Postprint of Temperature Field Simulation for Tumor Microwave Hyperthermia

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Abstract

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Full Text

Preamble

A Numerical Study on Temperature Field Simulation for Microwave Thermal Therapy of Tumors

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Abstract

This paper establishes a mathematical model for tumor hyperthermia by simplifying the physical model of tumors and biological tissues and applying the bioheat transfer equation. Numerical simulation is employed to preview the hyperthermia process. By controlling the on/off switching of the probe, the temperature at the tumor center is maintained below 54°C while the temperature at the tumor edge varies between 43-45°C. The temperature distribution within the tumor is analyzed, and a temperature-control-based hyperthermia

protocol is proposed, providing a theoretical foundation for temperature control in clinical tumor hyperthermia.

Keywords: tumor; hyperthermia; temperature field; numerical simulation

0 Introduction

Hyperthermia has emerged as an effective tumor treatment modality in recent years. Characterized by its non-invasive or minimally invasive nature, hyperthermia produces minimal toxic side effects and causes relatively little patient discomfort. In addition to directly killing cancer cells, hyperthermia can serve as an adjunctive therapy for radiation and chemotherapy.

Long-term clinical practice has demonstrated that microwave hyperthermia offers superior advantages over other physical heating methods. Interstitial microwave thermal coagulation therapy represents the primary hyperthermia approach in Europe and America, yielding favorable therapeutic outcomes for tumors. In recent years, equipment for deep tumor heating using microwaves has been developed [1], enabling control over the specific absorption rate (SAR) distribution within the body to heat tumors at different depths. Zhu et al. [2] investigated prostate cancer hyperthermia, performing numerical simulations of the temperature field, thermal damage distribution, and blood perfusion rate changes during interstitial microwave hyperthermia, obtaining relatively accurate predictions of the hyperthermia temperature field. Cheng et al. [3] used SAR formulas derived from phantom experiments to simulate the microwave thermal field of a 915 MHz interstitial probe with finite element software ANSYS. Considering parameter changes caused by phantom deformation after microwave heating, they modified relevant simulation parameters to obtain temperature rise curves that closely matched experimental measurements. T. P. Ryan [4] employed a three-dimensional finite element model to predict the energy distribution of electric fields and thermal deposition near electrodes used in lumbar pain treatment, finding that simulation results were consistent with in vivo animal and human cadaver experiments.

Building upon these studies, this paper focuses on liver tumors, utilizing the finite element method to analyze the temperature field during hyperthermia and thereby proposing a temperature-control-based hyperthermia protocol.

1 Microwave Hyperthermia Model

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1.1 Physical Model of Microwave Hyperthermia

This study investigates liver tumor hyperthermia. In clinical practice, for liver tumors smaller than 2 cm in diameter (D $<$ 2 cm), a single heat source can complete treatment in one coagulation session. This paper assumes a spherical tumor with diameter D = 1.5 cm and employs a single probe for heating.

The microwave thermal coagulation tumor hyperthermia system model is shown in Figure 1 [Figure 1: see original paper] (cross-sectional view). A 915 MHz cylindrical microwave probe with radius $R_1 = 0.001$ m and effective microwave emission length H = 0.008 m is used. The computational domain is a sphere with radius $R_3 = 0.045$ m centered at the tumor center, with the surrounding area representing normal liver tissue. The probe' s effective emission tip is inserted at the tumor center, aligning the cylindrical axis with the tumor center.

1.2 Governing Equations and Boundary Conditions

This study employs the widely used Pennes bioheat transfer equation, expressed as:

$$\rho c \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda \nabla T) + W_b C_b (T_b - T) + q_m + q_r$$

where is the density of tissue or tumor (kg/m^3), c is the specific heat capacity (J/kg $\cdot$ K), τ is the computational time (s), T is the temperature (K), λ is the thermal conductivity (W/m $\cdot$ K), Wb is the blood perfusion rate (kg/m^3 $\cdot$ s), Cb is the blood specific heat capacity (J/kg $\cdot$ K), Tb is the blood temperature (°C), qm is the metabolic heat generation rate of tissue (W/m^3), and qr is the microwave energy absorption rate per unit tissue (W/m^3).

The boundary temperature of the computational domain is set as a constant value, and the temperature field before hyperthermia serves as the initial temperature field. Since the thermal field generated during heating is axisymmetric about the probe, this problem can be simulated using a two-dimensional numerical model.

1.3 Physical Parameters

The blood perfusion rate Wb, defined as the blood flow per unit volume per unit time, is an important characteristic that distinguishes living tissue from non-biological materials. The blood perfusion rate is calculated using equations (2) and (3) [5, 6].

The specific absorption rate (SAR) is a crucial indicator for measuring the effects of electromagnetic radiation on the human body, defined as the electromagnetic energy absorbed per kilogram of material per unit time. In this study, the SAR values are based on experimental data for a 915 MHz cylindrical microwave probe [7].

Due to the vigorous metabolism of tumor tissue, the metabolic heat generation rate differs significantly between tumor and normal tissue. The metabolic heat generation rates are set to qm-tumor = 29,000 W/m^3 and qm-liver = 450 W/m^3 [8].

