Investigation for the dual phase lag behavior of bio-heat transfer

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Abstract

The success of hyperthermia treatment depends on the precise prediction and control of temperature distribution in the tissue. It was absolutely a necessity for hyperthermia treatment planning to understand the heat transport occurring in biological tissue. The tissue is highly non-homogenous, and non-Fourier thermal behavior in biological tissue has been experimentally observed. The dual phase lag model of heat conduction has been used to interpret the non-Fourier thermal behavior. This work attempts to be an extension study of Antaki [12] and explore whether the DPL thermal behavior exists in tissue. The inverse non-Fourier bio-heat transfer problem in the bi-layer spherical geometry is analyzed. In order to further address whether the dual phase lag model of bio-heat transfer merits additional study, the comparisons of the history of temperature increase among the present calculated results, the calculated values from the classical bio-heat transfer equation, and the experimental data are made for various measurement locations.

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1. Introduction

It is an instinct of the human body to use heat to fight disease. The use of heat in order to necrotize undesirable tissue for therapeutic purposes has been in many applications, such as laser, microwave and magnetic fluid hyperthermia. The success of these thermal therapies depends on the precise prediction and control of temperature in the tissue. An ideal thermal treatment should selectively destroy the target region without damaging the surrounding healthy tissue. Knowledge of temperature distribution in the entire treatment region is essential for limiting the temperatures in the healthy tissue to prevent damage. However, it is not easy to accurately determine the temperature field over the entire treatment region during clinical hyperthermia treatments, because the pain tolerance of patients makes the number of invasive temperature probes limited [1]. Hence, the analysis and modeling of the underlying thermal mechanisms are important to optimize the temperature distribution in the treated region. As Wren et al. [2] stated, in order to further improve the thermal treatment methods, bio-heat models are essential during development of equipment, for pre-planning purposes, for on-line monitoring and decision support as well as for evaluation of the extent of thermal damage.

The most commonly used model among many bio-heat transfer models is the Pennes bio-heat model for simplicity and validity. The Pennes bio-heat equation was developed on the base of the classical Fourier’s law that depicts an infinitely fast propagation of thermal signal. However, the contents of the literatures [3–5] indicated that thermal behavior in non-homogenous media needs a relaxation time to accumulate enough energy to transfer to the nearest element and the relaxation time in biological tissues is to be 20–30 s. The experiments of Mitra et al. [6] with processed meat showed the evidence of non-Fourier conduction in tissue. The relaxation time for processed meat is of the order of 15 s. Roetzel et al. [7] also made the experimental investigation for processed meat and had the value of relaxation time about 2 s. Obviously, the concept of infinite heat propagation velocity is incompatible with physical reality in tissues. As a result, the thermal wave model of bio-heat transfer received the attention from relevant researchers [8–11].

For developing better tools to predict transient temperature in tissue, Antaki [12] treated the processed meat as a composite material that is a heterogeneous compacted mixture of meat particles and water and used the dual phase lag (DPL) model to interpret heat conduction in it. After that, Liu and Chen [13] studied temperature rise behavior in a two-layer concentric spherical region during magnetic tumor hyperthermia treatment with the DPL model. The DPL model describes a macroscopic temperature with the micro-structural effect by introducing the phase lag times of heat flux and temperature gradient. Specifically, the DPL model combines the wave features of hyperbolic conduction with a diffusion-like feature of the evidence not captured by the hyperbolic case [12]. Recently, Zhang [14] developed a bio-heat equation,