Original Contribution

Interstitial Microwave Hyperthermia Using Coaxial-slot Antennas — Clinical Trials Based on Numerical Calculations of Heating Patterns —

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Abstract : The interstitial microwave hyperthermia is a treatment applied to a localized tumor. In the treatment, some thin microwave antennas are inserted into the tumor. Up to now, the authors have been studying the coaxial-slot antenna as one of the thin microwave antennas to apply to such a treatment. This paper describes the effectiveness of the coaxial-slot antenna and the array applicators composed of two or four coaxial-slot antennas through clinical trials. As a result of treatments, we could confirm the effectiveness of the coaxial-slot antennas.

Key words : clinical trial, coaxial-slot antenna, heating pattern, interstitial microwave hyperthermia

Introduction

The interstitial microwave hyperthermia is applied to a localized tumor. In such a treatment, thin microwave antennas are inserted into the tumor and radiate the microwave energy directly into the target¹⁾²⁾. Therefore, the tumor can be effectively heated. Moreover, although this technique is an invasive technique, a large volume of heating region can be generated with a small number of antennas by choosing the appropriate array structure.

Until now, the authors have been studying the coaxial-slot antenna³⁾ which is one of the thin microwave antennas for the treatment. It is important to generate a localized heating region only around the tip of the antenna. We could find the structural parameters of the antenna, which generates a localized heating region only around the tip by improving the coaxial-slot antenna⁴⁾. In addition, we have already confirmed that the heating pattern of the improved antenna was independent of the antenna insertion depth⁵⁾.

This paper describes the effectiveness of the coaxial-slot antenna and the array applicators composed

of several coaxial-slot antennas through clinical trials. Firstly, heating pattern around the antenna and the array applicators composed of two or four coaxial-slot antennas is discussed by means of numerical calculations. Secondly, results of the clinical trials by use of the coaxial-slot antennas and the array applicators based on the above calculations are described.

Structure of the antenna

The basic structure of the coaxial-slot antenna is shown in Fig. 1. The antenna is composed of a thin semi-rigid coaxial cable with some ring slots cut on the outer conductor and a short-circuited tip. The antenna is inserted into a catheter made of PTFE (polytetrafluoroethylene) for hygiene. The operating frequency is 2.45 GHz, which is one of the ISM (Industrial, Scientific, and Medical) frequencies. From our previous investigations, it is clear that the coaxial-slot antenna with two slots, whose lengths L_{ts} and L_{ls} are equal to 20 mm and 10 mm, respectively, restricts the heating region only around the tip of the antenna⁴⁾ (see Table I). Therefore, we employ these structural parameters of the antenna in this paper.

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

Table I. Structural parameters of the coaxial-slot antenna with two slots.

d_b (diameter of the antenna) [mm]	1.19
d_c (external diameter of the catheter) [mm]	1.79
t_c (thickness of the catheter) [mm]	0.3
L_{ts} (length from the tip to the center of the slot close to the feeding point) [mm]	20.0
L_{ls} (length from the tip to the center of the slot close to the tip) [mm]	10.0
W_{sl} (width of the slot) [mm]	1.0
ϵ_{rc} (relative permittivity of the catheter)	2.6

Numerical calculations of heating pattern around the coaxial-slot antenna

Procedure for calculation

Figure 2 shows the flowchart of the numerical calculations to analyze the temperature distribution around the antenna inside the biological tissue. Firstly, we analyze the electric field around the antenna by the FDTD (Finite Difference Time Domain) method to calculate the SAR (Specific Absorption Rate) from the following equation :

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

Fig. 2. Flowchart of numerical calculation.

where σ is the conductivity of the tissue [S/m], ρ is the density of the tissue [kg/m³], and E is the electric field (rms) [V/m].

The SAR value is proportional to the square of the electric field generated around the antenna and shows the heat caused by the electric field in the tissue. Parameters used in the FDTD calculations are listed in Table II. In addition, a steady state analysis is performed by enforcing a sinusoidal electric field between the inner and outer conductors of the coaxial cable.

