1.74	1,047	3,500	0.60	8.30×10^{-6}
Fat	5.28	0.10	916	2,300	0.22	5.00×10^{-7}

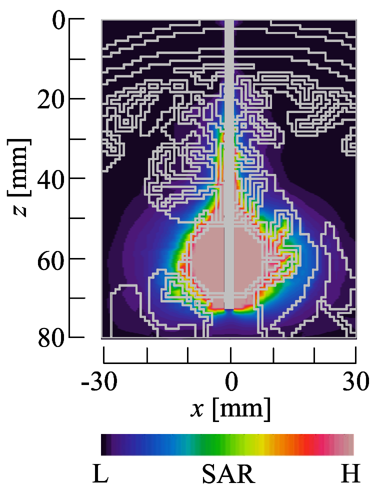

Fig. 4 Calculated SAR distribution.

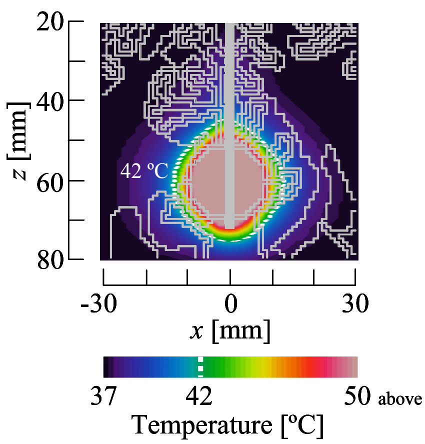

Fig. 5 Calculated temperature distribution.

Figure 5 shows the calculated temperature distribution in the same observation plane than the SAR distribution. Here, net input power of the antenna (= input power – reflection power), initial temperature, and heating time are set as 5.0 W, 37 °C, and 600 s, respectively. From Fig. 4, we can observe a uniform heating region around the tip of the antenna because of heat transfer, whereas the SAR distribution is not uniform. Moreover, we may say that the region of the tumor is almost covered by the therapeutic temperature (42 °C or more) under the above-mentioned conditions.

5. Conclusions

In this paper, we analyzed the heating patterns around the coaxial-slot antenna inserted into a brain tumor based on the realistic human head model. As a result, we could confirm the possibility of the treatment for the brain tumor by use of the coaxial-slot antenna. Moreover, if a system able to automatically create the calculation model as Fig. 3 can be developed from MRI data or X-ray CT (Computer Tomogram), it is very useful for treatment planning in the actual case.

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