Proceedings of IMECE'04
2004 ASME International Mechanical Engineering Congress and Exposition
Anaheim, CA, November 13-19, 2004

IMECE2004-61792

RF ABLATION IN A RECONSTRUCTED HEPATIC GEOMETRY WITH AN ELECTRICAL HEAT SOURCE

Prasanna Hariharan[1], Ajit Pandey[1], Rupak K. Banerjee[1,2]

(1) Mechanical Engineering Department, University of Cincinnati, Cincinnati, OH 45221
(2) Biomedical Engineering Department, University of Cincinnati, Cincinnati, OH 45221

ABSTRACT

This research aims to develop a methodology for modeling three-dimensional radiofrequency (RF) ablation using a reconstructed hepatic vasculature geometry with an electrical heat source. Coupled mass, momentum, heat transfer, and electric field, including voltage potential, equations are solved. The effects of heat convection through the nearby arteries and elevated level of blood perfusion through the tissue on the temperature distribution near the tumor zone is studied. The results show that for an arterial inlet velocity of 13.8 cm/s and '.6 cm/s the peak tumor temperature drops by 7% and 10%, spectively, whereas the temperature along the outer periphery of the tumor close to the arteries drops by 50% and 75%, respectively. Asymmetries in the temperature profile indicate that the ablation procedure elevates the temperature to the required level only at localized regions. In the other regions the heat energy is not adequate for tumor destruction thereby permitting possible tumor recursion.

INTRODUCTION

The RF technique involves inserting a needle (RF probe) under the guidance of computed tomography (CT). The needle is placed directly into the tumor and a RF is sent through the needle. This RF energy generates heat, which destroys the tumor. Temperatures in the range of 50-60^{0}C can start the process of denaturation in minutes (Tungjitkusolmun et. al., 2002). Treatment sessions are generally 10-30 min in duration and produce spherical necrotic regions that are 3-5.5 cm in diameter.

The Pennes bioheat transfer model does not include the presence of large vascular vessels in tissue domain. Our earlier study (Pandey et. al., 2003) simulated the effect of the blood perfusion and convection, within a reconstructed tissue and arterial domain by implementing a Gaussian distributed heat source. This study aims to provide an improved and more curate formulation to determine an RF heat source using tage potential and electrical field equations.

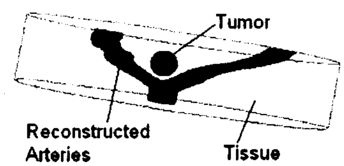

Figure 1: Reconstructed bifurcated arteries with surrounding hepatic tissues

METHOD

MRI images of a sectioned liver tissue containing arterial vessels are processed and converted into a finite-element mesh [Fig. 1]. In order to get a realistic representation of the electric field generated by the RF probe, the RF ablation procedure requires a four-way coupled model (mass, momentum, heat transfer, and electric field including voltage potential equations). First, the momentum equation is solved to get the velocity field in the tissue domain and is used as input to the coupled energy and electrical field equations to calculate the temperature distribution across the tumor and tissue domain. The energy equation is given by

$$(\rho c_p)_e \frac{\partial T}{\partial t} + (\rho c_p)_e u_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k \frac{\partial T}{\partial x_j}\right) + Q_s \quad (1)$$

where T is the temperature (^{0}C), ρ is the density (Kg/m^3), c_p is the specific heat (J/kg/K), u is the fluid velocity (m/s), k is the thermal conductivity (W/m/K) and Q_s is the electrical heat source (W/m^3). The distributed heat source (Joule heating) is calculated by:

$$Q_s = J.E \quad (2)$$

where J is the current density (A/m^2) and E is the electric field intensity (V/m). These are calculated from the Laplace equation (Chang, 2003).

To incorporate probe geometry, a spherical void, equivalent to the probe dimension, is included at the center of the tumor [Fig. 1]. Standard mass, momentum and energy equation are used in the arterial (continuum blood flow) region.

Boundary Conditions: For the Laplace equation (solved for the tissue domain), an electrical potential of +20V is imposed at the outer periphery of the probe and the electric potential diminishes to the zero value at the outer periphery of the tissue domain. Flow and thermal boundary conditions applied in the tissue and arterial domain are analogous to the boundary conditions discussed in Pandey et al., 2003.

RESULTS AND DISCUSSION

The axial (z-direction) temperature profiles are displayed quantitatively in figure 2. In the case of no blood flow, the maximum temperature rise (as a function of axial position) for a 32-minute ablation time is 34 deg. (Fig 2A). In the presence of blood flow, the maximum temperature rise for a 32-minute ablation is 31.5 deg. for the lowest arterial inlet velocity (Fig. 2B) and 30.5 deg. for the highest (Fig. 2C).

For nonzero arterial flow (Figs. 2B and 2C), the location of the maximum tumor temperature shifts upward (to the right in Fig. 2) relative to the no-flow case. For the 32-minute heating duration, the shift increases by 1.5mm with an increase in arterial flow rate. The location of the maximum temperature also shifts upward for all other times. This increase in shift is most evident at high flow rates (Fig. 2C).

