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Advanced energy technology for improving efficiency for lung cancer microwave therapy using microwave antenna

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Abstract. In the past, energy technology was often used to analyze the cost-effectiveness of energy use. However, the use of advanced energy technology for improving efficiency has become popular in various applications, such as the medical field. Medical technology has continuously advanced in recent years, aiming to improve medical treatment efficacy while lowering patient hazards. Lung cancer is one of the most dangerous cancers that can affect everyone of any gender or age. One of the emerging and promising technologies for cancer treatment is microwave ablation (MWA). This study presents a computational approach to investigate the use of microwave energy for lung cancer treatment. A realistic three-dimensional model of human lung tissue was developed, and simulations were conducted using the finite element method (FEM). Key variables such as frequency, power, and heating time were systematically analyzed to evaluate their effects on temperature distribution and the treatment efficacy. Simulation results revealed that microwave energy at a frequency of 2.45 GHz produced the highest temperature values, followed by 1.8 GHz and 0.9 GHz, respectively. Notably, the application of 20 W of microwave power was found to reduce the time required for effective tumor ablation. The findings from this research provide valuable insights and a foundational framework for further energy for enhancing clinical treatment planning, enabling more precise and safer cancer therapy.

1 Introduction

In recent years, the integration of advanced energy technologies to enhance operational efficiency has gained increasing attention across a range of sectors, including the medical field. Lung cancer is a significant global public health concern due to its high incidence and mortality rates. It ranks as the second most diagnosed cancer among both men and women and is associated with a 5-year survival rate of only 18% [1]. Tumor ablation is a new cancer treatment that uses energy, as heat or chemicals, to directly destroy cancer cells, causing cellular necrosis [2]. A variety of techniques, such as cryoablation, laser ablation,

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high-intensity focused ultrasound (HIFU), radiofrequency ablation (RFA), and microwave ablation (MWA), can be used to ablate tumors. Among these, RFA has historically been the most widely adopted ablation technique globally [3]. However, in recent years, more people are interested in different and newer cancer treatments, especially microwave ablation (MWA), because it can accurately deliver heat to specific areas without needing major surgery, making it a good option that is less invasive [4]. MWA uses frequencies between 900 and 2450 MHz to operate in the electromagnetic field. When tissue is exposed to microwave energy, the rapid oscillation of water molecules induces thermal effects, leading to tissue heating. However, a major challenge in MWA remains the accurate control of energy distribution and temperature within biological tissues [4]. To overcome this, numerical simulation with the finite element method (FEM) has become an effective method for analyzing and predicting how heat transfer and microwave energy propagation will behave inside the human organism. Previous studies have shown that numerical simulation has been widely used to investigate thermal cancer treatment phenomena using various energy sources such as lasers, HIFU, RFA, and MWA. Most simulations initially employed two-dimensional (2D) tissue models. For example, Keangin P. and Rattanadecho P. [5] considered the effects of tumor sizes, tumor porosities, and microwave powers on the specific absorption rate (SAR) distribution, temperature distribution, and blood flow velocity distribution. In 2019, Selmi M., et al. [6] established a 2D model to analyze the influence of microwave power in liver tissue. Their findings confirmed that microwave power strongly affected both SAR and temperature distributions. Radmilović-Radjenović M. et al. [7] studied the impact of variations in dielectric properties and electrical conductivity of lung tissue during respiration on temperature distribution, ablation volume, and SAR distribution using the FEM. In 2022, Radmilović-Radjenović M. et al. [8] used a 2D FEM model to investigate the effects of tissues, including the liver, lung, kidney, and bone, on temperature distribution and tissue damage. Wessapan T. and Rattanadecho P. [9] investigated the acoustic pressure, fluid flow, and temperature distribution in HIFU therapy using FEM. In the same year, a 2D cylindrical lung tissue model with a single-slot antenna and a spherical tumor was studied by Mai X. et al. [10] to simulate microwave treatment of lung cancer. The results indicated that increasing tumor size led to a decrease in temperature and ablation length. For 3D model analysis with numerical simulation, Gorman J. et al. [11] developed a realistic 3D model of liver tissue with surrounding tissues (fat, muscle, and bone) during MWA. In the following year, Bini F. et al. [12] utilized a 3D model of the neck region-including skin, fat, muscle, thyroid, and a nodule within the thyroid-to study thyroid tumor treatment using RFA.

