The employment of porous media model to simulate lung microwave ablation

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Abstract

Purpose: Microwave ablation is one of the minimally invasive local treatment techniques for lung tumors. But lung tissue contains plenty of air. In order to study the problem that poor ablation or excessive ablation in the treatment of lung tumors, the lung was used as a porous media model for numerical simulation, and compared with the traditional biological tissue model.
Methods: In this paper, based on finite element method, COMSOL Multiphysics is used to simulate numerically. Two-dimensional microwave antenna model, porous media lung model and biological tissue lung model are constructed. Coupled calculation of electromagnetic field, temperature field and flow field is carried out to obtain the temperature distribution of lung tissue. The Pennes bio-heat transfer model is used in the temperature field. The Brinkman equation is used for the flow field of the porous media model. The ablation frequency was 2450 MHz, the ablation power was 30 W, 40 W and 50 W, and the ablation time was 6 min.
Results: The ablation area is approximately spherical. When the power was 30W, 40W and 50W, the ablation area of porous media lung models were 25.9mm, 31.0mm and 35.1mm in transverse diameter, 44.8mm, 50.5mm and 54.4mm in longitudinal diameter, and the maximum temperature were 121℃, 149℃, 176℃, respectively. The ablation area of traditional biological lung models were 40.5mm, 46.9mm and 51.9mm in transverse diameter, 56.3mm, 62.1mm and 66.7mm in longitudinal diameter, and the maximum temperature were 183℃, 232℃, 280℃, respectively. Compared with the biological tissue model, the porous media model is 29% smaller in ablation area and 36% smaller in maximum temperature. The simulation results of porous media model are more close to the results of ex-vivo experiments.
Conclusions: In the traditional biological tissue model, lung ablation does not consider the influence of air, so its ablation area is often large. The porous media model is more suitable for lung tissue with sufficient air. The method combines the electromagnetic field emitted by microwave, the flow field of air in lung tissue and the heat transfer field of porous media. It can accurately simulate the real-time distribution of temperature field in lung tissue under microwave irradiation, which plays an important role in real-time monitoring of temperature field in the process of microwave ablation of lung tissue.

Keywords: Microwave ablation; Numerical simulation; Lung; Porous media

1. Introduction

Lung cancer is one of the most common malignant tumors, ranking first in the causes of cancer incidence and death. Currently, resection is still the mainstream treatment. However, the limitations of resection surgery are very large, only about 20% of patients are suitable for surgery [1][2]. Microwave ablation for lung cancer is the use of microwave antenna puncture into lung tumors by using medical imaging equipment, such as ultrasound imaging, magnetic resonance imaging and computed tomography imaging. Under the action of microwave electric field, the tumor tissue produces high temperature above 60 ℃ in a short time, which causes the degeneration and necrosis of the tumor tissue. So as to achieve the purpose of treatment of tumors [3][4].

But lung tissue contains enough air, so the conductivity and thermal conductivity of lung tissue are very small, the temperature is difficult to control. Therefore, some large tumors and irregular tumors will have poor curative effect. It can also cause serious complications due to excessive ablation, which limits the application of this technology in clinical practice [5].

In this study, lung tissue is regarded as porous media, and the porous media model is used for simulation calculation, and compared with the traditional biological tissue model, in order to establish a more realistic simulation model.

2. Methods

2.1 Geometric model

COMSOL Multiphysics multi-physical field coupling analysis software is used in the simulation, and finite element method is used in the calculation.

The microwave antenna used in this study is a commonly used microwave antenna in clinic. Its frequency is 2450 MHz. Its geometric model structure is shown in Fig. 1 and Table 1 [6]. In this study, microwave antenna model, porous media lung model and biological tissue lung model are constructed. Because the action area of microwave antenna is axisymmetric, it is simplified to an axisymmetric two-dimensional. At the same time, assuming that the lung is isotropic homogeneous organization, the microwave antenna is inserted into the lung tissue for 10 cm. The two-dimensional model is constructed as shown in Figure 2.

