Evaluation of the Effect of Blood Vessel Position and RF Power in Tumor Ablation Simulation

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Abstract

Background

Radiofrequency ablation (RFA) is a medical procedure in which part of the electrical conduction system of the heart, tumor or other dysfunctional tissue is ablated using the heat generated from medium frequency alternating current (in the range of 350–500 kHz). In RFA procedure, blood vessel position and RF power are often critical issues to consider.

Methods

In this article, we utilize finite element model software COMSOL Multiphysics (Burlington MA, USA) to establish a RF tumor ablation model and explore the effect of blood vessel position and RF power in temperature distribution and necrosis tissue fraction distribution.

Results

When blood vessel is near the electrode, temperature distribution is asymmetric, in which temperature around blood vessel is lower than that in corresponding area that is equidistant from electrode. Besides, higher power leads to faster tissue necrosis and larger necrosis area.

Conclusion

The conclusion is that big blood vessels take away heat, resulting in lower temperature and necrosis tissue fraction around. What's more, RF power and effective time, which determine the total energy outputs to tissue, exhibit a great effect in temperature distribution and necrosis fraction distribution.

Introduction

1.1 Background

Radiofrequency ablation (RFA), a local thermal ablative technique for the treatment of unresectable hepatic tumors including hepatocellular carcinoma, proved to be tumoricidal. RFA takes place at frequencies 460–550 kHz. Electrical voltage is being applied to the ablation zone by means of an electrically active probe. The flow of electrical current transfers the energy to the tissue, and the temperature there reaches 100 °C during time interval of 10–15 min [1]. The basic physical processes taking place during RFA are the electrical current flowing in the tissue and causing volumetric heat generation, as well as, the heat exchange due to thermal conductance of tissues.

While the usage of radiofrequency ablation devices is well established, efforts to optimize treatment strategies are ongoing. An important consideration in optimizing ablation is determining what treatment volumes are necessary and acceptable. Blood vessel position and RF power are often two critical issues to consider. A proper positioned probe and moderate power facilitates a successful therapy, in which tumor tissue is killed completely and fast, while surrounding normal tissue isn't affected very much.

1.2 Literature review

Several studies have performed to provide comprehensive information of the relation between blood vessel position, source power and thermodynamic response of the tissue. Dohyung et al. [2] performed studies where existence of big blood vessel was considered as a critical issue. They found that the heat sink caused by the flow of blood through the blood vessels around the tumor tissue could greatly increase

the extent of tumor tissue. Isaac et al. [3] found that source voltage greatly affected RFA results. However, these studies don't consider the two factors together, and they don't take blood vessel position into consideration.

1.3 Goal and techniques

On the one hand, to explore the effect of source power, this study compares corresponding results of different source voltage. The source voltage varies from 5V to 30V to see the difference.

On the other hand, to explore the effect of blood vessel position, we set different blood vessel distance from the electrode, and get the necrosis tissue distribution respectively.

Other material properties listed below are referred to S. Tungjitkusolmun [4].

Table 1 Material properties

Properties	Electrical conductivity S/m	Thermal conductivity W/(m*K)	Density Kg/m^3	Heat capacity at constant pressure J/(kg*K)	Blood perfusion rate 1/s
Liver	0.333	0.52	1079	3540	0.00641
Blood	0.667	0.543	1000	4180	
Electrodes	1e8	18	6450	840	
Trocar Tip	4e6	71	21500	132	
Trocar Base	1e-5	0.026	70	1045	

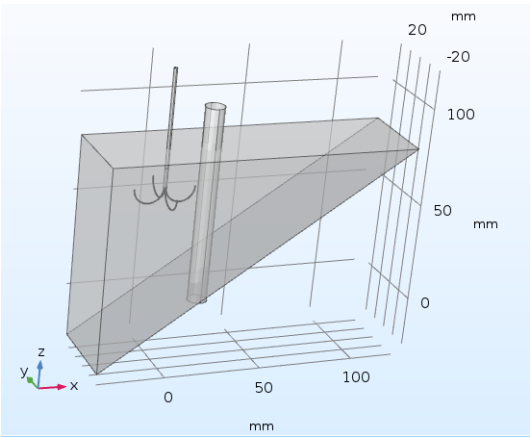
2. Model development

2.1 Geometry and parameters

The geometry includes liver, RITA-model-30 electrode, and a big blood vessel. The liver is represented by a 158*44*100 mm half cuboid to get a trade-off between similarity to real liver and simplicity to calculate. The blood vessel, in which blood flows at 0.14m/s speed [5], is represented by a thin cylinder whose radius is 5mm and length is 100mm. The electrode includes three parts: trocar tip, trocar base, and metal electrode.