Above studies, it is evident that numerical simulations of cancer treatment using thermal energy from various sources have been conducted using both 2D and 3D models. However, research employing realistic 3D models of lung tissue remains relatively limited. Therefore, this study aims to develop a realistic 3D lung tissue model with an embedded tumor for MWA using the FEM. The present study investigates the electromagnetic wave propagation and heat transfer in tissue using a single-slot microwave antenna, as well as the influence of microwave frequency (0.90 GHz, 1.80 GHz, and 2.45 GHz), microwave power input (10, 15, and 20 W), and heating time (0 -300 s) on temperature distribution and tissue damage.

2 Formulation of the problem

MWA is a type of hyperthermia treatment that utilizes electromagnetic energy to generate high temperatures, reaching approximately 50°C or higher, which is sufficient to induce coagulative necrosis and effectively destroy cancer cells [12]. Fig. 1 shows the MWA method for lung cancer treatment.

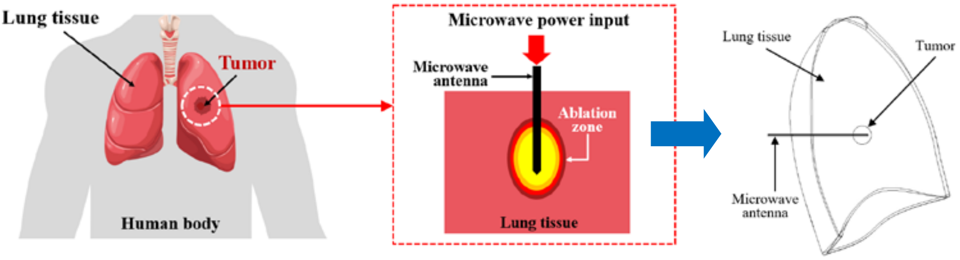

Fig. 1. The microwave ablation method is a minimally invasive approach for lung cancer treatment.

3 Methods and model

3.1 Physical Model

The 3D lung model used in this study consists of three main components: lung tissue, tumor, and single slot microwave antenna. The tumor has a diameter of 20 mm [13], while the lung tissue model represents the left human lung, with a volume of 2,738.53 cm³, a height of 28.2 cm, and a width of 12.3 cm [14]. Additionally, a microwave antenna with a radius of 0.895 mm is employed in the analysis. The dimensions and structural elements of the antenna are shown in Fig. 2 [13]. The thermal and dielectric properties of the tissues and tumor are summarized in Table 1.

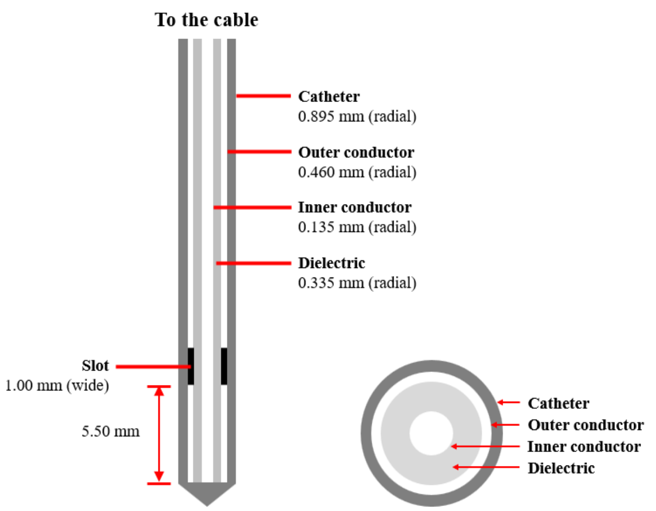

Fig. 2. The dimensions and structural elements of single slot microwave antenna.

In this research, the influence of frequency values on temperature distribution is considered, where the dielectric properties of lung tissue at different frequencies are referred to Radmilović-Radjenović M. et al. [7].

3.2 Equations for electromagnetic wave propagation analysis

The propagation of electromagnetic waves within the tissue can be described using Maxwell's equations, as shown in Equation (1).

$$\nabla^2\mathbf{E} - \mu_r\gamma_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\mathbf{E} = 0 \tag{1}$$

when $\mathbf{E}$ refers to the electric field (V/m), ε_r denotes the relative permittivity (-), σ indicates the electric conductivity (S/m), ϖ represents the angular frequency (rad/s); $\omega = 2\pi f$, ε_0 refers to the permittivity of free space (F/m); $\varepsilon_0 = 8.8542\times10^{-12}$ F/m [13], μ_r denotes the relative permeability (-), γ_0 indicates the free space wave number (m^{-1}).