Other physical parameters are assumed constant, with specific values listed in Table 1 .

2.1 Initial Temperature Field Before Hyperthermia

The initial temperature field before hyperthermia can be calculated by setting the unsteady term on the left side and the fourth term on the right side of equation (1) to zero. The mesh generation and simulated initial temperature field are shown in Figure 2 [Figure 2: see original paper]. The maximum temperature at the tumor center reaches 41.29°C due to the more vigorous metabolism of tumor tissue compared to normal tissue.

2.2 Temperature Field After Probe Heating

After 100 seconds of continuous heating, the temperature field is shown in the left panel of Figure 3 [Figure 3: see original paper]. The probe creates an asymmetric ellipsoidal temperature field along the probe axis, with temperatures perpendicular to the probe direction being significantly lower than those along the probe direction at the same radial distance. Therefore, this study selects point 1 at the tumor center as the central temperature monitoring point, and points 2, 3, and 4 located 1 mm outside the tumor edge as tumor ablation monitoring points, as illustrated in the right panel of Figure 3.

Figure 4 shows the temperature variation curves of the monitoring points during continuous microwave heating, while Figure 5 displays the temperature distribution along the radial direction (at the path location shown in the right panel of Figure 3) after 100 seconds of heating. When the probe is heated continuously for 100 seconds, the temperature at tumor center point 1 reaches 137°C, causing dehydration and carbonization at the center and affecting subsequent hyperthermia processes. Meanwhile, the minimum temperature at the three tumor ablation monitoring points has already reached 92°C, causing severe damage to surrounding tissues. The temperature distribution curve in Figure 5 shows that temperature gradually decreases along the radial direction, approaching a constant value of 37.5°C at a radius of 0.025 m.

3 Temperature-Control-Based Hyperthermia Simulation

In microwave hyperthermia, temperature control is achieved through real-time monitoring. However, under current conditions, invasive measurements increase patient discomfort, while the accuracy of non-invasive measurements cannot yet meet therapeutic requirements. To address these limitations, this study employs numerical simulation to preview the hyperthermia process and proposes

a temperature-control-based hyperthermia protocol that can eradicate the entire tumor while preventing excessive damage to surrounding normal tissues.

3.1 Temperature Control Principles

To achieve ideal tumor hyperthermia outcomes, heating must satisfy the following conditions: (1) tumor tissue must be heated above 43°C within a limited time and maintained for a certain duration; (2) no cold spots below 41°C should exist within the tumor tissue; and (3) the temperature of surrounding tissues must be kept below 45°C [9].

3.2 Control Protocol

As shown in Figure 4, when the probe has been heated for 14 seconds, point 4 reaches 45°C, while points 2 and 3 are at approximately 51°C and point 1 is at 54°C, with the corresponding temperature field distribution shown in the left panel of Figure 6 [Figure 6: see original paper]. To ensure therapeutic efficacy and meet the temperature control principles, the temperature at monitoring point 4 must satisfy hyperthermia requirements, while the temperatures at points 2 and 3 should not become excessively high to avoid damaging normal tissues.

Based on the initial temperature field distribution, the microwave heat source is applied. After 14 seconds of heating, the microwave probe is turned off to allow heat conduction from the high-temperature center to the cooler periphery. Blood perfusion simultaneously removes heat from the center, causing temperatures in the tumor and surrounding tissues to decrease. By 200 seconds, the temperature field corresponds to that shown in the right panel of Figure 6, with point 2 decreasing to 43.8°C, point 3 to 44.1°C, point 4 to 43°C, and point 1 to 45.8°C, thereby satisfying temperature control requirements and achieving tumor ablation without damaging normal tissues.

3.3 Hyperthermia Simulation

Through monitoring of the corresponding points during simulation, this study develops a temperature-control-based hyperthermia simulation that prevents excessive carbonization at the tumor center while controlling the tumor edge temperature to achieve complete tumor eradication without damaging normal tissues. Temperature control is implemented by regulating the on/off switching of the probe. The microwave probe is activated until monitoring point 4 at the tumor edge rises from the initial temperature of 37.5°C to 45°C, then deactivated until point 4 cools to 43°C, and then reactivated to control the entire hyperthermia process. The temperature variation curves during the hyperthermia simulation are shown in Figure 7 [Figure 7: see original paper]. The initial microwave heating duration is 14 seconds, followed by a cooling period of 186 seconds. Subsequent heating cycles are approximately 4 seconds, with cooling cycles of about 152 seconds.

4 Conclusions

This paper proposes a temperature-control-based hyperthermia protocol and employs numerical simulation to preview the hyperthermia process of a 915 MHz single-point interstitial microwave heat source for tumor ablation. Numerical simulation results indicate that an initial microwave probe heating duration of 14 seconds, followed by cooling to 200 seconds, and subsequently periodic heating and cooling cycles (heating for approximately 4 seconds and cooling for approximately 152 seconds) can control the maximum temperature at the tumor center below 54°C while maintaining the tumor edge temperature between 43-45°C. This protocol achieves the goal of preventing excessive temperature rise at the tumor center while completely killing the tumor without causing excessive damage to surrounding tissues.

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Note: Figure translations are in progress. See original paper for figures.