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Phase change heat transfer during cryosurgery of lung cancer using hyperbolic heat conduction model

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ABSTRACT

The paper reports a numerical study of phase change heat transfer process in lung cancer undergoing cryosurgery. A two dimensional hyperbolic bio-heat model with non-ideal property of tissue, blood perfusion and metabolism is used to analyze the problem. The governing equations are solved by finite difference method based on enthalpy formulation. Effects of relaxation time of heat flux in hyperbolic model on freezing process have been examined. A comparative investigation of two different models (hyperbolic and parabolic bio-heat models) is also presented.

1. Introduction

Cancer has become one of the most dangerous diseases in the world. It occurs mainly in lungs, liver, stomach, prostate and colorectal among others. Lung cancer is the leading cause of death among other cancer related deaths. It is uncontrolled growth of abnormal or diseased tissues in the lungs. As per the report of the World Health Organization (WHO), about 1.59 million people (19.4% of the total) die from lung cancer each year [1]. Main causes of the lung cancer are cigarette smoking, second-hand smoke and air pollution etc. Many medical techniques namely, cryosurgery, chemotherapy, radiation therapy and hyperthermia are available for the treatment of the lung cancer [2]. One of the important medical techniques to treat the lung cancer is cryosurgery.

Cryosurgery is the use of intense cold temperature in surgery to destroy diseased tissue. In cryosurgery, liquid nitrogen is introduced through an instrument called as cryoprobe within diseased tissues [3]. The main advantages of the cryosurgery are: (i) less pain, (ii) less cost (iii) shorter recovery time and (iv) shorter hospital stay [4,10,18]. Immediate and delayed effects are the two main mechanisms towards the destructive effect of freezing in cryosurgery. The immediate effect occurs due to the cooling rate, whereas the delayed effect appears due to the progressive failure of microcirculation [5]. The freezing process involves extracellular and intracellular ice crystallization. Extracellular ice crystallization form when the cooling rate is slow. As the freezing continues, the ice crystals increase, i.e., the water gets removed from the cells. As a result, the cells shrink and membrane gets damaged. During the high cooling rate, the extracellular ice crystallization does not have enough time to form. In this situation, the intracellular ice forms which causes destruction of cells [6].

For a successful cryosurgical treatment, a good knowledge of temperature distribution and the position of phase change interface within tumor tissues and neighboring normal tissues is required. The objective of cryosurgery in lung cancer is to maximize the damage of tumor tissues while preserving surrounding healthy lung tissues [7]. The cryosurgery is an important treatment of the lung cancer as it also provides the potential for long-term survival. A brief literature review related to the cryosurgery in lung cancer is given below.

Hoffmann et al. [8] have proposed a cryosurgical model to predict the thermal reaction of tumor and normal tissue to cryosurgery within a dorsal skin flap chamber. The detailed analysis of temperature distribution and rate of cell destruction in the tumor during cryosurgery has been presented by Chua et al. [9]. In their study, they observed that a single cryoprobe of bigger diameter is more effective in destroying the tumor while preserving healthy tissue as compared to multiple cryoprobes. Nakayama et al. [10] have simulated both analytically and numerically the growth of ice-ball and location of freezing front with time. It was reported that there exists a tumor tissue of limiting size, which can freeze at the maximum by a single cryoprobe. Niu et al. [11] have experimentally analyzed lung necrosis using different freeze-thaw cycles during cryosurgery in lung cancer. In their study, they found that three freeze-thaw cycles are required for complete destruction of lung cancer cells. Cryosurgical simulation of lung cancer based on efficient freezing time has been investigated by Tarwidi [12]. He showed that

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phase change interface position and temperature distribution in tissue can be used to maximize the damage to tumor tissue and minimize the injury to normal tissue.

Most of the above studies were based on Penne's bio-heat model [13]. The Penne's bio-heat model is given as

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

where c and ρ are the specific heat and density of the tissue, respectively.ρ_b is the density of blood, c_b is the specific heat of blood, w_b is the blood perfusion rate, T is the temperature, t is the time, T_b is the arterial temperature and Q_m is the metabolic heat generation in the tissue.

Eq. (1) is based on the Fourier's heat conduction law, which is given as

$$q(S, t) = -k\nabla T(S, t), \tag{2}$$

where k is the thermal conductivity of the tissue, $q(S, t)$ is the heat flux and $T(S, t)$ is the temperature at position $S(x, y, z)$ for time t.

