Review

**Microwave antennas for intracavitary thermal therapy
- Numerical calculations and animal experiment -**

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Abstract

Up to now, the authors have been studying various thin antennas for microwave thermal therapies. Especially, a coaxial-slot antenna aiming at intracavitary heating for bile duct carcinoma has been developed. In this paper, first, heating performances of the antenna are estimated by use of numerical calculations. Moreover, temperature rise around the antenna, which is inserted into the bile duct, are measured using the living swine to find a cooling effect of blood flow. As a result of the investigations, the possibility of this treatment by use of the coaxial-slot antenna could be confirmed.

Key words: intracavitary microwave thermal therapy, bile duct carcinoma, coaxial-slot antenna, blood flow

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Introduction

Microwave is one of the effective energies for thermal treatment of cancer. There are a few methods for heating the cancer cells by the microwave energy. **Figure 1** classifies the heating scheme into four. The external heating system is employed for treatment of a tumor in shallow portion of the body. On the other hand, the internal heating system is suitable for treatment of deep-seated tumor in the body. In this paper, heating performances of antenna for intracavitary heating, which is one of the internal heating systems, for treatment of bile duct carcinoma is investigated. **Figure 2** shows the scheme of the treatment. In this treatment, an endoscope is first inserted into the duodenum and a long and flexible coaxial antenna is then inserted into the forceps channel of the endoscope, which is used to insert the tool for surgical treatment. Finally, the antenna is guided to the bile duct through the papilla of Vater, which is located in the duodenum, and is inserted into the bile duct.

Figure 3a shows the structure of the proposed coaxial-slot antenna for this treatment. The basic structure of the antenna is the same as in^(1,2) except that this antenna is long and flexible. The antenna is fabricated using a commercially

available flexible coaxial cable. We confirmed that the fabricated prototype antenna can be inserted into the forceps channel without any problems (**Fig. 3b**). In addition, operating frequency is 2.45 GHz.

In this paper, first, heating performances of the antenna are estimated by use of numerical calculations. Here, a high resolution numerical human model is employed to estimate the temperature rise under actual situation. Moreover, temperature rise around the antenna, which is inserted into the bile duct, are measured using the living swine to find a cooling effect of blood flow.

Numerical calculation

1. Procedure for numerical calculation

In the numerical calculation, first, we analyze the electric field around the antenna by the FDTD (Finite-Difference Time-Domain) method³⁾ and calculate the SAR (Specific Absorption Rate) from the following equation:

$$\text{SAR} = \frac{\sigma}{\rho} E^2 \quad [\text{W/kg}] \quad (1)$$

where σ is the conductivity of the tissue [S/m], ρ is the den-

Figure 1 Variations of microwave heating

Figure 2 Scheme of the treatment

Figure 3 Structure of the coaxial-slot antenna for treatment of bile duct carcinoma

Table 1 Parameters for FDTD calculations

Cell size [mm] (minimum)	$\Delta x, \Delta y$ Δz	0.05 1.0 (const.)
Cell size [mm] (maximum)	$\Delta x, \Delta y$ Δz	1.0 1.0 (const.)
Absorbing boundary condition		Mur (1st. order)

sity 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 antenna and is equivalent to the heating source created by the electric field in the tissue.

Table 1 shows the parameters for FDTD calculations.

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 equation⁴⁾ including the obtained SAR values using the FDM (Finite Difference Method). The bioheat transfer equation is given by

Figure 4 Calculation model

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

where T is the temperature [$^{\circ}\text{C}$], t is the time [s], ρ is the density of the tissue [kg/m^3], c is the specific heat of the tissue [$\text{J}/\text{kg}\cdot\text{K}$], κ is the thermal conductivity of the tissue [$\text{W}/\text{m}\cdot\text{K}$], ρ_b is the density of the blood [kg/m^3], c_b is the specific heat of the blood [$\text{J}/\text{kg}\cdot\text{K}$], T_b is the temperature of the blood [$^{\circ}\text{C}$], and F is the blood flow rate [$\text{m}^3/\text{kg}\cdot\text{s}$].

As shown in **Fig. 3a**, the coaxial-slot antenna for the treatment of bile duct carcinoma has a thin and long structure. Therefore, it is difficult to analyze the whole structure of the antenna. In this paper, numerical calculations will be performed only around the tip of the antenna.

2. Calculation model

Figure 4 shows the calculation model based on the realistic human model developed at Brooks Air Force Laboratories⁵⁾. In order to construct this model, a region including the bile duct is extracted. In **Fig. 4**, only the bile duct is indicated inside the calculated region though there are a few other or-

gans such as liver, stomach, duodenum, small intestine, etc. The physical properties of the biological tissues and detail procedure of calculations are same as⁶⁾. In addition, in **Fig. 4**, two observation planes are shown for consideration in the next Section. Here, the observation plane #1 is the xy plane at $z = 50$ mm (including the slot) and the observation plane #2 is the xz plane at $y = 0$. **Figure 5** shows the organs which are included in two observation planes.

3. Calculated temperature distribution

Figure 6 shows the calculated temperature distributions. Here, feeding pattern is “on-feeding: 2 s” and “off-feeding: 2 s” for prevent overheating. The output power of generator is 20.0 W (actual radiation power from the antenna is 4.7 W due to the cable loss). The observation plane is defined in **Fig. 4**. In this figure, the white dotted lines indicate 42°C , which is the lowest temperature for the hyperthermic treatment. These temperature distributions, for which the minimum size of heating region by the on-off feeding control is chosen, are the results at the steady state.

From the result, possibility of the thermal treatment

Figure 5 Organs in the observation planes

could be confirmed.

Animal experiment

1. Experimental procedure

Figure 7 shows the experimental system for the experiment. The swine used in the experiment was three-months-old and weighed 49.15 kg. In actual treatment, an antenna is inserted noninvasively with an endoscope. However, in the experiment, the detection of the papilla of Vater of the swine with the endoscope was difficult. Therefore, in the experiment, the antenna was inserted invasively at laparotomy.

First, the resupine swine was given a general anesthetic. In order to prevent the loss of body heat in the experiment, electric blanket was put at the swine back. Then, an incision was made in the duodenum, and an orifice was created on the mucosal side of the digestive tract to insert the antenna into the bile duct, and the antenna was inserted into the bile duct through the papilla of Vater. Microwave energy was measured by using a microwave power reflection meter. Moreover, the temperature of the outer and inner surface of the bile duct was

measured by using an optical fiber thermosensor and a thermocouple on the antenna, respectively.

2. Results

Figure 8 shows the result of the experiment. In **Fig. 8**, the temperatures measurement by using the optical fiber and the thermocouple are shown. Here, temperature at each time instant was measured by using the thermocouple during no microwave irradiation a period of 2 s so that electromagnetic interference could be avoided.

From the results, we may say that in and around the bile duct can be heated by the coaxial-slot antenna under the blood flow.

Conclusion

In this paper, the possibility of treatment for bile duct carcinoma by the intracavitary microwave thermal therapy using the coaxial-slot antenna was described. From the result, the possibility of the treatment could be found. Moreover, the animal experiment by use of swine was also introduced. From

Figure 6 Calculated temperature distributions

Figure 7 Experimental system

Figure 8 Temperature transition during microwave radiation

the results of these investigations, we may say that the coaxial-slot antenna can generate localized heating region for the intracavitary thermal therapy.

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