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A Finite Element Modeling on Hepatocellular Carcinoma Radiofrequency Ablation

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Abstract

Radiofrequency Ablation is a widely employed method in the clinical applications. The thermal energy is induced through Radiofrequency ablation technique into the liver tissue which ablates the tumor cells. Hence, this paper presents a 3 Dimensional FEM model for RF ablation of the liver tumor. Here the computational model is defined using electric field pattern with a demonstration of temperature distribution in the liver cell. The simulation result verifies that the temperature distribution is uniform along the electrodes. Additionally, the study of necrotic tissue at various points verifies that the damaged tissue gets overheated and surrounding tissues remain unaffected.

Keywords: Liver Tumor, Radiofrequency Ablation (RFA), Hepatic-Cellular Carcinoma, matrix

INTRODUCTION

RFA technique is broadly employed for the treatment of Hepatic-Cellular Carcinoma for the smaller size of tumor approximately of size lesser than 3 cm. The technique of radiofrequency therapies is rapidly growing in clinical adoption as well as technical development (Ahmed, et al. 2011). While many more focal therapies exist, for example, cryoablation (Xu, et al. 2013), laser-instigated thermotherapy (Ei, et al. 2014), microwave ablation (Li, et al. 2011), irreversible electroporation (Yeung, et al. 2014) and electrochemotherapy (Miklavcˇic, et al. 2012). Clinically the RFA is preferred for small size tumor. Despite the fact that microwave ablation has turned out to be more common in the preceding years, no statically noteworthy contrast in death rates in comparison to RFA of smaller tumor in the liver could be found (Lee, et al. 2017) (Cobelli, et al. 2017).

In Radiofrequency Ablation, the annihilation of tissue is finished by utilizing hyperthermia, i.e. temperature related to tissue is concentrated in the central zone inside and surrounding area of the tumor (Brace 2011). The effective treatment is defined as total removal of the tumor without harming healthy tissue and the nearby region of the tumor.

In any case, clinical involvement with RFA shows a noteworthy confound among expected and observed injury estimate, prompting decreased survival rates because of excess treatment with outrageous wounds up to 8.9 % or lesser treatment with chances of occurrence of the tumor is approximately 40% (Wong, et al. 2010).

Radiofrequency ablation technique uses radiofrequency generators, electrodes, and traditional treatment method which are industriously being enhanced to broaden the ablation zone (Mulier, Yi, et al. 2005) (Berjano, et al. 2006) (Lee, et al. 2007) (Solazzo, et al. 2007) (Weisbrod, et al. 2007) (Eisele, Neuhaus and Schumacher 2008). During RF Ablation treatment, the electrode is injected under the guidance of image detection.

An alternating electric current (approx. 500kHz) is delivered to the inserted electrodes in the liver tissue. Whenever the electric field is applied, the electric current moves all over the liver tissue causing Joule heating effect. The joule heating causes movement of ions in the cell against the friction and the temperature rises. As soon as the temperature of the targeted tissue is raised above 50^0 C, irreversible tissue damage happens. So, the necrosis is formed near the electrodes. Also, by using the current electrodes, there can be an increment in the ablation zone but the problem arises in the prediction and completeness of the necrosis. The ablation zone relies on characteristics of physical tissue like electric conductivity, thermal conductivity, perfusion rate, blood density, and heat capacity. Physical tissue characteristics aspects that varies from one patient to another patient in terms of parenchymal perfusion rate, liver architecture, large vessel's proximity and focal liver composition (Lu, et al. 2002) (Z. Liu, et al. 2007) (Z. Liu, et al. 2008).

Remembering the ultimate objective to upgrade consistency and unwavering quality of the ablation zone, we are managing the change of RFA in which complete tumor volume evacuation is centered around the ablation inside the limits of the terminals with negligible removal outside was gotten reproducibly when the bury anode separate was up to 2 cm.

The bioheat transfer equation is broadly explored and analyzed (M 1998). The analysis is difficult for complex geometry and complicated tissue structure. So conventional numerical method is inefficient for solving these parameters simultaneously (San D and Jing 2002). Thus different ways to solve the bioheat transfer equation arose like Finite Difference Method, Finite Element Method and Monte Carlos method or Finite Volume Method (San D and Jing 2002). Supan et al. (Tungjitkusolmun, et al. 2002)simulated a 3D model of RF hepatic ablation with four electrodes based on thermal-electric effect. They analyzed the Joule effects and blood convection affects the temperature. By the year 2013, Ruxsapong et al. (Ruxsapong , et al. 2013) designed an RF ablation 3D FEM model for asthma therapy. They showed an ellipse-shaped probe to rise the airway wall dimension. They used an RF probe of frequency 380 kHz at 65-75°C to heat the airway wall for 10 seconds.