Secondly, we calculate the temperature distribution around the antenna. In order to obtain the temperature distribution in the biological tissue, we numerically analyze the bioheat transfer equation⁶⁾ including the obtained SAR values. The bioheat transfer equation is given by

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

where T is the temperature [°C], t is the time [s], ρ is the density [kg/m³], 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/m³], 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 [m³/kg·s].

In this study, we use the FDM (Finite Difference Method) to solve Eq. (2). In the calculations, we

Table II. Parameters for FDTD calculations.

Cell size [mm] (minimum)	$\Delta x, \Delta y$ Δz	0.1 1.0 (const.)
Cell size [mm] (maximum)	$\Delta x, \Delta y$ Δz	1.5 1.0 (const.)
Time step [ps]		0.235
Absorbing boundary condition		Mur (1st order)

Table III. Properties of biological tissues.

Electrical properties (Muscle, @2.45GHz)		
Relative permittivity ϵ_r	47.0	
Conductivity σ [S/m]	2.21	
Thermal properties	Muscle	Blood
Specific heat c [J/kg·K]	3,500	3,960
Thermal conductivity κ [W/m·K]	0.60	—
Density ρ [kg/m ³]	1,020	1,060
Blood flow (Muscle)		
Blood flow rate $F \times 10^{-6}$ [m ³ /kg·s]	8.30	

employed the same grid as those of the FDTD calculations and analyzed only inside the region of the tissue. In addition, the properties of biological tissues are listed in Table III⁽⁸⁾⁽⁹⁾. The details are given in paper 7).

Calculation models

In the clinical applications, the single antenna or the array applicators are chosen depending on the tumor size. Therefore, the temperature distributions around the single antenna and the array applicators are calculated. Figure 3 shows the calculation models of the single coaxial-slot antenna and the array applicators with their temperature observation planes discussed in the next section. The antenna spacing and the antenna insertion depth are 20 mm and 30 mm, respectively, considering the actual treatments.

Fig. 3. Calculation models for the coaxial-slot antenna and the array applicators. The position of the xy observation plane in the z direction is 20.0 mm which is same the position as the lower slot.

Results of calculations

Figures 4, 5 and 6 show the calculated temperature distributions in the observation planes, which are defined in Fig. 3, for the single antenna and the array applicators composed of two or four antennas, respectively. In the calculations, aiming at the actual treatment, the net input power of the antenna is 5.0 W for each element and the heating time is 600 s. In addition, the initial temperature of the biological tissue is 37°C.

From Fig. 4, in the case of the single antenna, a spherical heating region is generated around the tip of the antenna.

Fig. 4. Calculated temperature distributions of a single antenna.

Fig. 5. Calculated temperature distributions of a two-element array applicator.

The size of the effective heating region (the region higher than 42°C) in the z direction is almost the same as L_{ts} (length from the tip of the antenna to the upper slot).

In Fig. 5, we can observe the heating region not only around each antenna element but also at the center of two antenna elements ($x=y=0$ in xy plane). It is considered that the heating region around the center of two antenna elements in xy plane is generated by the enhancement of electric fields caused by each antenna element. The size of the effective heating region in the z direction is also almost the same as L_{ts} .

As shown in Fig. 6, when using the array applicator composed of four antenna elements, the heating region is generated inside the array applicator. Therefore, when the tumor is located inside this heating region, it can be completely heated. The size of the effective heating region in the z direction is also almost the same as L_{ts} .

In all cases, we cannot observe a hot spot around the surface of the tissue, which is placed at $z=0$ in the xz observation plane. It is considered that the injuries of the skin are well suppressed by use of the proposed antennas.