RITA-model-30 electrode serves as the heat source. Voltage of the trocar base is 0V, the same as the surrounding tissue boundary. The other parts, trocar tip and metal electrode, are centrosymmetric and have a high voltage V0.

The general geometry and electrode geometry are showed in Fig.1 and Fig.2.



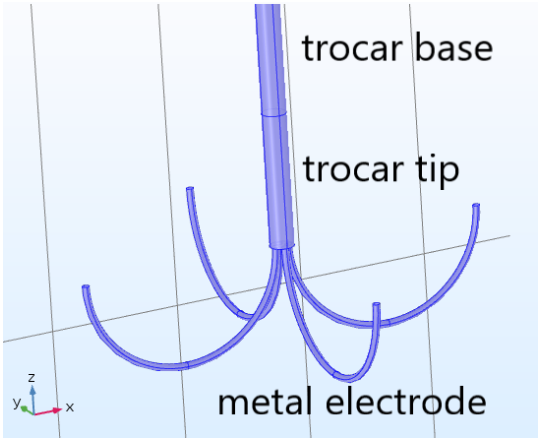


Fig.1 General geometry

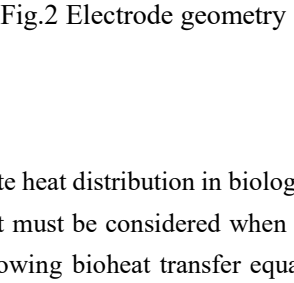


Fig.2 Electrode geometry

2.2 Mathematical model

Pennes equation

General heat transfer equation is not appropriate to estimate heat distribution in biological tissue because the characteristics of capillary vessels and metabolic heat must be considered when analyzing the heat transfer response of the living tissue. Therefore, the following bioheat transfer equation suggested by Pennes [6] was used in this study.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + Q_{\mathrm{hs}} - h_{\mathrm{bl}}(T - T_{\mathrm{bl}}) + Q_m$$

$$h_{\mathrm{bl}} = \rho_{\mathrm{bl}} c_{\mathrm{bl}} w_{\mathrm{bl}}$$

where ρ is the density (kg/m^3), c is the heat capacity (J /kg K), k is the thermal conductivity (W/m K),Q_{hs} is the heat source (W/m^3), Q_m is the metabolic heat source (W/m^3), T_{bl} is the temperature of blood (assumed to be 37°C), c_{bl} is the specific heat of blood (J /kg K), w_{bl} is the blood perfusion (s^{-1}), and h_{bl} is the connective heat transfer coefficient.

In the governing equation, the heat source term can be determined with the following equation:

$$Q_{hs} = J \cdot E$$

where J is the current density (A/m^2) and E is the electric field intensity (V/m). Since the electrical problem of this study was assumed as a quasi-static, the two parameter can be determined by Laplace's equation [7]

$$\nabla\sigma \nabla V = 0$$

where σ is electrical conductivity (S/m) and V is applied voltage source on the surface of electrode. The metabolic heat source Q_m was neglected since it has been shown to be insignificant compare with other terms in ablation. The blood perfusion in the liver tissue w_{bl} was assumed by 6.41*10^{-3}, which represented 100% perfusion at normal condition.

Necrosis tissue

To determine the boundary of necrosis tissue, we use the Arrhenius damage model as shown below:[8]

$$\Omega(t) = ln\frac{C_0}{C_{UD}(t)} = \int A exp\left[-\frac{E_a}{RT(t)}\right]dt$$

Where C_0 is the original concentration of undamaged cells, C_{UD} is the concentration of remaining living cells after time t, the treatment time; A is the frequency factor 2.984 × 10^{80} s^{-1}, E_a is the activation energy of irreversible ablation reaction 5.064 × 10^5 J/mol^{-1}, and R is the universal gas constant 8.314 J mol^{-1} K^{-1}.