In 2012, Yhamyindee et al. (Yhamyindee, et al. 2012) build a 3-dimensional Finite Element Method (FEM) model of microwave ablation in hepatocellular Carcinoma method. They demonstrated two different models, first without artery and the second with the artery. They also investigated the effects of the coagulative zone and blood perfusion rate. In 2015, Stefaan et al. (Mulier, Jiang, et al. 2015) designed a bipolar 2×2 electrodes FEM model. They performed the simulation focused on the effects of ablation duration and diameter of the electrodes. They also conducted an experiment with an ex-vivo bovine liver. Kok et al. (Kok , Wust and Stauffer 2015)explained the development of various software tools used for the treatment of hyperthermia in real time. They also showed the different steps involved from tissue segmentation, to electromagnetic calculation, to thermos-electric modeling and phase or amplitude optimization.

They did not explore the direction of the temperature diffusion. Few researchers designed different architectures of the probe while others examined the control of the injected drug. The proposed RF model is based on the controlled temperature diffusion in the liver.

COMPUTATION MODEL

The electro-physiological can be helpful for a better understanding of the radiofrequency thermal ablation technique. It involves the Joule heating phenomenon, modeling the electric field, and the heat transfer in perfused tissue.

Joule heating and current flow

RFA means a coupled electro-thermal issue wherein electromagnetic vitality is supplied to heat the tumorous tissue. Further, the cooperation of electric and magnetic field with the human body tissues relies upon the area and frequencies of the applied electromagnetic field [15]. In the lower range of frequency i.e., 450– 550 kHz, as is being utilized during RFA, the wavelength of the electromagnetic field, i.e., 600 m at around 500 kHz. Since the size of the active electrode is smaller than the wavelength which of various orders of magnitude. So, a quasi-static approximation can be applied to investigate the electromagnetics issue without trading off precision. Hence, a quasi-static estimation has been used in this investigation to compute the direct-current voltage from the model that relates to root mean squared RF voltage value that can be employed by resolving general Laplace Equation:

$$\nabla.(\sigma\,\nabla V) = 0 \tag{1}$$

The gradient of voltage gives the electric field:

$$E = -\nabla V \tag{2}$$

The total electric current is defined as:

$$J = \sigma E \tag{3}$$

The heat generated via RF is represented as Q_{ext}, this heat is calculated as volumetric heat generation rate Q (W/m^3):

$$Q_{ext} = \frac{1}{2} Real(J^{*}.E) \tag{4}$$

The electrical and thermal parameters are taken from literature (Trujillo and Berjano 2013) of electrodes and the liver tissue. Above 350 Hz, the alternating current is treated as direct current (Barauskas, et al. 2008). Where, E,V, and σ are an electric field (V/m), an electric potential(V) and electrical conductivity (S/m) respectively.

Heat Transfer Physics

The heat transfer mechanism can be described using Penne's bioheat equation, which depends on Fourier law of heat conduction. Bioheat transfer equation is an approximation to the heating transfer process in the tissues.

In the liver tissue region, the applied bioheat equation can be expressed as:

$$\rho c \frac{\partial T}{\partial t} = \mathrm{q} + q_b + Q_{met} + Q_{ext} \tag{5}$$

$$\mathrm{q} = \nabla(-k\nabla T) \tag{6}$$

$$q_b = \rho_b\, c_b\, \omega_b (T_b - T) \tag{7}$$

In the equation 5, on the Left side of equation ρ (kg/m^3), c (J/(kg.K)) are dthe ensity of the tissue and specific heat of the tissue respectively. On the other hand , Q_{met} (W/m^3) is the heat sources from metabolism, Q_{ext} (W/m^3) is spatial heating, q is heat due to conduction and q_b heat due to blood perfusion.

