Journal of Fiber Bioengineering and Informatics 8:3 (2015) 473–481
doi:10.3993/jfbim00135

Investigation on Reconstruction of Three-dimensional Temperature Field in a Biological Body with Finite Element Method

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Abstract

The noninvasive detection and reconstruction of 3D temperature field in a biological body have received increasing attention in bio-medical engineering field. Based on the classical Pennes bioheat transfer equation, the heat transfer mathematical model fitting for breast tissue is founded in this paper. Meanwhile, using the large analysis software ANSYS, the modeling and simulating of heat transfer in pork and intravital breast tissue are presented combining with Finite Element Method (FEM). The result shows, the 3D temperature field can be well reconstructed efficiently, which will play a positive role in promoting many research field such as tumor thermotherapy, cryosurgery, cryo-preservation of biomaterial and so on.

Keywords: Finite Element Method (FEM); 3D Temperature Field; Biological Tissue; Bioheat Transfer

1 Introduction

The development and improvement of the noninvasive detection and reconstruction of 3D temperature field in biological tissue will certainly promote the advances in bio-medical engineering and technology such as tumor thermotherapy, cryosurgery, cryo-preservation of biomaterial and so on [1]. The main objective of hyperthermia is establishing a temperature field fitting for oncotherapy of partial organ. In the early 1860s, W. Bush first proposed the cancer cells could be broken or killed in the temperature range 41-45°C, in which the normal cells could bear [2]. The key of hyperthermia is the temperature control or temperature field control. In order to get a suitable temperature field, one can focus some form of energy in the tumor and then acquires the distribution of temperature field by solving Pennes Bio-heat Transfer Equation (BHTE) [3]. Different heat source (including location, shape and energy) is corresponding to different temperature field and surface temperature distribution, that is to say there is a mapping relationship existing between the heat source and the temperature field. By analyzing on the infrared image taken with thermal infrared imager and the model simulated with FEM, one can obtain the caloric

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information and the detailed temperature field information of the tumor tissue in the process of hyperthermia, which will be a valuable reference for the temperature control in hyperthermia.

No matter how complex the geometries are, the finite element method can simplify and simulate them with finite correlative elements, which is very suitable for simulating complex model organisms [4]. ANSYS, a large general-purpose analysis software with powerful post-treatment function, is commonly used in the analysis of FEM, and can perform many analyses of physical field including stress analysis, heat analysis, electromagnetic field analysis and so on [5]. A typical thermal analysis includes three steps: (1) Pre-treatment: modeling and mesh; (2) Solving: apply load and calculate; (3) Post-treatment: view results.

2 Mathematical Model and Simulation Methods

2.1 Mathematical Model of Heat Conduction

The anatomical structure of the biological tissues or organs is very complex. In the past years, there appeared much research on bioheat transfer simulation but quite a few of them are based on ideal model. Due to extremely complex calculation process, only rather limited researches succeed to model the bioheat transfer by considering acceptable real anatomical structure. In 1948, Pennes et al. established the well known Pennes bioheat transfer equation that is recognized as the most suitable one in all bioheat transfer models so far. Its typical form can be expressed as follows [6]:

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

where, $\rho c\frac{\partial T}{\partial t}$ is the transient term, which indicates the change of biological tissue temperature as a function of time; $T(x, y, z)$ is the distribution function of temperature field in tissue; ρ and c represent the density and thermal capacitivity respectively; k is the thermal conductivity; w_b, ρ_b and c_b represent the perfusion rate, density and thermal capacitivity of the blood respectively; T_a is the temperature of arterial blood; Q_m is the metabolic heat in intravital tissue. This equation is homogeneous in steady-state condition. Therefore Eq. (1) should be written as follows:

$$\nabla(k \cdot \nabla T) + w_b\rho_b c_b(T_a - T) + Q_m = 0 \tag{2}$$

Physiological activity of tissues depends heavily on the temperature. The metabolic heat production Q_m can generally be expressed as a function of temperature, i.e.,

$$Q_m = Q_{m0} \cdot 3^{\frac{T_m-37}{10}} \tag{3}$$

where, Q_{m0} is the metabolic heat generation of tissue at basal state 37°C. However, if the part of human body such as foot, hand, knee and etc, is far away from body core, the number 37 should be written as 36. In this paper, the main analysis object is female breast tissue, which is very near from body core [7]. Therefore, Q_{m0} represents themetabolic heat production of tissue at 37°C. In addition, there are very few large vessels in the breast tissue. So the heat transfer model can be simplified as:

$$\nabla(k \cdot \nabla T) + Q_{m0} \cdot 3^{\frac{T_m-37}{10}} = 0 \tag{4}$$