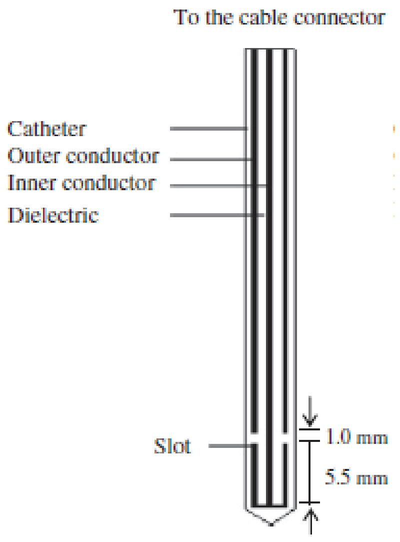


Figure 1. Geometric model of microwave antenna

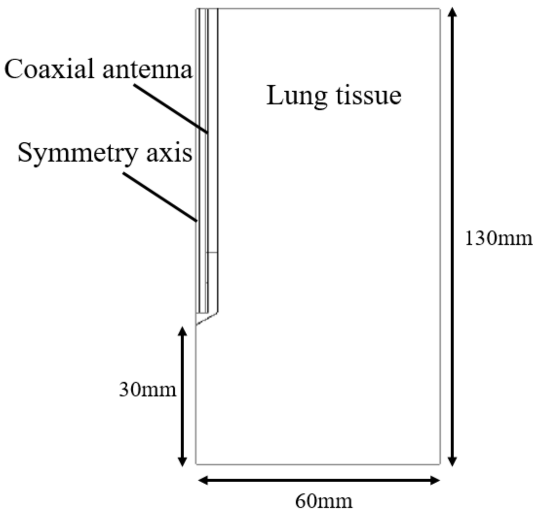


Figure 2. Two-Dimensional Simulated Geometric Model

Table 1. Dimensions of microwave antenna[6]

Materials	Dimensions (mm)
Inner conductor	0.135 (radial)
Dielectric	0.335 (radial)
Outer conductor	0.460 (radial)
Catheter	0.895 (radial)
Slot	1.000 (wide)

2.2 Bio-heat equation

The Pennes bio-heat equation (Eq. (1)) governs heating transfer during the thermal ablation [7].The equation is as follows:

$$\rho c\frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + \omega_b C_b(T_b - T) + q_m + q_r \qquad (1)$$

In the formula, T(℃)、ρ(kg/m3)、C(J/kg·℃) and k(W/m·℃) are the temperature, density, specific heat and heat conductivity of tissues, ω_b is the blood perfusion rate(kg/m3·s), C_b and T_b are the blood specific heat and blood temperature, q_m is the heat production rate of tissue metabolism, and q_r is the external heat source.

In the porous media lung model, the flow field is calculated by using Brinkman flow equation coupled with temperature field and electromagnetic field.

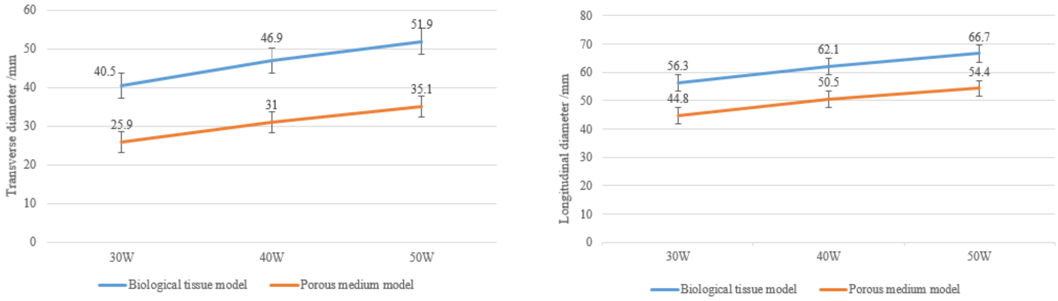
3. Results and Discussion

The temperature distribution and the data analysis of the ablation area at different ablation power (30W, 40W, 50W) were studied. The calculation time was 360 s. The temperature boundary was 60 ℃. The ablation area parallel to microwave antenna was longitudinal and the ablation area perpendicular to the microwave antenna was transverse. The experimental data and temperature distribution at different ablation power are shown in Table 2.