We use this model to calculate the necrosis tissue fraction:

$$\theta_d = 1 - \exp(-\Omega(t))$$

Boundary conditions & Initial value

The model sets the boundary conditions at the outer boundaries as 37 ℃. Assume initial temperature equals 37℃ in all domains. The boundary voltage at the tissue's outer boundaries is ground (0 V potential), the same as the electrode trocar base and trocar tip. At the metal electrode boundaries, the potential equals a constant V0 (set as a parameter). Assume continuity for all other boundaries.

3. Results and Analysis

3.1 Voltage distribution

At setting of 20V electric source, we get the following voltage distribution:

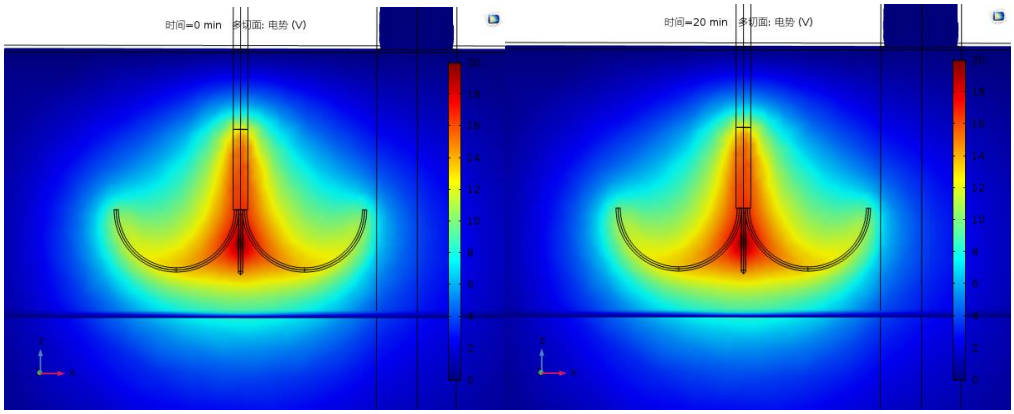


Fig.3 Voltage distribution at 0min　　Fig.4 Voltage distribution at 20min

We can see from the figures that:

(1) The voltage distribution doesn't change with time. After 20 min, the voltage distribution is still the same with that of 0 min.

(2) The blood vessel doesn't change the voltage distribution. The voltage distribution is symmetrical.

3.2 Temperature distribution

At setting of 20V electric source, we get the following temperature distribution:

