Thermal Behavior in Layered Tissue with Continued Pulse Heating

Department of Mechanical Engineering, Far East University
*Email: kcliu@feu.edu.tw

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Abstract

This paper investigates the thermal behavior in laser-irradiated layered tissue, which was stratified into skin, fat, and muscle. Taking the effect of micro-structural interaction into account, a modified non–Fourier equation of bio-heat transfer was developed based on the second-order Taylor expansion of dual-phase-lag model. This equation is a fourth order partial differential equation and can be simplified as the bio-heat transfer equations derived from Pennes’ model, thermal wave model, and the linearized form of dual-phase-lag model. The broad beam irradiation method is adopted to calculate the laser energy deposition in the scattering tissues. The boundary conditions at the interface between two adjacent layers become complicated. There are mathematical difficulties in dealing with such a problem. A hybrid numerical scheme is extended to solve the present problem. The deviations of the results from the bio-heat transfer equations based on Pennes’ model, thermal wave model and dual-phase-lag model are presented and discussed.

Keywords: Bio-heat transfer, Dual-phase-lag mode, Laplace transform, Modified discretization

1. Introduction

From the viewpoint of the thermal treatment, if well controlled, the high-intensity pulsed heating can produce accurate and appropriate heating amount. The entire treatment time can be shortened, and the treatment quality will be enhanced. This characteristic is particularly important to the bulky objects. Therefore, in the last decade, the applications of pulse heating in the skin treatment are booming, and a revolutionary impact is on the skin beauty. For example, in the past surgical excision, dermabrasion and other methods were used to remove tattoos, which can be easily removed with a laser. In addition, a variety of skin vascular lesions, pigmented birthmarks, moles, spots, scars, even hair, wrinkles are removal with a laser.

The Pennes bio-heat transfer model is commonly used to simulate thermal behavior in biological bodies due to simplicity and validity. The Pennes bio-heat equation describes the thermal behavior based on the classical Fourier’s law which depicts an infinitely fast propagation of thermal signal. In reality, the living tissues are highly non-homogenous and need a relaxation time to accumulate enough energy to transfer to the nearest element. As a result, to solve the paradox occurred in the Pennes model, the thermal wave model of bio-heat transfer was proposed for the investigation of physical mechanisms and the behaviors in thermal wave propagation in living tissues [1].

The properties of hyperbolic diffusion in bio-heat transfer have attracted the relevant researchers’ attention. Liu [2] and Özen [3], respectively, studied the thermal wave propagation bio-heat transfer in homogenous and multi-layer tissues. Shih et al. [4] explored the impact of thermal wave characteristics on thermal dose distribution during thermal therapy. However, in order to consider the effect of micro-structural interactions in the fast transient process of heat transport, a phase lag for temperature gradient absent in the thermal wave model was introduced [5]. The corresponding model is called the dual-phase-lag (DPL) model. Antaki [6] used the DPL model to interpret heat conduction in processed meat that was interpreted with the thermal wave model. Antaki [6] estimated the phase lag time of heat flux to be 14-16 s and the phase lag time of temperature gradient to be 0.043-0.056 s for processed meat. Xu et al. [7] presented a system discussion on the application of the DPL model in the biothermomechanical behavior of skin tissue. The more rational prediction of temperature distribution is always needed in the development of hyperthermia.

For more realistic predictions, this work would employ the DPL model of bio-heat transfer to analyze the thermal behavior in tissue, which was stratified into skin, fat, and muscle. The DPL equation of bio-heat transfer was always developed with the first-order Taylor series expansion of DPL model. For a more general form, this paper develops a modified DPL equation of bio-heat transfer based on the second-order Taylor expansion. For convenience of statement, this paper, calls the former first-order DPL equation and another second-order DPL equation. The second-order DPL equation is a fourth order partial differential equation. Due to the difference in physiological and thermal properties, the boundary conditions at the interface between two adjacent layers become complicated. There are mathematical difficulties in dealing with such a problem. The hybrid numerical scheme [8] based on the Laplace transform and the modified discretization technique is extended to solve the present problem. The deviations of the results from the bio-heat transfer equations based on Pennes’ model,