In the presence of pure diffusion (Fig. 2A), the temperature profile is symmetric. The temperature rise in Fig. 2A at the upper and lower borders of the tumor is approximately 8 deg. for an ablation time of 32 min For an arterial velocity of 13.8 cm/s, the temperature rise at the bottom of the tumor is about 4 deg. in the case of a 32 min ablation, while for the higher arterial velocities the temperature rise in 32 min is 1 deg. at the bottom of the tumor. On the upper tumor boundary, the temperature rise is between 7 and 8 deg. for the two arterial velocities.

These plots demonstrate the importance of accurately modeling the effects of convection when the RF heat source is located near a large vessel. While the temperature rise at the center of the tumor may be high enough to achieve destruction, tumor regions located nearest to the vessel boundary experience minimal temperature elevation. Thus model predictions can identify locations where tumor recursion is likely without further intervention. It was also found that the behavior in the x-direction is more symmetrical in contrast to the axial dependence of the temperature field.

The important asymmetry in the z-direction exhibited in Fig. 2 is a natural effect of direct physical modeling, and difficult to capture using scalar perfusion models. The closer the heat source resides to the vessel boundary, the more important the local flow phenomena become.

The shift in the location of maximum temperature in Figs. 2B and 2C occurs even at an early ablation time of 1.0 minute. This time is not sufficient for significant amounts of heat to diffuse from the tumor to the arterial boundary. The shift is due to perfusion of blood from the bifurcation region upward through the heated region. The slight upward flow serves to cool the bottom of the tumor. Additionally, however, blood perfusing upward through the center of the heated region serves to warm, rather than cool, the upper tumor volume.

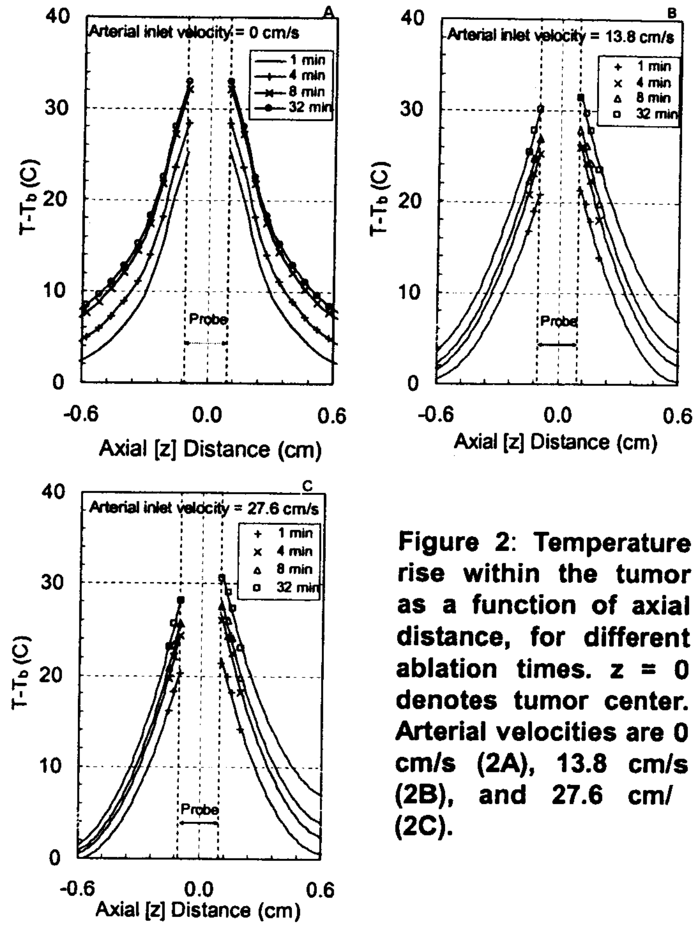

Figure 2: Temperature rise within the tumor as a function of axial distance, for different ablation times. z = 0 denotes tumor center. Arterial velocities are 0 cm/s (2A), 13.8 cm/s (2B), and 27.6 cm/ (2C).

The presence of blood vessels within or near tumors causes the transfer of heat away from the target. Due to the perfusion and convection, the heat sink effect causes irregular shapes of the ablated zone, thus resulting in subsequent tumor recurrence.

REFERENCES

Pandey, A, Chang I., Myers M., and Banerjee R.K., 2003, "RF Ablation with a Gaussian Heat Source In a Realistic Reconstructed Hepatic Geometry", *ASME, IMECE 03.*

Tungjitkusolmun, S. et al., 2002 "Three Dimensional Finite-Element Analyses For RF Hepatic Tumor Ablation", *IEEE*, Vol. 49, pp.3-9.

Chang, I, 2003, "Finite-element analysis of hepatic RF ablation probes using temperature-dependent electrical conductivity," Biomedical Engineering Online, www.biomedical-engineering-online.com/content/2/1/12