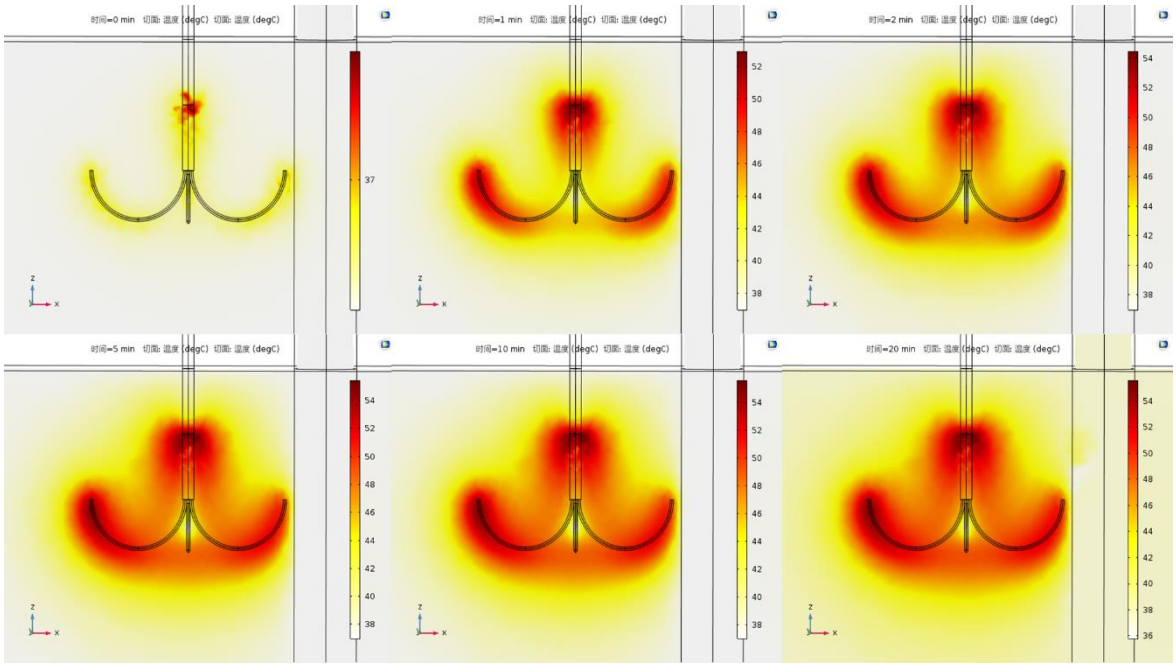


Fig.5 Temperature distribution of x-z plane at 0, 1, 2, 5, 10, 20 min. (blood vessel is right of electrode)

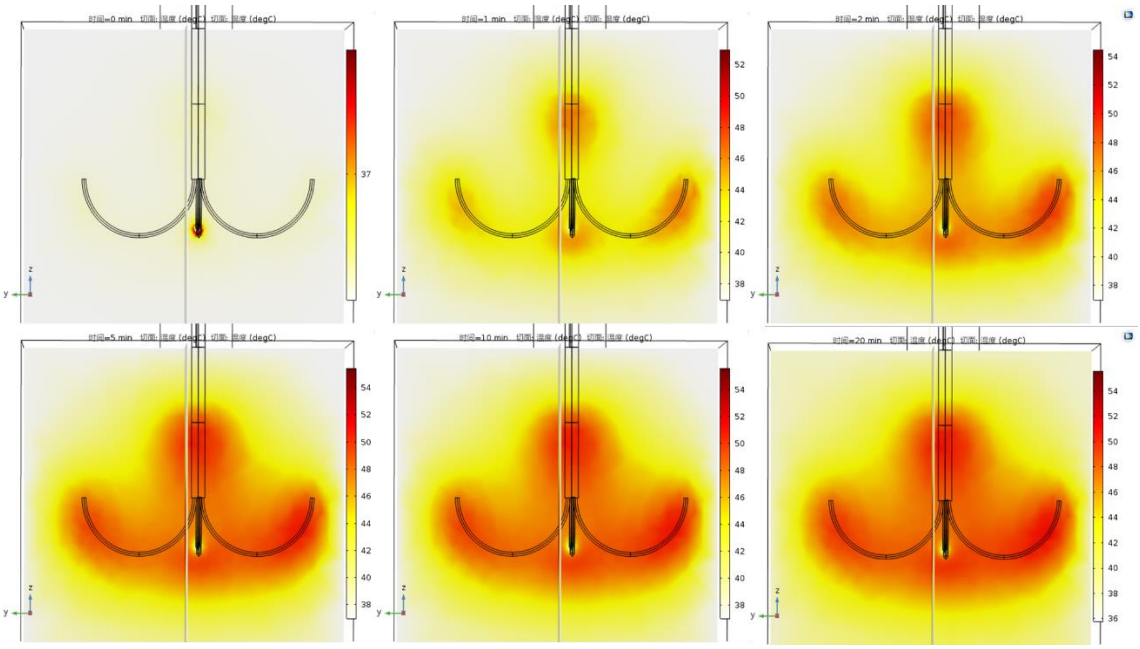


Fig.6 Temperature distribution of y-z plane at 0, 1, 2, 5, 10, 20 min.

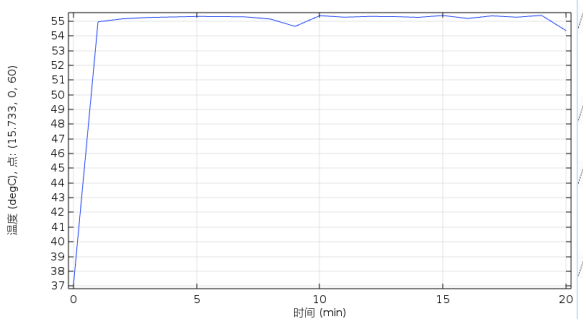


Fig.7 Temperature of one electrode arm tip.