Also in equation 6 and 7, k(W/(m.K)) - thermal conductivity, ρ_b(kg/m^3) – dethe nsity of the blood, c_b(J/(kg.K)) – blood's specific heat, ω_b(s^{-1}) - Blood's perfusion rate and T_b(K) - arterial blood temperature. The bioheat equation used in RFA can be modified for the examination of the thermal impact due to large vessels. The employed equation can be explained as:

$$\rho c \frac{\partial T}{\partial t} = \mathrm{q} + q_b + Q_{bio} \tag{8}$$

Thermal lesion calculation can be expressed as:

$$\Omega(t) = A_1 \int_0^t \exp\left(\frac{\nabla E}{RT(\tau)}\right) d\tau \tag{9}$$

where $\Omega(t)$ is the damaged tissue factor, R (J/mol.K) - universal gas constant and A_1 (s^{-1}) - frequency factor. It is also known that the blood perfusion rate is slower in damaged tissue compared to healthy tissue of the liver. The blood perfusion rate of liver carcinoma is 2.11 x 10^{-3} s^{-1} whereas the perfusion rate of healthy tissue is 6.40 x 10^{-3} s^{-1} (Jain and Ward-Hartley, Tumor Blood Flow-Characterization, Modifications,and Role in Hyperthermia 1984). Also, Q_{bio} is the metabolism heat source (W/m^3). θ_d , is fractia on of the necrotic tissue that can be calculated as:

$$\theta_d = 1 - \exp(\Omega) \quad (10)$$

Simulation Model

The proposed model is based on electro-thermal analysis, which is solved using Multiphysics solver. In this simulation, the hepatic liver under the study is a cylinder of height 100 mm and radius 5 mm as illustrated in figure1. In this model, five cylindrical electrodes in a matrix form are placed at the center of the bigger cylinder. The diameter and length of electrode 1.5 mm and 60 mm respectively. Where the four electrodes are a positive probe and one is a negative probe. These electrodes modeled into two parts: 30 mm electrode base and 30 mm active electrode tip having a conical tip of 1 mm. Electrical and thermal properties of tissue are represented in table 1.

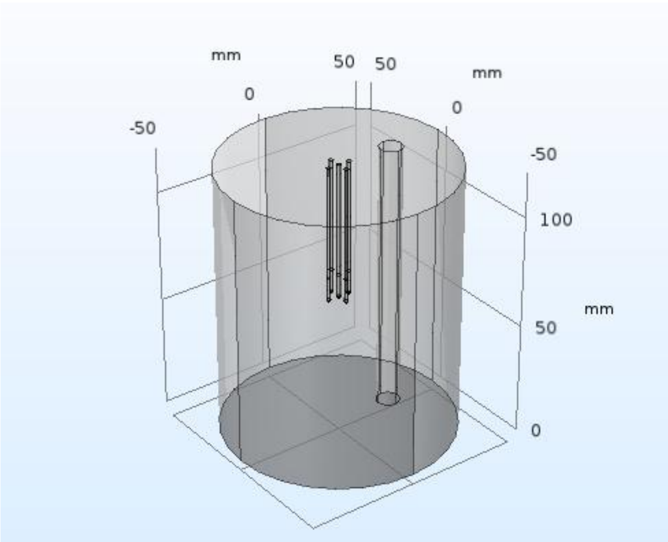

Figure 1: 3 D geometric model

Table 1: Electrical and Thermal parameters of the various component used in the model (Tungjitkusolmun, et al. 2002).

Components	Density	Heat Capacity	Thermal Conductivity	Electric conductivity
Electrode Tip	6450	840	18	1 X 10^8
Electrode Base	70	1045	0.026	1x10^{-5}
Tissue	1060	3600	0.512	0.333

The assumption is all the surfaces of the electrodes are equipotential since electrodes are perfect conductors as compared to the tissue. Since the insulation is supposed to be perfect, these domains are neglected in modeling. The electric insulation boundaries are described in equation 11.

The boundaries condition of the Electrical interface: (11)

$V = 0$ on cylindrical wall and also at one central electrode;

$V = V_0$ on electrode surface

$n.J = 0$ at remaining boundaries

The boundaries condition of the Thermal interface: (12)

$T = 37\,^0C$ on the cylindrical wall

$n.q = 0$ on remaining boundaries

RESULT

A 3D model is simulated in FEM Solver and results are reported. In the previous section of the paper, the focused heating of the targeted tissue because of Joule heating effect has been explained. Also, the necrotic tissues and the distribution of temperature are reported in the below figures. Figure 2 shows the tip temperature of the electrodes. Here in figure 2, we can analyze that the tip temperature increases with the increase in time and become constant at 75^{0}C. We have implemented matrix form of Radiofrequency ablation for complete coagulation of entire ablation zone. Further, the active part of the electrode can be varied within certain limits and distance between two electrodes can be changed up to a certain margin.

