Tissue Damage Analysis and Bioheat Transfer Simulation of Radio Frequency Ablation in Hepatic Tumor

Manjunath N\textsuperscript{1}, Sanchu S\textsuperscript{2}, Sujith Kumar P\textsuperscript{3}, Praseetha K\textsuperscript{4}

\textsuperscript{1,2,3}Department of Mechanical Engineering, College of Engineering Adoor, Kerala, India
\textsuperscript{4}Department of Electrical & Electronics Engineering, College of Engineering, Trikaripur Cheemeni, Kerala, India

Abstract—Heat transfers occurring inside biological systems are known to be Bioheat transfer. Radio frequency ablation is a method under Hyperthermic treatment. It is proven to be effective for treatment of certain tumors. Computerized simulations of various treatment methods have very significant and important value in clinical situations. Numerical simulations provide a theoretical framework which can be used to substantiate, evaluate, and interpret experimental results. In this work a detailed numerical study of the heat transfer occurring in the RFA procedure of a liver tumor. The liver tumor tissue is modelled with an electrode placed inside it. And the heat transfer occurring during the RFA treatment is numerically simulated. The obtained electric potential and temperature distributions are analysed to study the behaviour of heat transfer problem occurring in them

Keywords— Bioheat transfer, Numerical simulation, Cancer treatment, Radio-frequency ablation.

I. INTRODUCTION

Cancer known medically as malignant neoplasm, is a broad group of diseases involving unregulated cell growth. In cancer, cells divide and grow uncontrollably, forming malignant tumors, and invading nearby parts of the body. Cancer is generally treated with methods such as chemotherapy, radiation therapy and surgery. Hyperthermia is one of the treatment for cancer in which the local body temperature is increased with artificial methods to cure the disease. RFA is one typical hyperthermic treatment procedure.

Using a radiofrequency generator and electrodes certain amount of energy is allowed to flow through the electrodes into the tissue. This causes the tissue to heat up. Temperature is constantly measured by tiny thermometers at the tips of the electrodes. This heat kills and destroys the tumor and the destroyed tissue is absorbed into normal body wastes.

Since the numerical simulations of hyperthermia treatments are most promising technique for the assessment of the treatment methods than any other methods and we can optimise the treatment methods and also plan treatment modalities for specific patients. This work is such an effort to simulate the heat transfer occurring during a RFA treatment using a commercially available electrode model.

II. FORMULATION OF PROBLEM

Usually RFA procedures are used in tumors in size greater than 3cm. The RFA procedures are commonly preferred in the treatment of hepatic malignancies. The numerical analysis of the treatment method can reveal the heat transfer occurring inside the human body especially in the tumor and surrounding regions. A type of commercially available electrode is selected to simulate the heat transfer in the tumor. The selected electrode type is cool-tip electrode which uses electrode cooling to increase the heat transfer extend. Due to ethical consideration exposing a human body to experimental purpose is not allowed. So it is more convenient to develop a 3D model and analyse it under near realistic manner to understand the bioheat transfer. Therefore a 3D model of cylindrical tumor tissue together with a cool-tip electrode is modelled and analysed in FEM based software, the system of governing equations as well as boundary conditions are solved numerically in the software.

The liver tissue is modelled as cylindrical in shape for the simplicity of analysis and the probe is placed in the axial position of the tissue cylinder. The cool-tip probe consists of two regions; a conducting region and an insulating region. The wire frame model of the geometry is shown in figure 1 for the better visibility of the probe. The liver tissue is modelled as solid cylinder without any blood vessels. The blood perfusion within the tissue is only considered in this model. The geometry is developed, meshed and analysed in the selected analysis software.
The geometry was meshed with free tetrahedral elements for the simplicity and ease of analysis. The meshing was refined many times for generating a good mesh.

A. Governing equation for bioheat transfer interface

The bioheat equation governs heat transfer in the tissue

\[ \delta_t \rho C \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{\text{met}} + Q_{\text{ext}} \]

Where \( \delta_t \) is a time-scaling coefficient; \( \rho \) is the tissue density (kg/m\(^3\)); \( C \) is the tissue’s specific heat (J/(kg·K)); and \( k \) is its thermal conductivity (W/(m·K)). On the right side of the equality, \( \rho_b \) gives the blood’s density (kg/m\(^3\)); \( C_b \) is the blood’s specific heat (J/(kg·K)); \( \omega_b \) is its perfusion rate (1/s); \( T_b \) is the arterial blood temperature (°C); while \( Q_{\text{met}} \) and \( Q_{\text{ext}} \) are the heat sources from metabolism and spatial heating, respectively (W/m\(^3\)).

B. Governing equation for the Electric Currents interface

The governing equation for the Electric Currents interface is

\[ -\nabla \cdot (\sigma \nabla V - J^e) = Q_j \]

Where \( V \) is the potential (V), \( \sigma \) the electrical conductivity (S/m), \( J^e \) an externally generated current density (A/m\(^2\)), \( Q_j \) the current source (A/m\(^3\)). For the present study there is no current density and current source term in the procedure.

C. Assumptions for heat transfer analysis

To solve the thermal problem, the temperature distribution in the human body has been evaluated by the coupled bioheat and Maxwell equations. To simplify the problem, the following assumptions were made.

- a) Human tissues are biomaterial with constant thermal properties.
- b) No phase change in substance occurs within the tissues.
- c) There is no energy exchange throughout the human body model.
- d) There is no chemical reactions occur within the tissues.
- e) Local thermodynamic equilibrium is considered.