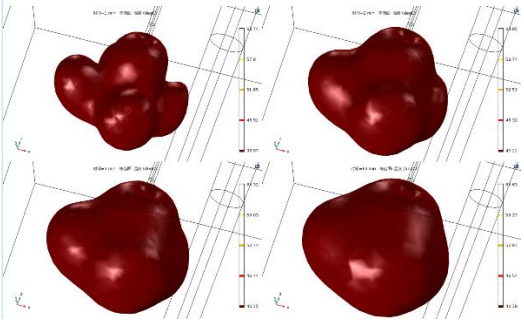


Fig.8 Contour in 1, 2, 5, 10 min

We can see from the figures that:

(1) The temperature distribution of x-z plane is asymmetric because of blood vessel. The blood vessel serves as the heat sink and takes away much heat, resulting in lower temperature around it.

(2) The temperature distribution of y-z plane is nearly symmetric.

(3) Temperature rises rapidly in about 2 min and changes a little in the following time. However, the temperature does change in the following time. We can see in 20 min, even the blood is heated to about 38 ℃.

3.3 Necrotic tissue fraction

At setting of 20V electric source, we get the following necrosis tissue fraction distribution:

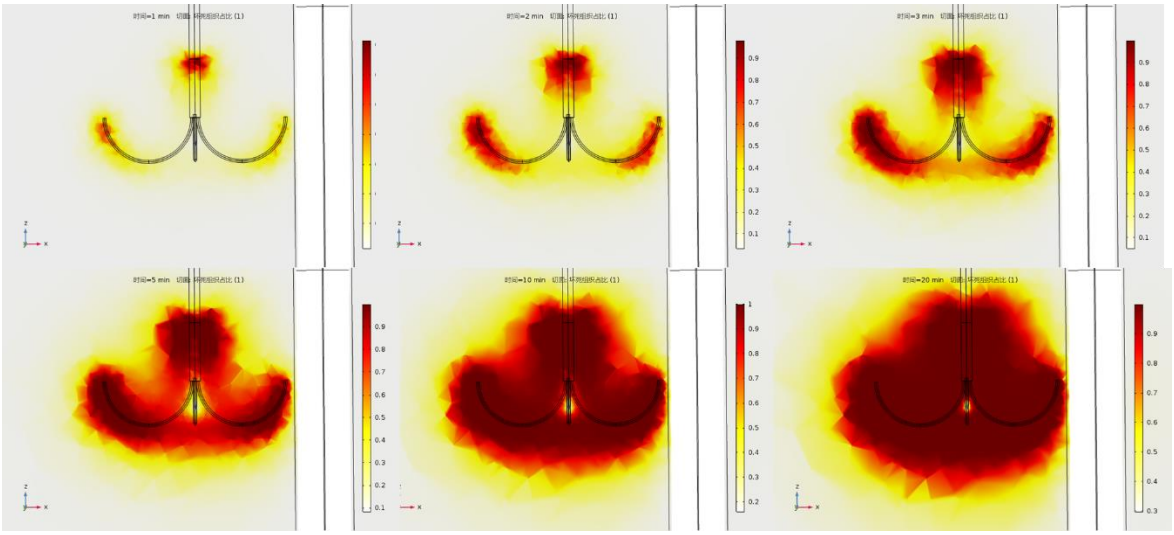


Fig.9 Necrosis tissue fraction of x-z plane in 1, 2, 3, 5, 10, 20 min

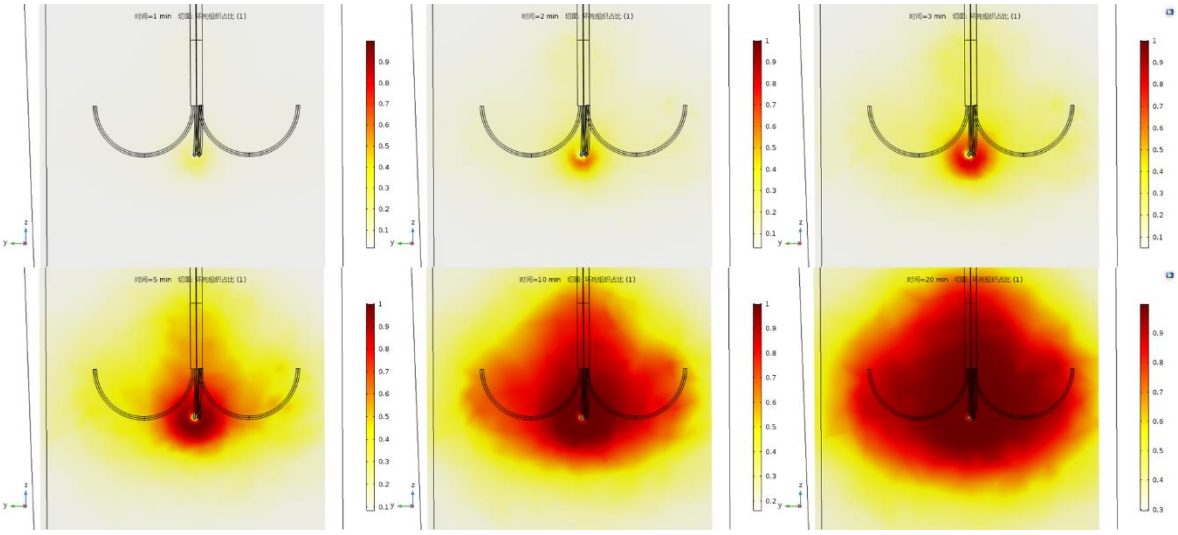


Fig.10 Necrosis tissue fraction of y-z plane in 1, 2, 3, 5, 10, 20 min

We can see from the figures that:

(1) The necrosis tissue fraction distribution of x-z plane is asymmetric because of blood vessel. The blood vessel serves as the heat sink and takes away much heat, resulting in lower temperature and lower necrosis tissue fraction.

