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Numerical study on triple layer skin tissue freezing using dual phase lag bio-heat model

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ABSTRACT

The present article proposes dual-phase lag (DPL) bio-heat model in triple layer skin tissue for freezing procedure during cryosurgery with non-ideal property of tissue, metabolism and blood perfusion. The enthalpy formulation and the finite difference schemes are used to evaluate temperature distribution, solidus and liquidus interfaces in soft skin tissue during the freezing process. The effect of phase lags of heat flux and temperature gradient are also discussed in this study. It is mentioned that the different values of phase lags of heat flux and temperature gradient have important effect on temperature distribution, liquidus and solidus interfaces within the skin tissue.

1. Introduction

The skin is one of the organs of human body and protects us from microbes and elements, helps to regulate body temperature and permits the sensation of touch, heat and cold. The skin has three layers: epidermis, dermis and subcutaneous. The thickness of these layers varies depending on the location of the skin. Epidermis is the external layer of the skin and contains both living and dead cells. The epidermis is composed of 95% of keratin-synthesizing epithelial cells (keratinocytes) and 5% of non-keratinocytes. The dermis is much thicker than the epidermis. It constituents of three fibrin proteins: collagen elastin, little reticulin and group substance. Dermis plays the important role of thermoregulation and supports the vascular network to supply the non-vascularized epidermis with nutrients. The subcutaneous fat or subcutis is also known as hypodermis. It is a composition of loose fatty connective tissue. Hypodermis is composed of mainly fat and carries major blood vessels and nerves to the overlying skin [1]. Moreover in medicine, various thermal therapeutic methods have been widely used to cure diseased/injured involving skin tissue, where the objective is to induce thermal injury within skin tissue precisely, without affecting the surrounding healthy tissue.

Heat transfer in living tissues has been used in various applications like cryosurgery, cryopreservation, hyperthermia, thermal diagnostic, thermal comfort analysis, thermal parameter estimation and burn injury evaluation [2–16]. The transport of thermal energy in a living tissue is a complex process involving multiple phenomenological mechanisms including conduction, convection, radiation, metabolism, evaporation and phase change.

Heat transfer in skin is basically a heat conduction process coupled with a complicated physiological process, including blood circulation, sweating, metabolic heat generation and sometimes heat dissipation via hair or fur above the skin surface. Pennes bioheat model [17] is used by many researchers for the study of heat transfer in skin tissue due to its simplicity, ease application and effectiveness [2–10]. It is given as

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

where ρ is density of tissue; c, specific heat of tissue; k, thermal conductivity; c_b, specific heat of blood; w_b, blood perfusion rate; ρ_b, density of blood; T, temperature; t, time; T_b, arterial blood temperature and Q_m is the metabolic heat generation in the tissue. The Pennes model has been describes the thermal behaviour using the classical Fourier's law,

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

where $q(x, t)$ and $T(x, t)$ represents heat flux and temperature at position x and time t respectively. The classical Fourier's law assumes that the propagation speed of thermal disturbance is infinite i.e. infinitely fast propagation of thermal signal in the medium, which is contradictory to physical reality. The living tissues are highly non-homogeneous and need a relaxation time to accumulate enough energy to transfer to the nearest element. As a result to solve the paradox occurred in Pennes model different other models were developed. Cattaneo [18] and Vernotte [19] independently discussed a modified Fourier law considering the finite propagation speed of heat as

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

where τ_q is phase lag in heat flux. Using the first order Taylor's expansion of Eq. (3) and combining with Eq. (1), one can get the following hyperbolic bioheat equation

$$\tau_q \rho c \frac{\partial^2 T}{\partial t^2} + \left(\rho c + \tau_q \rho_b w_b c_b\right)\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + \rho_b w_b c_b (T_b - T) + Q_m. \tag{4}$$

This equation is called thermal wave model of bioheat equation as it predicts a wave like behaviour of heat transport. It is also called as Cattaneo and Vernotte (CV) constitutive relation.