The input microwave power is assigned to the inlet of the microwave antenna. The outer surface of the lung tissue is considered a scattering boundary condition, which is defined as:

$$\mathbf{n}\times(\nabla\times\mathbf{E}) - jk\mathbf{n}\times(\mathbf{E}\times\mathbf{n}) = 0 \tag{2}$$

The wall of a microwave antenna is assumed to be a perfect electric conductor boundary condition. For the interface between lung tissue, the tumor, and the microwave antenna, continuity boundary conditions are considered.

3.3 Equations for heat transfer analysis

The local thermal equilibrium (LTE) equation models heat transfer within biological tissue by analyzing it as a porous medium and assuming thermal equilibrium between blood and tissue temperatures. No phase changes or chemical reactions occur within the 3D lung model. Heat transfer within the microwave antenna is neglected in the simulation.

$$(\rho c)_{\text{eff}}\frac{\partial T_{\text{t}}}{\partial t} + \phi(\rho c)_{\text{b}}(\mathbf{u}\cdot\nabla T_{\text{t}}) = \nabla\cdot k_{\text{eff}}\nabla T_{\text{t}} + (1-\phi)Q_{\text{MET}} + Q_{\text{MW}} \tag{3}$$

where $(\rho c)_{\text{eff}} = (1-\phi)(\rho c)_{\text{t}} + \phi(\rho c)_{\text{b}}$ and $k_{\text{eff}} = (1-\phi)k_{\text{t}} + \phi k_{\text{b}}$
When subscripts eff b and t represent the effective value blood phase and tissue phase, respectively. In addition, ϕ refers to the porosity of tissue, with a value of 0.7 (-) [10], ρ denotes the density (kg/m^3), c indicates the specific heat capacity ($J/kg\cdot K$), $\mathbf{u}$ represents velocity (m/s), k refers to the thermal conductivity ($W/m\cdot K$), T denotes the temperature (° C), Q_{MET} indicates the metabolic heat generation source (W/m^3), which assumed negligible and Q_{MW} represents the external heat source (W/m^3) from microwave energy as follows:

$$Q_{\text{MW}} = \frac{\sigma|\mathbf{E}|^2}{2} \tag{4}$$

A thermally insulated boundary condition is imposed to the microwave antenna wall in both lung tissue and tumor regions. The outer surface of the lung tissue is assigned a fixed temperature of 37 °C, representing the core body temperature under normal physiological conditions.

In this study, Arrhenius equation is used to describe the rate of tissue damage caused by heat, expressing the relationship between temperature and the exposure time that leads to tissue necrosis. It is employed to calculate the damage integral, which represents the accumulated amount of damage in the tissue. The general form of the Arrhenius equation for the damage integral is:

$$\alpha(t)=\int_0^t Ae^{-\frac{\Delta E}{RT(t)}}dt \tag{5}$$

The fraction of tissue necrosis:

$$\theta_d = 1-e^{-\alpha} \tag{6}$$

when α represents the degree of tissue injury, A denotes the frequency factor (1/s), and ΔE refers to the activation energy for the irreversible damage reaction (J/mol). The frequency factor of lung tissue and tumor indicate 7.39×10^{39} 1/s and 3.247×10^{43} 1/s, respectively. The activation energy for the irreversible damage reaction of lung tissue and tumor are 2.577×10^{5} J/mol 2.814×10^{5} J/mol, respectively. R represents the universal gas constant, with a value of 8.314 J/mol [10] and θ_d denotes the fraction necrosis of tissue (-), where a value of 0 means no tissue necrosis, and a value approaching 1 indicates that most of the tissue is necrotic.

3.4 Equations for blood flow analysis

In both the lung tissue and tumor, the Brinkman equation is employed to describe the blood velocity profile, incorporating both the continuity and momentum equations. The blood flow is incompressible and Newtonian.

Continuity equation:

$$\rho_{\mathrm{b}}\nabla\cdot(\mathbf{u})=0 \tag{7}$$

Momentum equation:

$$\rho_{\mathrm{b}}\frac{\partial\mathbf{u}}{\partial t}=\left(-pI+\frac{\mu}{\phi}\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^{\tau}\right)\right)-\frac{\mu\mathbf{u}}{\kappa}+\mathbf{g}\beta\left(T-T_{\mathrm{b}}\right) \tag{8}$$

when p refers to the pressure of blood in tissue (Pa), μ denotes the viscosity of blood (Pa/s); μ =0.003 Pa/s [16], $\mathbf{g}$ indicates the gravitational acceleration (m/s^2); $\mathbf{g}$ = 9.81 m/s^2 [16], β represents the coefficient of thermal expansion (K^{-1}); β =1×10^{-4} K^{-1} [16].