(2) The necrosis tissue fraction distribution of y-z plane is nearly symmetric.

(3) Temperature rises rapidly in about 5 min and change a little in the following time. The reason why the rising time is longer than temperature rising time is energy needs to accumulate.

From these results, we can find similar results to temperature distribution.

3.4 Parametric study

Existence of blood vessel

If there's no blood vessel, at the very point of the electrode, the temperature rises very fast at first, and become steady gradually. And we can also see the necrosis tissue fraction is different greatly.

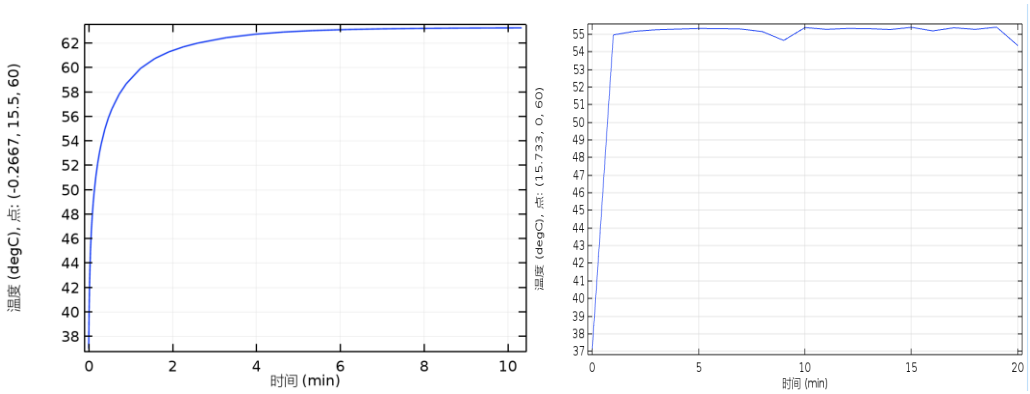


Fig.11 Temperature of one electrode arm tip with(right)/without(left) blood vessel

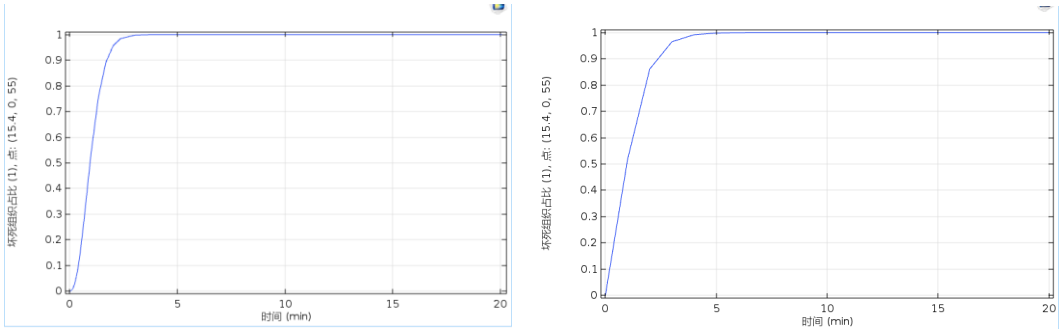


Fig.12 Necrosis tissue fraction of one electrode arm tip with(right)/without(left) blood vessel

Varying blood vessel distance

In previous analysis, the blood vessel distance from the electrode is 1mm, which is very close. We change it to 5mm, 20mm.

