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Research Paper

Theoretical evaluation of high frequency microwave ablation applied in cancer therapy

Wu Xi [a,*], Liu Baolin [a], Xu Binkai [b]

[a] Institute of Biothermal Technology, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] AccuTarget MediPharma (Shanghai) Co., LTD, Shanghai 201318, China

HIGHLIGHTS

- Complex biological tissue consists of liver and tumor tissue in microwave ablation modeling.
- The dielectric properties of liver and tumor tissue lead to different material response at various microwave frequency.
- High frequency (6 GHz, 18 GHz) microwave causes more concentrated ablation area and less collateral damage.
- Internal cooling system is indispensable to conventional microwave ablation system (915 MHz, 2450 MHz).

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ABSTRACT

Microwave ablation (MWA) is a type of hyperthermia therapy to cancer disease area. Conventional MWA with electromagnetic frequency as 915 MHz and 2450 MHz have been widely used to clinical surgery. However, higher frequency sources for Industrial, Scientific and Medical (ISM) bands have been available for tumor detection. In this paper, we evaluated the effect of high frequency microwave (6 GHz and 18 GHz) applied to liver cancer therapy against conventional microwave (915 MHz, 2450 MHz) by a finite element model coupled electromagnetic field and bio-heat transfer equation. Tissue damaged region, temperature rise and distribution characteristics were analyzed in the biological tissue consists of liver and tumor tissue that may represent a realistic situation of cancer treatment. The results show that high frequency MWA can cause less collateral damage, more concentrated ablation region and better material response than conventional MWA. The investigation indicates that high frequency microwave can be applied to cancer therapy.

1. Introduction

Microwave ablation (MWA) is an efficacious form of thermal therapy for tumor treatment [1–3]. The MWA systems were introduced to clinical use in the 1990 s. Current generation MWA systems have needle-like, thin, coaxial-based interstitial antennas that can create large ablation zones during percutaneous use [4]. The early clinical applications were primarily to treat patients who were not candidates for surgical resection due to inadequate future liver remnant, multinodular tumors, or tumors in patients who declined resection [4,5]. More recently, MW has been increasingly applied as one of several curative therapies for small hepatic cellular cancer (HCC) [6].

The goal of MWA is to kill diseased tissue without damaging surrounding normal tissue [7]. So far, the frequencies used in the existing microwave ablation systems have been limited to the low-frequency spectrum such as 915 MHz or 2.4 GHz. Because of the inherent low radiation efficiency, very high microwave input power of several tens of Watts (0–150 W) is required at these frequencies, thus greatly increasing the cost and size of the equipment [8–10]. Besides, additional internal cooling system must be designed because of the self-heating caused by excess microwave power [12,13]. Hoffmann et al. tested various microwave antenna in ex vivo bovine liver and increased power level to 180 W as a maximum generator power to get the largest ablation volume [11]. An internal water cooling system was applied, otherwise, great collateral damage and charring area would result in the therapy failure [11].

Complex permittivity of biological tissue can reflect its weakening ability to the applied electric field, which could describe the interaction with microwave field of a specific frequency [14]. The real part of permittivity is the dielectric constant, which determines the ability to store the electric field, meanwhile, the imaginary

* Corresponding author.
E-mail address: imwuxi@gmail.com (X. Wu).

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part is the loss factor, which indicates how much energy is converted into heat and dissipated [14]. Gabriel et al. proceeded experimental research on the permittivity of different biological tissue at a wide band microwave frequency from 10 Hz to 20 GHz [15]. The results suggest that different biological tissue shows the different permittivity at the same microwave frequency spectrum, the same biological tissue shows the different permittivity at different microwave frequency spectrum [15]. Based on this different phenomenon, microwave with various frequency spectrum has been used in tumor detection yet [16].

The application of permittivity difference caused by different microwave frequency to optimize MWA is rarely researched. High frequency microwave shows higher radiation efficiency, requires lower input microwave power, and reflects more remarkable tissue permittivity difference than conventional MWA (915 MHz, 2450 MHz), which can overcome the limitations of conventional MWA [17]. Jeonghoon et al. suggested that 18 GHz was identified as the optimum frequency in the 0.9–30 GHz range for MWA of xenografted mice tumors with high tissue specificity (low collateral damage) and high efficiency (low input power as 1–3 W) [14]. Hung et al. demonstrated the feasibility of using high-frequency microwaves for tissue ablation by comparing the performance of a 10 GHz microwave ablation system with that of a 1.9 GHz system at a power level of 42 W for either 5 or 10 min [18]. Jones et al. used a novel high-frequency 14.5 GHz microwave applicator (10–50 W) in ex vivo human hepatic parenchyma and colorectal liver metastases to further investigate how ablation affects these cells, and to confirm non-viability [19]. Most of these studies with ex vivo experiment may not represent a realistic situation of cancer treatment. As a consequence, the modeling of MWA in biological tissue is required [20].