The boundary condition for blood flow analysis at the lung tissue surface is modeled as an open boundary condition, which allows blood to flow freely in and out of the lung tissue surface without restrictions. For surface between the microwave antenna and the lung tissue and tumor are considered as no-slip boundary condition. The velocity of blood between the interface of the lung tissue and the tumor is equal, which is considered a continuity boundary condition.

A mesh convergence test was conducted on the 3D lung model, revealing that approximately 728,947 elements are required to ensure mesh-independent results.

Table 1. Thermal properties of tissues.

Thermal Properties	Lung	Tumor	Blood
Density, ρ (kg/m^3)	1,060 [15]	1,040 [16]	1,040 [16]
Thermal conductivity, k (W/m·K)	0.39 [15]	0.57 [16]	0.45 [16]
Specific heat capacity, c (J/kg·K)	3,886 [15]	3,960 [16]	3,960 [16]

4 Result and discussion

4.1 Verification of the model

To confirm and verify the accuracy of the present numerical study, the model was validated by comparing its results with those reported by Radmilović-Radjenović M. et al. [7]. For validation, a 2D cylindrical model of lung tissue with axial symmetry was employed. The microwave power input was set to 10 W, with varying microwave frequencies (1.5, 2.0, 2.5, 3.0, 4.0, and 6.0 GHz), and the heating duration was 600 s under identical conditions. The maximum tissue temperature obtained in the present study closely matches the results reported by Radmilović-Radjenović M. et al. [7], with an average error of 1.938%.

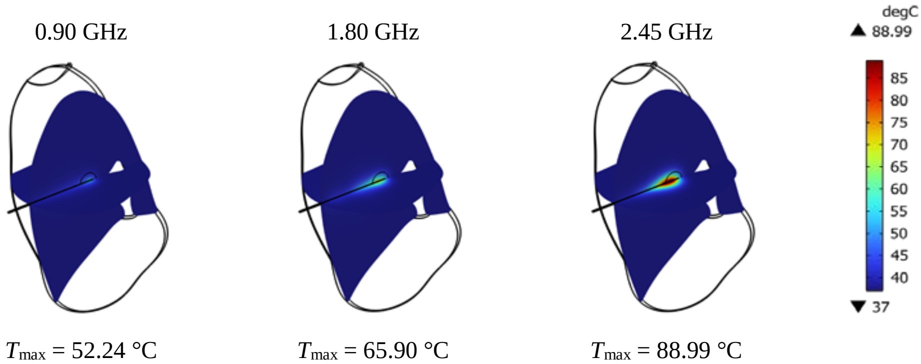

Fig. 3. The temperature profiles of the 3D lung model based on microwave power input of 10 W and heating time of 300 s at various microwave frequency.

4.2 Influence of microwave frequency

This study investigates the effects of microwave frequencies at 0.90 GHz, 1.80 GHz, and 2.45 GHz under a constant input power of 10 W and a heating time of 300 s, with tissue porosity set at 0.7. The simulation results based on a 3D lung model illustrate the temperature profile within lung tissue, as shown in Fig. 3. The results demonstrate a progressive increase in the maximum temperature over time.

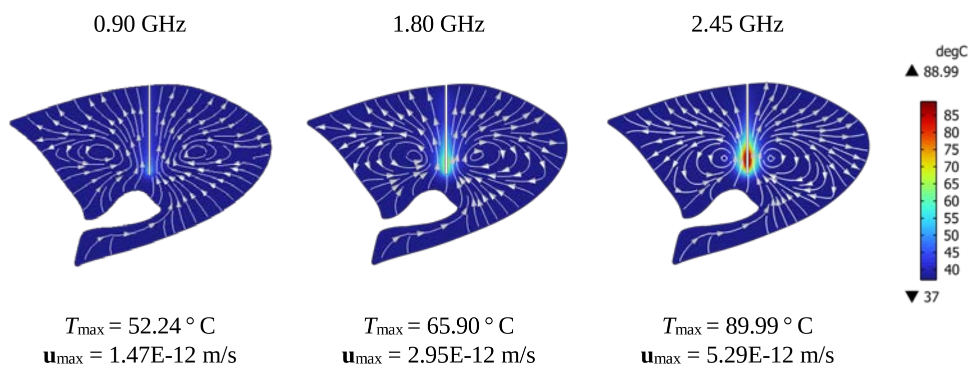

Fig. 4. The temperature and velocity profiles in the y-z plane of the 3D lung model at various microwave frequency, evaluated at a fixed microwave power input of 10 W and heating time of 300 s.