### Table 1 Properties of liver tissue [10]

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>.512 [W/m·K]</td>
</tr>
<tr>
<td>Density</td>
<td>1060 [kg/m(^3)]</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>3600 [J/kg·K]</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>.333 [S/m]</td>
</tr>
</tbody>
</table>

D. Initial and Boundary Conditions

1) Boundary conditions for the Electric Currents interface

The applied voltage only creates an external effect on the tissues. No current or current source is present within the volume under study. So electrical insulation is assumed in the outer boundaries of the tissue cylinder i.e., 0V on cylinder walls and the applied initial electrode voltage is set as 22V.

2) Boundary Condition for Heat Transfer Analysis

The heat transfer analysis is considered only in the liver tissue domain, which does not include parts of the surrounding organs. The boundaries of the human body are considered as an insulated boundary condition. It is assumed that no contact resistance occurs between the internal organs of the human body. Therefore, the internal boundaries are assumed to be a continuity boundary condition. The liver tissue as well as the blood has the body temperature and the body temperature is assumed to be constant. The body temperature is taken as \( T_b = 37^\circ C \).

III. RESULTS AND DISCUSSION

A Temperature Distribution

The electric potential applied in the tissue generates a field within the tissue which in turn attenuates, owing to the energy absorbed, and thereafter the absorbed energy is converted to thermal energy, which increases the tumor tissue temperature. It is found that for different models, the distribution patterns of temperature at a particular time are quite different. Fig.2 shows the temperature increase of the tumor tissue exposed to RFA at various times.
The hot spot zone is strongly displayed at the 30s for the cool-tip model. After that a gradual increase in the temperature distribution can be seen as time step increase. It is evident from the figure that the maximum temperature is found at the two ends of the conducting region of the electrode. The reason for the increased temperature at the ends of the active region of the electrode is due to the increased electric potential accumulation at these sites. The accumulation of electric potential at these regions may be because these regions are the interface of conducting-insulating media. By analysing the Fig.5(d),(e) and (f) it is seen that the time dependant temperature variation is retarding.

After 8 minutes we can say that the temperature variation has attained a steady state. And the temperature gradient is also retarding.

The isotherms can be used to verify the retardation in the transient temperature after 8 minutes in the both models. The isotherms of the cool-tip probe model after 8 and 15 minutes are shown in the Fig.3 After analysing the isotherms of both models for the time steps 8 and 15 minutes it is evident that the temperature variation has nearly ceased in both models. So the continuous RFA procedure beyond 7 or 8 minutes is not having any expected impact on the tumor tissue and also in the treatment procedure.

**B. Arrhenius Damage Model**

The Arrhenius damage model based on first-order rate kinetics was used to quantify thermal injury by evaluation of certain parameters based on the simulation performed. The mathematical formulation of the Arrhenius model is given by:

\[
\frac{d\alpha}{dt} = \frac{1}{\tau} = Ae^{-E/RT}
\]
In above equation the damage accumulation measured by the specific assay in a given time (s⁻¹), \( t \) is the time for damage accumulation (s), \( \frac{d\Omega}{dt} \) represents the threshold of damage and is assay dependent, \( \tau \) is the time required to accumulate irreversible damage (s), \( E \) is the activation energy (kJ/mol), \( A \) is the frequency factor (s⁻¹), \( T \) is the absolute temperature (K), and \( R \) is the universal gas constant (8.315 J/mol K). By fitting above equation to the simulation data for injury accumulation, it is possible to extract the two unknown parameters in the model, \( E \) and \( A \). This is accomplished by plotting the natural logarithm of time (in seconds) to reach a specific injury versus one thousand times the inverse of the absolute temperature (in Kelvin). \( E \) is given by the slope and \( A \) the y-axis intercept corresponding to infinite absolute temperature (1000/K = 0) of the line that fits the simulation data. The obtained values of \( E \) and \( A \) is found to be 667 kJ/mol and 1.98x10⁵⁴ s⁻¹ respectively. The obtained values are a dependant variable on the given simplified boundary conditions and material properties.

IV. CONCLUSION

The numerical simulation of the Radio-Frequency ablation procedure is carried out even though on simple geometrical model of liver tissue. Successfully simulated the bioheat transfer in selected electrode model. The basic bioheat equation by H.H. Pennes is taken for the numerical analysis. The coupled electric and bioheat models are solved in a FEM based simulation software. The transient heat and electric field analysis was approximated by Lagranges interpolation techniques to incorporate the time varying results.

The temperature distribution, extend of heat transfer, electrode tip temperature variation and Arrhenius damage model was studied. The electric potential is the only external quantity applied to the tumor tissue via electrode. It is found that the electric potential accumulation is greater in the interfaces. This may be due to the effect of electric conductivity of the tissues and effective permeability. The electric potential applied to the tissue is selectively absorbed by the tissues due to ionic movements or vibrations. This absorbed energy is then converted into heat energy, which in turn causes a bioheat transfer within the tissue.

The maximum temperatures are found in the regions of high electric potential accumulation for all the case. This shows the direct relation of the applied electric potential in the heat generation. The maximum temperatures are found at the electrode tips for all cases. This may be due to the properties of electrode and tissues and also due to the tissue-electrode interface formed.

The study of the temperature distributions shows that the temperature variation approaches a steady state after a particular time interval in both models. This is due to the thermal properties of the liver tissue and blood. The temperature variation almost ceased after 8 minutes of operation. This shows the necessity of replacing the electrode to new low temperature region to increase the extend of thermal damage in the tumor tissue. The tip temperature increases rapidly at first and the retards and reaches a constant temperature after 6 minutes. Thereafter the tip temperature does not vary with the time steps taken.

REFERENCES