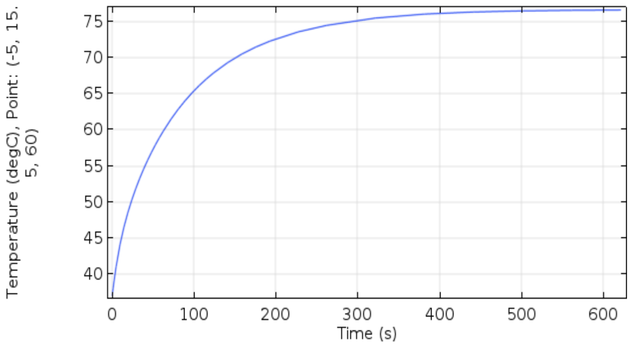

Figure 2: Electrode tip temperature

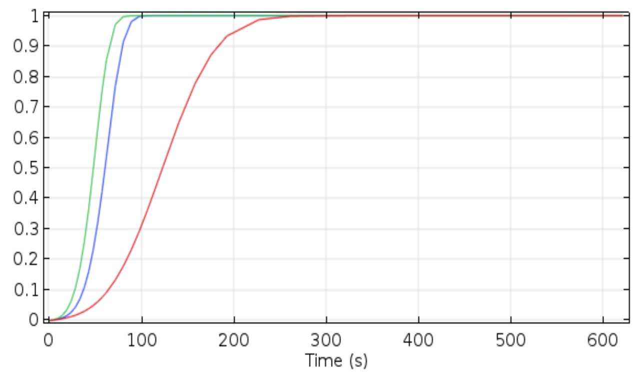

Figure 3: Fraction of necrotic tissue at three different points

Finally, Figure 4 shows the fraction of necrotic tissue at three different points above the electrode arm. For better understanding the effect of the heating process, we evaluated the necrotic tissue at three points to visualize the necrotic process in figure 3. Further, the first (the blue color) and second (the green color) point is adjacent to the electrodes and the last one is on the exterior boundary of ablation. The tissue damage is presented in figure 3. Further, with a specific end goal to favor the higher execution of proposed model, the simulation uses the constant values as material's properties for example electrical and thermal conductivity and blood perfusion. In addition, temperature of the tip is represented in figure 2. Also, the temperature distribution along the electrodes is depicted in figure 3.

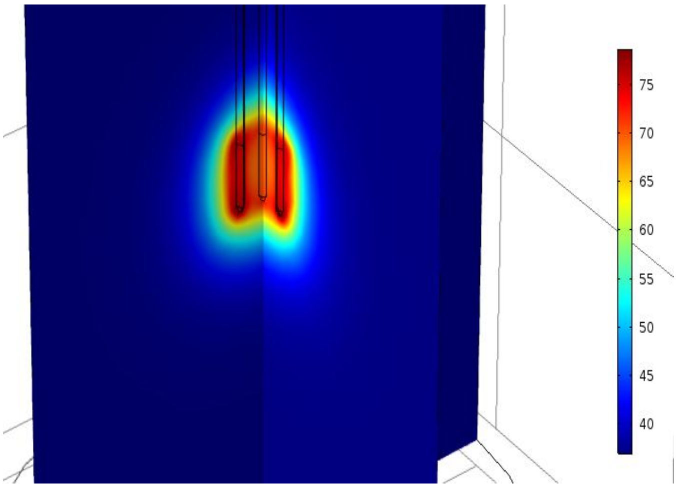

Figure 4: Fraction of necrotic tissue

CONCLUSIONS

The simulation is performed using FEM solver. It is observed that temperature distribution is uniform near the electrodes. In this paper, the computational model is explained to restrict the directional temperature diffusion in the liver tissue. Also, the calculation of the necrotic tissue is performed to verify the number of cells killed in this process. The results verify that the affected cells are damaged and killed by heating under the Joule effect in the direction of electrodes. We have also computed numerically the process of thermal ablation in the treatment method. By using multiple electrodes, the temperature distribution is uniform and number of cells died in fewer seconds of time. In Future work, we will compare the computation model with real data from clinical experiments to validate our simulation.

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