Fig. 4 presents the temperature and velocity profiles in the y–z plane, comparing the effects of different microwave frequencies on the maximum temperature and blood flow velocity. The results reveal that a frequency of 2.45 GHz yields the highest maximum temperature at 88.99 °C, followed by 1.80 GHz and 0.90 GHz, respectively. A similar trend is observed for blood flow velocity within the tissue, where the highest velocity also occurs at 2.45 GHz. These results indicate that higher microwave frequencies enhance both thermal penetration and the induced physiological flow response.

4.3 Influence of microwave power input and heating time

When analyzing the temperature distribution and the fraction of necrotic tissue at positions P1 (5 mm) and P2 (10 mm) along the center of the microwave antenna slot, as shown in Fig. 5. At position P1, the tissue temperature increases rapidly with increasing microwave power levels. Specifically, at 20 W, the temperature rises to approximately 90°C within 300 s. The temperature is lower at 15 W and 10 W, respectively. Regarding tissue necrosis, it is evident that necrosis begins clearly around 90 s when using 20 W, whereas lower power levels, such as 10 W, require a longer time to achieve similar effects. At position P2, which is located farther from the microwave source, the temperature rise is significantly slower, even under the same power conditions. For instance, at 10 W, the temperature reaches only around 60°C after 300 s. The tissue necrosis at this location also occurs more slowly and less completely, particularly under low-power conditions. These findings highlight the strong relationship between the distance from the heat source and the effectiveness of energy transfer to the target tissue during microwave ablation.

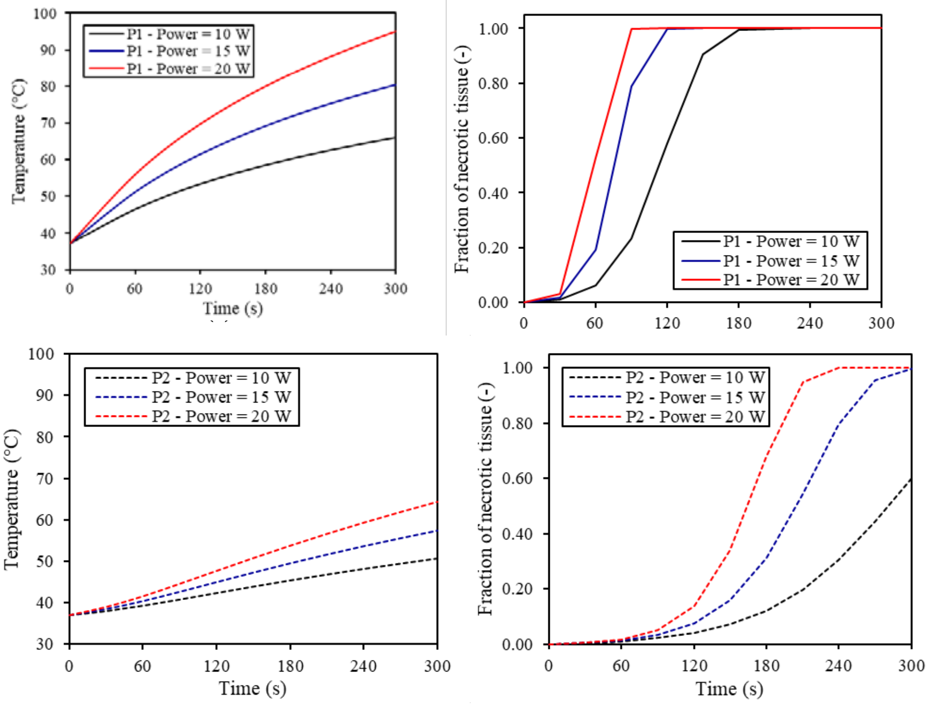

Fig. 5. Temperature distribution and fraction of necrotic tissue at points P1 and P2 with varying heating times: (a) temperature distribution at P1, (b) fraction of necrotic tissue at P1, (c) temperature distributions at P2, and (d) fraction of necrotic tissue at P2.

5 Conclusions

In this research, a 3D model of lung tissue with an embedded tumor was developed to simulate lung cancer treatment using the FEM. The findings of this study can be summarized as follows:

Microwave frequency significantly influences the effectiveness of lung cancer treatment. Among the frequencies studied, 2.45 GHz demonstrated the highest efficiency by producing the highest tumor temperature and the greatest fraction of necrotic tissue.

A microwave power input of 20 W results in the highest temperature and the greatest extent of tumor destruction, while requiring the shortest treatment duration.

The findings of this study provide fundamental insights that can be applied to the treatment of lung cancer as well as other cancers in different regions of the body.

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