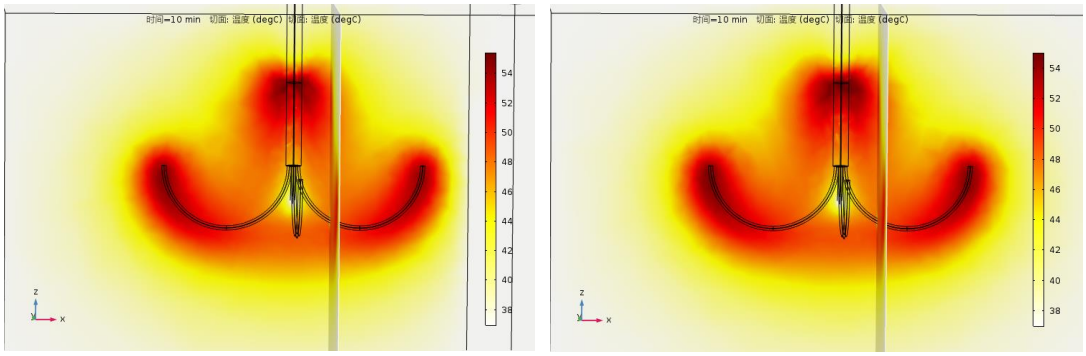


Fig.12 Temperature distribution of x-z plane with blood vessel distance 5mm(left), 20mm(right)

We can see from the figures that blood vessel effect can be small if it's far from electrode. In 1mm distance the effect of heat sink is very obvious, but in 5mm the effect is neglectable.

Varying source voltage

In previous analysis, the source voltage is 20V, which is moderate. We change it to 5V, 30V.

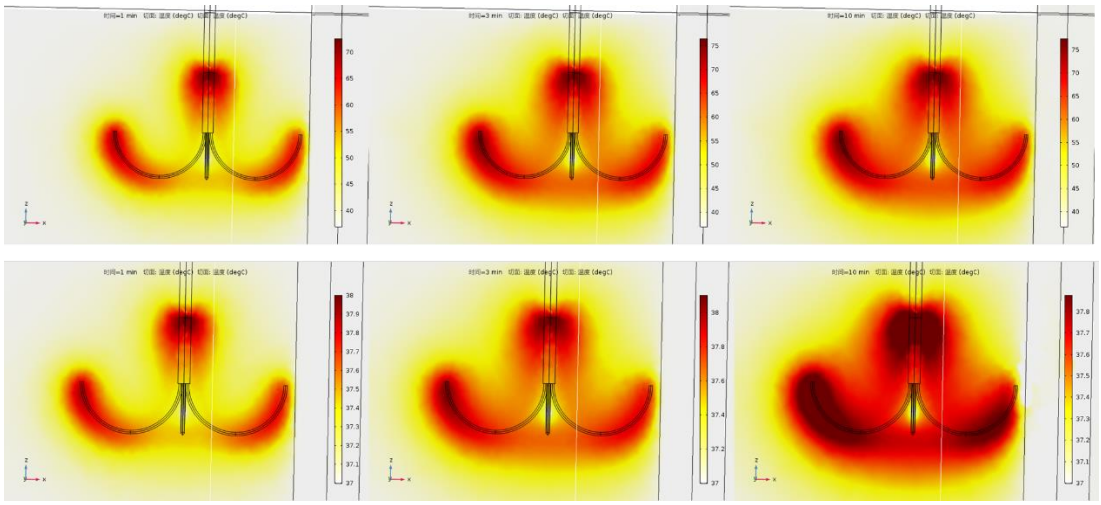


Fig.13 Temperature distribution of x-z plane with source voltage 5V(up), 30V(below) in 1, 3, 10 min