Table 2. Experimental data

Input powers	30W		40W		50W	
	Biological tissue model	Porous medium model	Biological tissue model	Porous medium model	Biological tissue model	Porous medium model
Transverse diameter /mm	40.5	25.9	46.9	31.0	51.9	35.1
Longitudinal diameter /mm	56.3	44.8	62.1	50.5	66.7	54.4
Highest temperature/ ℃	183.2	121	231.9	149	280.7	176

As can be seen from Table 2, with the increase of ablation power, the range of ablation temperature field increases gradually, the maximum temperature rises continuously, and the ablation areas are ellipsoidal. When the power was 30W, 40W and 50W, the ablation area of porous media lung models were 25.9mm, 31.0mm and 35.1mm in transverse diameter, 44.8mm, 50.5mm and 54.4mm in longitudinal diameter, and the maximum temperature were 121℃, 149℃, 176℃, respectively. The ablation area of traditional biological lung models were 40.5mm, 46.9mm and 51.9mm in transverse diameter, 56.3mm, 62.1mm and 66.7mm in longitudinal diameter, and the maximum temperature were 183℃, 232℃, 280℃, respectively. Compared with the biological tissue model, the porous media model is 29% smaller in ablation area and 36% smaller in maximum temperature. As shown in Figure 3, although the bio-tissue model is higher than the porous media model in terms of ablation zone range and maximum temperature field, the growth trend of ablation zone length with power of the two models is highly consistent. But comparing the two simulation results with the experimental results in vitro, the results obtained by the porous media model are closer to the ablation data in vitro [8].



(a)Transverse diameter (b) Longitudinal diameter

Figure 3. Changes in the length of the lung tissue with power

4. Conclusions

In the traditional biological tissue model, lung ablation does not consider the influence of air, so its ablation area is often large. The porous media model is more suitable for lung tissue with sufficient air. The method combines the electromagnetic field emitted by microwave, the flow field of air in lung tissue and the heat transfer field of porous media. It can accurately simulate the real-time distribution of temperature field in lung tissue under microwave irradiation, which plays an important role in real-time monitoring of temperature field in the process of microwave ablation of lung tissue.

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References

[1] F Bray, J Ferlay, I Soerjomataram, et al. Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries.[J]. Ca Cancer J Clin, 2018, 68, 394–424.
[2] Carrafiello G , Mangini M , Bernardi I D , et al. Microwave ablation therapy for treating primary and secondary lung tumours: technical note[J]. La Radiologia Medica, 2010, 115(6):962-974.
[3] Ahmed M, Solbiati L, Brace CL, et al. Image-guided tumor ablation: standardization of terminology and reporting criteria-a 10-year update[J]. Radiology, 2014, 273(1): 241-260.
[4] Brace C L . Microwave Tissue Ablation: Biophysics, Technology, and Applications[J]. Critical Reviews in Biomedical Engineering, 2010, 38(1):65-78.
[5] Huang W, Ma X S, Liu Y E. Application of Microwave Ablation for Lung Cancer [J]. Chinese Journal of Clinical Thoracic and Cardiovascular Surgery, 2015(3):265-268.
[6] Rattanadecho P , Keangin P . Numerical study of heat transfer and blood flow in two-layered porous liver tissue during microwave ablation process using single and double slot antenna[J]. International Journal of Heat and Mass Transfer, 2013, 58(1-2):457-470.
[7] Pennes H H . Analysis of tissue and arterial blood temperatures in the resting human forearm. 1948.[J]. Journal of Applied Physiology, 1998, 85(1):5-34.
[8] Luo G C. Experimental study on 2450Mhz microwave ablation for poreine lung in vitro [D]. Taishan Medical University, 2014.