International Journal of Heat and Mass Transfer 83 (2015) 1–10

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Analytical and numerical study of tissue cryofreezing via the immersed boundary method

M.Y. Ge, K.J. Chua *, C. Shu, W.M. Yang

*Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore*

A R T I C L E   I N F O

*Article history:*
Received 12 June 2014
Received in revised form 25 September 2014
Accepted 24 November 2014

*Keywords:*
Cryosurgery
Major blood vessel
Immersed boundary method
Freezing fronts

A B S T R A C T

Cryosurgery is accepted as a favorable treatment option for eradicating undesirable cancerous tissue due to its minimally invasive nature. This work presents a finite difference study of a biological liver tissue undergoing cryofreezing using the immersed boundary method (IBM). The liver tissue is treated as a non-ideal material having temperature-dependent thermophysical properties. Numerical results exhibit good agreement with available data from literature with maximum errors of 1.7% and 1.5% for simulations and experiments, respectively. The influence of heating effect due to blood flow (through the vessel surface) has been investigated by applying the boundary condition-enforced IBM. Results have indicated that the heat source term due to the blood flow in the vessel embedded in the bioheat transfer equation significantly impacts the tissue temperature profiles and thermal gradient histories. In addition, the ice fronts, namely, 0 °C and −40 °C, progression can vary by as much as 35% at 500 s when the distance between the cryoprobe and the major blood vessel varies. This work has also demonstrated that applying the IBM to a bioheat model focusing on tissue cryofreezing is highly appropriate as far as the analysis of tissue freezing in the vicinity of major blood vessels is concerned.

## 1. Introduction

Hepatocellular carcinoma, with the survival rate of 25–30%, is the most common malignancy worldwide [1]. Cryosurgery is rapidly becoming a popular option for cancer treatment, particularly adept for ablating prostate and liver tumors. Compared with conventional therapies such as surgical resection, cryosurgery can reduce pain, minimize bleeding, and simplify surgical complications. Besides, being a comparatively cheaper therapy, patients need shorter hospital stay due to faster post-surgical recovery time. However, due to the heating effect between large blood vessels and cancerous tumor tissue, it has become a major challenge to completely freeze the target tumor. Insufficient freezing is the major reason for tumor survival which results in many local recurrences [2,3]. The key reason for recurrence after cryoablation is the untreated tumor cells around large blood vessels [4]. Furthermore, the possibility of unexpected complication will arise if the adjacent blood vessels are correspondingly damaged. Various research works have been devoted specifically to investigate the convective effects of large blood vessels, particularly the vessels with diameter above 0.5 mm [2,5].

One of the key issues that limits the widespread use of cryosurgery is the difficulty in controlling the destruction volume of cancerous tissue while minimizing cryoinjury to its surrounding healthy tissue. Moreover, the depth of the ice ball and the location of the critical isotherm (the one that marks total cell destruction) have to be estimated and this significantly reduces the accuracy of the treatment process. Consequently, various experiments [6] and numerical simulations [1,2,6–10] have been conducted to investigate the thermal and kinetic behaviors of tissues during ablation.

Kim et al. [2,7] developed a finite element model (FEM) to solve the cryosurgical problem with or without large blood vessels. Experimental validation of the model was conducted with good agreement up to 0.8%. Keangin and Rattanadecho [8] carried out the microwave ablation of porous liver samples using single slot microwave coaxial antenna. The coupled model of electromagnetic wave propagation and heat transfer analysis were solved using FEM. Xue et al. [10] conducted a three-dimensional FEM analysis on the behavior of knee joint's temperature distribution and heat flux from large blood vessels. Neufeld et al. [11] proposed a new conformal technique to reduce the staircase effects brought by the finite difference time domain (FDTD) method. It has the advantage of solving heat transfer problems with complex geometry and the potential of similar applications. Nevertheless, the computing

---

* Corresponding author. Tel.: +65 6516 2558; fax: +65 6779 1459.
*E-mail address:* mpeckje@nus.edu.sg (K.J. Chua).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.077

**Nomenclature**

| | |
|---|---|
| $T$ | temperature (K) |
| $T_{ml}$ | lower phase transition temperatures of tissue (K) |
| $T_{mu}$ | upper phase transition temperatures of tissue (K) |
| $c$ | specific heat (J kg$^{-1}$ K$^{-1}$) |
| $k$ | thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $k_{eff}$ | effective thermal conductivity tensor (W m$^{-1}$ K$^{-1}$) |
| $k'$ | the thermal equilibration parameter (0 or 1) |
| $q'''_m$ | metabolic heat rate (W m$^{-3}$) |
| $q_l$ | latent heat (kJ kg$^{-3}$) |
| $\vec{v}$ | blood velocity (m s$^{-1}$) |
| $h$ | local volumetric/interfacial convective heat transfer coefficient |
| $t$ | time (s) |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density (kg m$^{-3}$) |
| $\omega$ | the blood perfusion rate per unit tissue volume (kg m$^{-3}$ s$^{-1}$) |
| $\tau_q$ | phase-lags arising due to thermal inertia (s) |
| $\tau_\theta$ | phase-lags arising due to micro-structural interaction (s) |
| $\varepsilon$ | porosity |