Many researchers have studied the heat transfer in skin tissue using thermal wave bioheat model [20–22]. Although a lot of experiments confirmed that CV constitutive relation produces a more accurate prediction than the classical Fourier law, it still establishes an instantaneous response between the temperature gradient and the energy transport [23–25]. It also establishes that the temperature gradient is always the cause for heat flux while heat flux is always effect in the process of heat transfer [23,24]. Further hyperbolic model does not consider the micro scale response in space although it considers the micro scale response in time [24,26–28]. In order to solve the paradox in Fourier model and to consider the effect of micro structural effect in the fast transient process of heat transport, Tzou [24] proposed a new model by considering phase lag in heat flux and temperature gradient as follows:

$$q(t+\tau_q, x) = -k\nabla T(t+\tau_T, x), \tag{5}$$

where τ_T is phase lag in temperature gradient. This model is called dual phase lag (DPL) model and considers the effect of micro structural interaction in fast transient process of heat transport. The first order Taylor's expansion of the Eq. (5) gives

$$q + \tau_q \frac{\partial q}{\partial t} = -k\left(\frac{\partial T}{\partial x} + \tau_T \frac{\partial^2 T}{\partial t \partial x}\right). \tag{6}$$

Using the Eq. (6) and Eq. (1) one can get

$$\tau_q \rho c \frac{\partial^2 T}{\partial t^2} + \left(\rho c + \tau_q \rho_b w_b c_b\right)\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \tau_T \frac{\partial^3 T}{\partial t \partial x^2}\right) + \rho_b w_b c_b (T_b - T) + Q_m. \tag{7}$$

The above equation is known as DPL bioheat equation. It reduces to hyperbolic model for $\tau_T = 0$ s and to parabolic model for $\tau_q = 0 = \tau_T$.

Freezing and thawing process are two most important processes of phase change and are associated with high heat transfer rate. The heat transfer involved in phase change is essential in biomedical applications. Two potential applications of heat transfer involved in phase change are cryosurgery and cryopreservation. Cryopreservation is applied to enhance survival of biological materials such as cells, tissues, organs, etc; while cryosurgery is applied to destruct undesired tissues using a freezing process. Cryosurgery is a surgical technique which has been used to treat skin lesion for approximately 100 years. Liquid nitrogen is used as cryogen and introduced through cryoprobe to targeted region to freeze them within. Liquid nitrogen became available in the 1950 and is currently the most widely used cryogen and is particularly useful in the treatment of malignant lesions [29,30]. The aim of cryosurgery is to maximize the damage to undesired tissues within the define domain and minimize the injury to the surrounding healthy tissues [31,32]. The controlled destruction of tissue is generally used in medicine. The major advantages of cryosurgery are the low invasiveness of the procedure, easy, safe, minimal blood flow, localizing of the site of surgery and reducing the recovery and hospitalization time for the patient.

In biological tissues phase change occurs over a wide range and there exist moving boundaries between the two phases thus resulting mathematical models are non-linear. Analytical solutions are only possible for one dimensional, steady state cases [33]. Numerical methods appear to offer a more practical approach for solving these problems. Existing numerical approaches can be divided into two categories: front tracing and non front tracing [33]. Enthalpy method, a non front tracing method is easy to implement as fixed grids can be used for computation purpose and the non-linearity at the moving boundary can also be avoided. Finite difference methods are the most popular choice for numerical solution of the phase change problems [12,14–16,34–37] though finite element methods [38–40], boundary element methods [14] have also been introduced for the phase change problem in biological tissue.

Dual phase lag bioheat model has been used by many researchers without phase change [41–51]. Liu and Chen [42,46] discuss the DPL model during hyperthermia treatment. Zhou et al. [41,44] explain DPL model during laser heating of living tissues. Antaki [49] used DPL model to interpret heat conduction in processed meat. Xu et al. [50] presented a system discussion on the application of the DPL model in the bio-thermo-mechanical behaviour of skin tissue. Liu et al. [51] studied the effect of microstructural interaction on bio-heat transfer in skin, which was stratified into epidermis, dermis and subcutaneous using DPL model.

The present study presents, dual-phase lag (DPL) bio-heat model in triple layer skin during freezing procedure of cryosurgery with non-ideal property of tissue, metabolism and blood perfusion. The complication of the problem is due to moving interfaces, discontinuity of phase change interfaces, different thermal properties of triple layer skin. The enthalpy formulation is used for freezing phenomena and finite difference scheme is used to solve the resulting mathematical model. The temperature profiles and phase change interfaces in the skin tissue are obtained to study the effect of phase lags on freezing process. The comparative study of three different models of heat conduction i.e. parabolic, hyperbolic and DPL models is also given.

2. Mathematical model

The schematic diagram of triple layer skin is shown in Fig. 1. The thickness of epidermis, dermis and subcutaneous layer are 0.00008 m, 0.002 m and 0.01 m respectively. The total thickness of skin tissue is taken as l.