Clinical trials

Until now, four clinical trials were done by use of the coaxial-slot antenna or the array applicators. Figure 7 shows the treatment system and an example of the photograph during the treatment. The treatment system consists of a microwave generator (Alfresa pharma, AZM-520), a microwave power reflection meter (Rohde & Schwarz, NRT and NRT-Z44), a thermometer (Laxtron, M-790), and power dividers (order made). In all cases, we measured the temperature in and around the tumor up to four points. Figure 8 explains the positions of the antennas and the temperature probes in the xy plane where

Fig. 6. Calculated temperature distributions of a four-element array applicator.

Fig. 7. Equipments and example of treatment.

Fig. 8. Positions of the antennas and the temperature probes.

Only two important temperature measurement points are denoted.

Fig. 9. Transition of temperature during the treatment.

Table IV. Results of the treatments.

	Case 1	Case 2	Case 3	Case 4
Age	59	89	62	77
Sex	Female	Female	Male	Female
Primary	Gingiva	Soft palate	Esophagus	Lip
Pathology	Squamous cell carcinoma	Adenocarcinoma	Squamous cell carcinoma	Squamous cell carcinoma
Heated site	Supraclavicular node recurrence	Primary lesion	Supraclavicular node recurrence	Submandibular node recurrence
Number of antennas	1	1	2 or 4	1
Follow up time	7.3 months	1 year 7 months	1 year 7 months	4 months
Result	Dead of other metastasis No evidence of tumor growth in heated site	Alive without disease	Alive without disease	Alive No evidence of tumor growth

the size of the tumors is maximum. During the treatment, we especially focused on the temperature of reference point (probe no. 2, in Fig. 8), which is placed at the border of the tumor, and controlled the output power of the microwave generator by checking the temperature at this point. In order to heat the tumor sufficiently, the minimum temperature of the reference point was maintained to 42°C. Therefore, it is considered that the tumors were completely kept within the therapeutic temperature in all cases.

Figure 9 is the example of measured temperature transition during the treatment using the array applicator composed of four antennas (result of the single antenna and the array applicator composed of

two antennas could not be clearly recorded). The input power of each antenna element is several Watts (it is very difficult to measure the power exactly). In Fig. 9, temperatures “A” to “C” are more than 42°C in the steady state. From this result, we may say that the effective heating region is generated inside the array applicator. Moreover, this fact corroborates the calculated result shown in Fig. 6 (b), because the temperatures at “A” and “C” are placed at the border of the tumor.

If a precise calculation model, which is created from the tomograms of the patient, can be constructed, we will observe a good agreement between the calculated temperatures and the measured results¹⁰⁾.

Table IV summarizes the results of the treatments which are treated by the coaxial-slot antennas. As shown in table IV, we could observe the efficiency of the treatments whichever the heated site was. Moreover, any critical side effects including injury of skin etc. did not occur. Therefore, it is considered that we could effectively heat the tumor without any problems in all cases.

Conclusions

In this paper, the effectiveness of the coaxial-slot antenna and the array applicators composed of several coaxial-slot antennas were described. Firstly, the temperature distributions around the antennas were calculated. Secondly, four cases of clinical trials were done based on those calculated results. We could observe the effectiveness of the treatments in all cases. Therefore, it is concluded that the interstitial microwave hyperthermia by use of the coaxial-slot antennas was effective for those treatments.

Further study is needed to prove the effectiveness of the treatments from the clinical side with many other cases.

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同軸スロットアンテナによるマイクロ波組織内加温 — アンテナ周辺の加温分布計算に基づいた臨床応用 —

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要 旨：筆者らはこれまで、マイクロ波組織内加温法に用いる同軸スロットアンテナの研究開発を行ってきた。本論文では、1本の同軸スロットアンテナおよび2ないし4本の同軸スロットアンテナで構成したアレーアプリケーションが生体内において発生させる温度分布の数値シミュレーションを行った。さらに、これらの検討結果を基にして、これまでに4例の臨床応用を行い、本アンテナの有効性を確認した。