*Subscripts*

| | |
|---|---|
| $t$ | tissue |
| $b$ | blood |
| $a$ | arterial blood |
| $m$ | metabolism |
| $f$ | frozen tissue |
| $u$ | unfrozen tissue |

speed, scale and accuracy of the model, even the success of calculation are highly related to the mesh segmentation. The method usually suffers from the level of complexity involved in regenerating the mesh to conform to the boundary due to direct implementation of the boundary conditions, especially for very complex or moving boundary surface. Besides the finite element method, other commercially available software, such as CFDRC and FLUENT, have been adopted to investigate the influence of neighboring blood vessels on tissue temperature profiles development during heat therapies. Solovchuk et al. [1] investigated the influence of blood vessels on temperature distributions during high-intensity focused ultrasound ablation of liver tumors. Zhao and Chua [9] developed a cryoablation model with complex blood vessel network using FLUENT. Sun et al. [6] conducted both in vivo experiments and numerical investigations on nanocryosurgery of tissue having large blood vessels. He et al. [12] proposed a novel method which combines the ADI-FDM and the local adaptive mesh generation. Table 1 highlights the different key points between present work and several recent studies about numerical analysis of thermal effects with large blood vessels.

Effective simulation of thermal flows with complex geometry of vascular network presents a phenomenological challenge with the need to accurately modeling the bioheat transfer problem with multiple heat-source effects. Conventional body-fitted numerical methods, which strongly couple the solution of governing equations with the implementation of boundary conditions, require tedious grid generation based on the solid boundary. To address this issue, an immersed boundary method (IBM) was first proposed by Peskin [13] in 1971. It was first applied to study flow patterns in heart valves. This method employs Cartesian Eulerian grid points for the solution of governing equations and Lagrangian points to represent the boundary of immersed objects. Navier–Stokes equations are solved over the entire domain as a unified system of both sides of the physical boundary is considered. As a result, the complicated grid generation task is avoided by imposing a regular Cartesian grid system on the entire computational domain. The simplicity and ease of implementation through the IBM have propelled it to become an intensive academic pursuit among researchers. Various modifications and refinements [14–18] have subsequently been proposed following Peskin's work in the area of computational fluid dynamics. Recently, trials have been made to extend the IBM to thermal flow problems. Among the most notable works, Zhang et al. [19] extended the IBM to investigate several heat transfer problems. In the similar vein of introducing a force term to the momentum equation, they incorporated a heating term to the energy equation to evolve a virtual heat source effect. Wang et al. [20] investigated both natural convection and forced convection problems around a stationary cylinder using a multi-direct heat source scheme. Similar to the conventional IBM, the heat source term introduced to the energy equation is calculated explicitly. As a result, the temperature condition on the boundary cannot be accurately satisfied. To mitigate this problem, Ren et al. [21] conducted research on applying the implicit IBM to solve convective problems in order to implement the appropriate boundary conditions. The boundary heat source is evaluated implicitly so that the temperature on the boundary, interpolated from the corrected temperature field, satisfies the given temperature condition.

In this paper, we will introduce the IBM to study cryofreezing of a biological tissue by adding a heat source in the bioheat transfer equation. This is equivalent to making a correction to the temperature field. Based on an extensive literature search and to the best of our knowledge, this is the first time to do such work for a bioheat model to study tissue cryofreezing.

In the model, the temperature correction is considered as an unknown and is determined implicitly [21]; making the corrected boundary temperature equal to the physical condition. This boundary condition-enforced IBM is well organized to solve the Dirichlet boundary condition problem. Additionally, we also compared three different bioheat transfer models with existing experimental results obtained from existing literatures.

## 2. Model development

### 2.1. Bioheat transfer model

To study the heat transfer problem of bio-tissue embedded with large blood vessels, we employed the classical Pennes bioheat equation [22]. Pennes bioheat equation is a modified form of the transient heat conduction equation and it includes the effects of blood flow and metabolic heat generation rate. The equation can be described as

$$\rho_t c_t\left(\frac{\partial T_t}{\partial t}\right) = \nabla\cdot(k_t\nabla T_t) + (1-k')\omega_b c_b[T_a - T_t] + q'''_m \tag{1}$$

where $t$ is the time, $T$ is the temperature, and subscripts $t$, $b$, $a$ and $m$ stand for tissue, blood, arterial blood and metabolism, respectively, $\rho$ is the density, $c$ is the specific heat, $k$ is the thermal conductivity, $\omega$ is the blood perfusion rate per unit tissue volume, $k'$ is the