In this paper, a numerical simulation model was built to evaluate the feasibility of high frequency MWA used in cancer thermal therapy. The simulated biological tissue consists of normal liver tissue and tumor tissue, which may better fit the realistic situation. The ablation area, temperature distribution at various frequency spectrum as 915 MHz, 2450 MHz, 6 GHz, 18 GHz were analyzed respectively at a power level of 45 W for 5 min to evaluate the effect of high frequency microwave ablation applied in liver cancer therapy.

2. Numerical methods

2.1. Electromagnetic model

In the axisymmetric FE model, the electromagnetic wave transmitted in biological tissue associates with the time-varying transverse electromagnetic (TEM) wave [21]. The wave formulation is derived from Maxwell equation as [21,22]:

$$\nabla \times (\nabla \times \vec{E}) - \mu_r k^2 \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0} \right) \vec{E} = 0 \tag{1}$$

where $\vec{E}$ is the electric field generated by the coaxial-antenna, ∇ is the integral coefficient, μ_r is the differential permeability, k is the propagation constant in free space (m^{-1}), ε_r is the relative permittivity of the tissue, $\varepsilon_r = 8.854 \times 10^{-12}$ F/m is the relative permittivity of vacuum, σ is the conductivity of tissue, $\omega = 2\pi f$ is the angular frequency.

Electronic field:

$$\vec{E} = \vec{e_r} \frac{\xi}{r} e^{j(\omega t - kz)} \tag{2}$$

Magnetic field:

$$\vec{H} = \vec{e_\phi} \frac{\xi}{Zr} e^{j(\omega t - kz)} \tag{3}$$

where $\xi = \sqrt{\frac{ZP_{in}}{\pi \ln(r_{outer}/r_{inner})}}$ is the integration constant [21], Z is the wave impedance of conductor, P_{in} is the input microwave power, r_{inner} and r_{outer} are inner diameter and outer diameter of antenna.

Specific absorption rate (SAR) is the important index to measure the microwave absorption rate of biological tissue in unit time:

$$\mathrm{SAR}(r) = \frac{P}{\rho} = \frac{\sigma |\mathrm{E}(r)|^2}{2\rho} (\mathrm{W/kg}) \tag{4}$$

where P is the power density absorbed by biological tissue, ρ is the density of biological tissue, σ is the conductivity of biological tissue.

The association between permittivity and conductivity can be described as the formulation: $\varepsilon = \varepsilon' + i\sigma/\omega$. The imaginary part as the loss factor that indicates how much energy is converted into heat and dissipated shows positive correlation with conductivity. Hence permittivity is proportional to SAR. During MWA process, biological tissue always be complex components with different permittivity, that may cause different normal tissue damage and temperature distribution. Table 1 shows the relative permittivity of biological tissue measured by Yoon et al. [14] and Gabriel et al. [15] with different microwave frequency spectrum. Difference between liver and tumor tissue may shows the material response degree to different frequency microwave spectrum.

2.2. Biological heat transfer model

In 1948, Pennes fully considered of blood perfusion and heat transfer and proposed the Pennes equation, which has been widely applied to solve the biological heat transfer issues [23].

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_b C_b \omega_b (T_b - T) + Q_m + Q_r \tag{5}$$

where ρ is the density of tissue and ρ_b is the density of blood, C is the specific heat capacity of tissue and C_b is the specific heat of blood, K is the thermal conductivity coefficient of tissue, Q_m is the heat created by metabolism which is negligible compared to the heat created by microwave ablation [17], $\omega_b = 4.5 \times 10^6$ kg/m^3 s is the blood perfusion. $Q_r = \rho \cdot \mathrm{SAR}$, which is the heat generated by outside heat source that means microwave in this paper. Table 2 shows the parameters of biological materials [24].

2.3. Verification of the simulation model

In order to verify the reliability of the parameters and equations of MWA simulation model, the simulated results are compared to the previous studies obtained by Keangin et al. [25], as are shown in Fig. 1. Keangin et al. proceeded an analysis of heat transfer in liver tissue to discuss the difference between single and double slot antenna and verified their solution methods against Yang et al. [2,25,27]. Fig. 1(a) shows the geometry of the validation MWA model. In the case of the single slot MWA model, microwave signal with 10 W and 2450 MHz was applied to the liver tissue of 37 °C as its initial temperature. Five temperature monitoring positions of 1 mm, 2 mm, 4 mm, 8 mm and 12 mm radially away from the antenna slot were settled during the ablation process. Fig. 1(b) shows no obvious mismatch between the present simulation

Table 1
Permittivity of different tissue.

Frequency (GHz)	Relative permittivity		
	Liver	Tumor	Difference (%)
0.945	46.764	24.020	−48.636
2.450	43.035	17.529	−59.268
6.000	37.849	16.927	−55.278
18.000	23.898	24.334	1.824