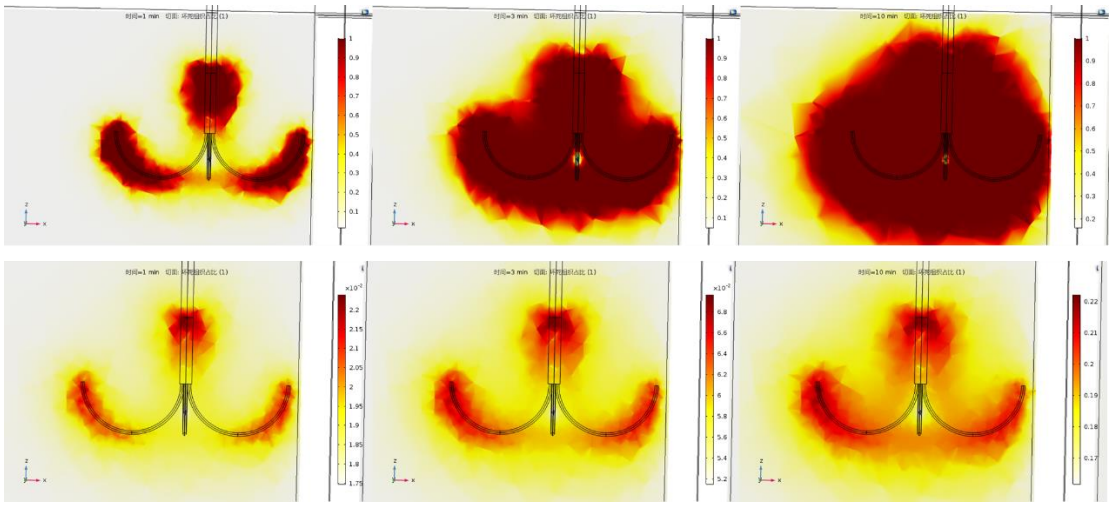


Fig.14 Necrosis tissue fraction distribution of x-z plane with source voltage 5V(up), 30V(below) in 1, 3, 10 min

We can see that:

(1) Higher voltage results in faster speed of necrosis and heating, and also larger necrosis area.

(2) If voltage is too low, it's not suitable to serve as the heat source because even though in enough time, temperature is still too low and necrosis tissue fraction is smaller than 0.3. The potential reason is the blood vessel, which takes away much heat.

4. Discussion

4.1 AC/DC current

We use DC power as a approximation of RF source. Practically it should be a microwave or AC power. It could make a difference but it could be very small.

4.2 Necrosis tissue properties

We build this model referred to S.Tungjitkusolmun [4] model. The building procedure is similar so it could validate results. But this model may have potential improvements: Necrosis tissue has different heat transfer and electric conduction properties and in my models these issues are neglected. If we take them into consideration the results could be more accurate.

4.3 Model limitations

Theoretical analysis

There are many other equations, besides to Pennes equation and Arrhenius equation to calculate the temperature distribution and degree of damage. If we use multiple methods to analyze the problem results could be more accurate.

Also, in liver there's abundant blood vessels. I only set one big blood vessel to see its effect. If I set more, about five to ten vessels, the results could be very complex but accurate. A more complex geometry of liver may be helpful too.

Tissue Properties

Necrosis area properties are not considered different with normal tissue in this study. Tumor destruction and heterogeneity should be taken into consideration.

Also, tissue properties like thermal conductivity, specific heat capacity and microvascular blood perfusion rate could be time-dependent and in this study, they are neglected.

Other methods

There's many other methods, such as using multiple free-standing conventional RF electrodes in an array, injecting saline during RFA, and performing overlapping ablations. These methods are very interesting and worth exploring. Further study may starts from these points.

Mesh

The mesh used in the model might not be the optimal because of the limitations of computer memory.

4.4 The significance of the study

In this study, I learn to construct a finite element model in COMSOL and study based on that. Then by modifying it over and over again I learn a lot. From my point of view, this is the greatest significance.

What's more, this study takes blood vessel and source power into consideration and makes a precise analysis of the two issues. It's someway common thought but rarely done by previous study. We validate this point and make a very reasonable result. From the result, we can see improper parameters of RFA could have a bad effect, therefore, clinical therapy should have a pre-clinical computational simulation to ensure the success of surgery. As we say in the very start, a proper positioned probe and moderate power facilitates a successful therapy, in which tumor tissue is killed completely and fast, while surrounding normal tissue isn't affected very much.

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