Analysis for the dual-phase-lag bio-heat transfer during magnetic hyperthermia treatment

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1. Introduction

Cancer cells have a higher chance of dying when the temperature is above 42.5 °C, and the rate of death drastically increases with increasing temperature [1]. Magnetic fluid hyperthermia is one of hyperthermia modalities for tumor treatment. In magnetic tumor hyperthermia, fine magnetic particles are localized at the tumor tissue. Then, an alternating magnetic field is applied to the target region, which heats the magnetic particles by magnetic hysteresis losses. These particles might act as localized heat sources. An ideal hyperthermia treatment should selectively destroy the tumor cells without damaging the surrounding healthy tissue. Moroz et al. [2] stated that magnetic fluid hyperthermia had the maximum potential for such selective targeting. It was absolutely a necessity for hyperthermia treatment planning to understand the heat transport occurring in biological tissues [3]. Especially, the temperature distribution inside as well as outside the target region must be known as function of the exposure time in order to provide a level of therapeutic temperature and, on the other hand, to avoid overheating and damaging of the surrounding healthy tissue.

Several papers [4–8] have studied the behavior of bio-heat transfer in multi-layer living tissues during hyperthermia treatment with the Pennes’ equation. Andrä et al. [4] modeled small breast carcinomas surrounded by extended healthy tissue as a solid sphere with constant heat generation. They gave an elementary solution of the original heat conduction problem without the effects of blood perfusion and metabolism. Bagaria and Johnson [5] considered the tissue model as two finite concentric spherical regions with the blood perfusion effect and presented analytical and numerical solutions to the model with the mixed boundary conditions. Maenosono and Saita [6] carried out theoretical assessment of FePt magnetic nanoparticles as heating elements for hyperthermia. The temperature rise behavior in vivo with the Newman boundary conditions in spherical co-ordinates was estimated. Durkee et al. [7] offered the exact solutions to the Pennes’ bio-heat equation in one-dimensional multi-layer spherical geometry. Tsuda et al. [8] developed an inverse method to optimize the heating conditions during a hyperthermia treatment.

It was well known that the Pennes’ equation was based on the classical Fourier’s law that depicted an infinitely fast propagation of thermal signal. In reality, accumulating enough energy to transfer to the nearest element would take time in the process of heat transfer. The literatures [9–11] reported the relaxation time in biological bodies to be 20–30 s. Mitra et al. [12] found the relaxation time for processed meat is of the order of 15 s. The experimental investigation made by Roetzel et al. [13] showed the value of relaxation time about 2 s for processed meat. The above literatures further supported the phenomenon of finite thermal propagation velocity in the process of bio-heat transfer. Since the concept of finite heat propagation velocity received the attention from relevant researchers [14–17], the paradox occurred in the classical heat transfer model was solved. Although the thermal wave model

Abstract

Magnetic fluid hyperthermia is one of hyperthermia modalities for tumor treatment. The control of temperatures is necessary and important for treatment quality. Living tissue is highly non-homogeneous, and the velocity of heat transfer in it should be limited. Thus, this work analyzes the temperature rise behaviors in biological tissues during hyperthermia treatment within the dual-phase-lag model, which accounts the effect of local non-equilibrium on the thermal behavior. A small tumor surrounded by the health tissue is considered as a solid sphere. The influences of lag times, metabolic heat generation rate, blood perfusion rate, and other physiological parameters on the thermal response in tissues are investigated. While the metabolic heat generation takes little percentage of heating source, its effect on the temperature rise can be ignored. The control of the blood perfusion rate is helpful to have an ideal hyperthermia treatment. The lag times, \( t_1 \) and \( t_2 \), affect the bio-heat transfer at the early times of heating. The total effect of \( t_1 \) and \( t_2 \) on the bio-heat transfer may be different for the same \( C_1/C_2 \) value.