Numerical simulations to analyze the impact of vascular network complexity over cryosurgical treatment process of 2D liver tumor tissue

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1. INTRODUCTION & OBJECTIVE

Cryosurgery is the process of ablating an undesirable tissue by inducing extremely low temperature. It is minimally invasive and accepted to be an effective cancer treatment for the liver. Even though the process of treatment is simple, it experiences a phase transition when the temperature is between -1˚C and -8˚C causing discontinuity in the phase transition front [1,2,3]. Moreover, the vascular network plays a significant role in determining the success of the surgery. The thermal effects of blood flow in the vascular network causes irregularities in the ice ball form which may result in insufficient tumor ablation[2].

Numerous numerical investigations have been performed for tumors in liver tissue without considering vascular network complexity which may have inadequate freezing. Although there are studies involving the vascular network, there is limited study available to the best of the authors' knowledge for irregular tumors in a tissue with vascular complexity. This study focuses upon 2D numerical investigation for cryoablation of irregular tumors in liver tissue with vascular network. Pennes bioheat equation has been used for both the tissue and the tumor. The continuity and Navier Stoke equations were solved for the vascular network. The convection-diffusion heat transfer equation is analysed numerically for the fluid domain coupled to the tissue domain. Numerical simulations have been carried out using finite element method with COMSOL. The temperature distribution across the tissue will determine the size and number of probes required to destroy the irregular tumor. Analysis of tissue necrosis would play an important role for the efficiency of the cryosurgery process.

2. RESULTS & HIGHLIGHTS OF IMPORTANT POINTS

2.1 Computational model geometry under consideration

In this study, the cryosurgery process is numerically simulated for a 2D liver tissue with a vascular network having irregular tumor which is illustrated in Fig.1. The vascular network is constructed according to Murray's law given below:

$$d_1^x = d_2^x + d_3^x$$

where x ranges from 2 to 3, d_1 is the diameter of the parent segment, d_2 and d_3 are the diameters of the two child segments at the same bifurcation. Bifurcation angle should be between 75˚ to 90˚. The vessel length is proportional to vessel diameter

$$L = K * d$$

where K is constant for a given vessel. [2].

2.2 Mathematical formulation

This study considers the liver and tissue as solid domain and the vascular domain as fluid domain. The Pennes bioheat model mentioned below is solved for the solid domain[1,3]

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T + w_b \rho_b c_b (T_b - T) + Q_m \tag{1}$$

where ρ,c,k, ρ_b, c_b, w_b, T_b, T, Q_m are the tissue density, specific heat capacity of tissue, thermal conductivity of tissue, blood density, specific heat capacity of blood, blood perfusion rate, temperature of blood, tissue temperature and metabolic rate of the tissue respectively. The heat transfer and blood flow in the fluid domain is govern by the following[2] :

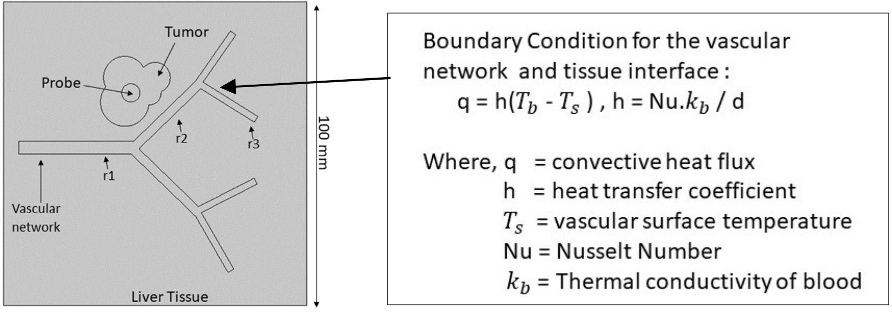
$$\rho_b c_b \frac{\partial T}{\partial t} + \rho_b c_b \boldsymbol{u}.\nabla T = \nabla.(k_b \nabla T) \tag{2}$$

$$\frac{\partial \rho_b}{\partial t} + \nabla.(\rho_b \boldsymbol{u}) = 0 \tag{3}$$

$$\rho_b \left[\frac{\partial \rho_b}{\partial t} + (\boldsymbol{u}.\nabla)\boldsymbol{u}\right] = \nabla.\left[-p\boldsymbol{I} + \mu \nabla \boldsymbol{u} + \mu(\nabla \boldsymbol{u})^r - \frac{2}{3}\mu(\nabla.\boldsymbol{u})\boldsymbol{I}\right] \tag{4}$$

where u, ***I,*** k_b, μ and p are the velocity vector, Identity matrix of space, thermal conductivity of blood, dynamic viscosity and pressure of blood respectively. A fixed temperature of -196 ˚C which is a boiling point of liquid nitrogen is used as the probe temperature. Initial temperature of 37˚C is considered for the whole domain and also to the inlet surface of the vascular network. The convection boundary condition is applied to the vascular and tissue interface as shown in Fig.1. The solid domain will go through phase transition when temperature falls in between -1˚C to -8˚C and is solved using an effective heat capacity method. However, the fluid domain will not undergo phase transition due to the convection inside the significant vessels [1,3].

The numerical simulations are performed using a finite element method with COMSOL with the assumption that the tissue and tumor have the same thermal properties. The complexity of the vascular network can reduce the efficiency of the cryosurgery process and an irregular tumor may require multiple probes to fully ablate the tumor. Patient specific model may be considered in future to pre-plan cryosurgery for the size and number of cryoprobes required, time duration and the necrosis of the healthy tissue may be analysed for a successful surgery.



Boundary Condition for the vascular network and tissue interface :
$q = h(T_b - T_s)$, $h = Nu.k_b / d$

Where, q = convective heat flux
h = heat transfer coefficient
T_s = vascular surface temperature
Nu = Nusselt Number
k_b = Thermal conductivity of blood

Fig.1 : Schematic diagram of the computational domain and the boundary condition in the vessel-tissue interface. The vascular network radius r1 = 2mm, r2 = 1.49mm, r3 = 1.1 mm

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