In classical Fourier's law of heat conduction, it is assumed that the propagating speed of a thermal signal is infinite [14]. But in reality, thermal signal propagate with finite speed because in any thermodynamic process an equilibrium state takes some relaxation time to establish. Also, biological tissues have non-homogeneous structure and they require a relaxation time to acquire sufficient amount of energy for transfer to the nearest element [15]. To account the thermal behavior, which is not captured by Fourier's law, Cattaneo [16] and Vernotte [17] have simultaneously proposed a modified form of the Fourier's law as

$$q(S, t + \tau_q) = -k\nabla T(S, t), \tag{3}$$

where τ_q is the thermal relaxation time for heat flux. The first order Taylor expansion of Eq. (3) gives

$$q(S, t) + \tau_q\frac{\partial q(S, t)}{\partial t} = -k\nabla T(S, t), \tag{4}$$

Eq. (4) is called as Cattaneo-Vernotte's constitutive equation. After using Eqs. (1) and (4), we get a hyperbolic bio-heat equation of heat transfer as:

$$\tau_q\rho c\frac{\partial^2 T}{\partial t^2} + (\rho c + \tau_q\rho_b c_b w_b)\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \rho_b c_b w_b(T_b - T) + Q_m. \tag{5}$$

If the relaxation time for heat flux, i.e, τ_q=0, then the above hyperbolic bio-heat model becomes parabolic bio-heat model.

Heat transfer in biological tissues is a complex process. It involves several mechanisms such as thermal conduction, convection, radiation, metabolic heat generation, blood perfusion and phase change. Phase change process is the characteristic of cryosurgical treatment of lung cancer. The Penne's bio-heat model has been used by various authors in the literature [18–22] to solve the phase change problem in cryosurgery. The nature of phase change problems is non-linear due to the unknown position of the freezing front and the direction of ice growth. The major difficulty in the solution of phase change heat transfer problem of biological tissue appears because of non-linearity in the model due to discontinuity between phase change regions and the unknown position of the solidius-liquidus interfaces [23], though some researchers have ignored the temperature discontinuity at the solid-liquid interface [24–26].

Many studies are available in the literature [15,26–30], where hyperbolic bio-heat model with freezing has been used. Among others, Deng and Liu [26] have studied phase change heat transfer and thermal stress inside the skin tissue during freezing by using hyperbolic heat conduction model. They neglected the temperature discontinuity at phase change interface. To investigate temperature distribution and thermal damage in laser-irradiated biological tissues a two-dimensional non-Fourier bio-heat conduction model was presented by Zhou et al. [27]. An analytical and numerical solution of the hyperbolic bio-heat conduction equations was given by Torabi et al. [28]. Ahmadikia and Moradi [29] used the hyperbolic heat conduction model to describe the non-Fourier effect of biological tissue during freezing. In their study, the authors included the temperature discontinuity at solid-liquid interface without the heat source term due to metabolic heat and blood perfusion. Singh and Kumar [30] studied the freezing in biological tissue during cryosurgery by using one dimensional hyperbolic bio-heat conduction model with the non-ideal property of tissue and source of heat due to blood perfusion and metabolism. They obtained the temperature distributions and phase change interface positions in biological tissue for different values of relaxation time.

The above literature review reveals that the hyperbolic bio-heat model is still not used for the cryosurgical treatment of the lung cancer. In the present study, we propose a two dimensional hyperbolic bio-heat model for cryosurgery in lung cancer. A finite difference scheme is used to solve the model. To study the effect of relaxation time for heat flux on cryosurgery, temperature distributions and position of phase change interfaces in the tissue are obtained for different values of relaxation time (τ_q).

The rest of the paper is organized as follows. Mathematical formulation and governing equations are described in Section 2. Numerical solution is given in Section 3. Results and discussion are presented in Section 4. Finally, some concluding remarks are reported in Section 5.

2. Mathematical formulation

We consider a lung tissue of dimension 4.0 cm×4.0 cm in which a tumor tissue of dimension 1.5 cm×1.5 cm is embedded. A cryoprobe is located at the position $x = 0$, 1.8 cm $\leq y \leq$ 2.2 cm. The physical configuration of the present problem is given in Fig. 1 [19]. The governing equations of two dimensional hyperbolic bio-heat model in frozen and unfrozen regions are given as:

$$\tau_q\rho_f c_f\frac{\partial^2 T_f}{\partial t^2} + \rho_f c_f\frac{\partial T_f}{\partial t} = k_f\left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2}\right). \tag{6}$$

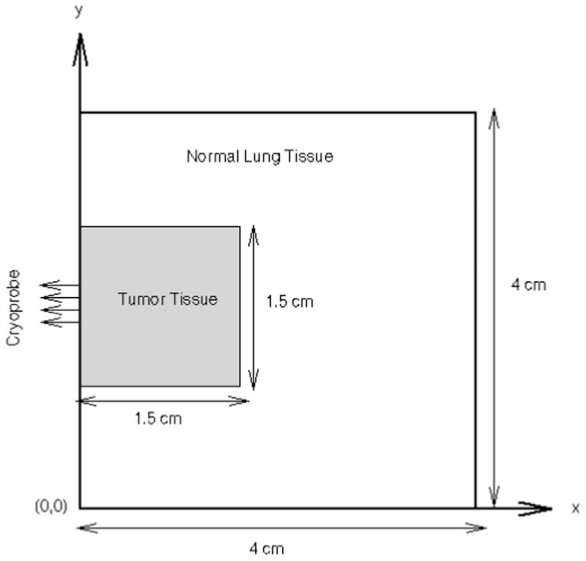

Fig. 1. Sketch of the physical problem.