Selected problems of bioheat transfer modelling

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Abstract

The problems connected with the numerical modelling of heat transfer in biological tissues subjected to the high and low temperatures are considered. To describe these processes different models of bioheat transfer are used, namely Pennes equation, Cattaneo-Vernotte equation, dual-phase lag model and generalized dual-phase lag equation. The problems of laser-tissue interactions, the action of electromagnetic field on the biological tissues and the tissue freezing are discussed. At the stage of numerical solutions mainly the finite difference method and the boundary element method are used.

Keywords: bioheat transfer, numerical methods, dual-phase lag model, Pennes equation, Cattaneo-Vernotte equation, finite difference method, boundary element method, hyperthermia, hypothermia

1. Introduction

Knowledge of thermal phenomena occurring in the human organism allows one, among other, the proper planning of artificial hyperthermia or hypothermia treatments. Such treatments are carried out in order to destroy the pathologically changed tissues. Analysis of the tissue heating or the tissue freezing can be done using the numerical methods. For this purpose, the proper selection of the mathematical model is very important. In this paper the different mathematical models are discussed. At the stage of numerical computations mainly the finite difference method and the boundary element method are used. The examples connected with the laser-tissue interactions, the impact of the electromagnetic field on the biological tissue and the freezing process modelling are presented.

2. Mathematical models

The transport of thermal energy in the living tissues is a complex process involving conduction, convection, radiation, metabolism, evaporation and phase change. Currently, there are a lot of mathematical models describing thermal phenomena occurring in the living organisms exposed to the high and low temperatures. The oldest Pennes model [1] is based on the Fourier equation in which two source functions associated with the metabolism and blood perfusion are taken into account. The Cattaneo-Vernotte equation [2] contains the relaxation time which is a measure of the delay of the heat flux in relation to the temperature gradient. In the dual-phase lag equation (DPL) [3] additionally the thermalization time occurs, which takes into account the delay of temperature gradient in relation to the heat flux. They are also the models based on the theory of porous media, which consist of two coupled equations describing the temperature of the tissue and blood. One of them is the generalized dual-phase lag equation [4] in which the phase lag times are expressed in terms of the blood and tissue properties, the interphase convective heat transfer coefficient and the blood perfusion rate.

3. Heating of biological tissue

Heating of the tissue is carried out in the several ways e.g. using the electromagnetic field or the laser irradiation. As an example, in Figure 1 the simplified radio frequency (RF) hyperthermia system is shown [5]. The mathematical model of the process analyzed consists of two parts. The electric field distribution is described by the Laplace equation, while the temperature distribution is described by the Pennes equation (steady state is considered). The problem has been solved using the boundary element method. In Figure 2 the temperature distribution in the domain considered is presented for the case when in the tumor region the nanoparticles are introduced [5].

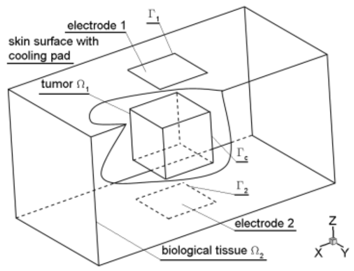

Figure 1: Action of electric field on biological tissue [5]

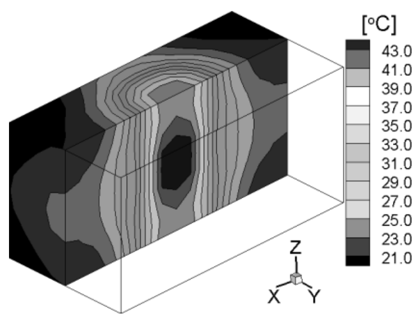

Figure 2: Temperature distribution (tumor with nanoparticles)

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In the case of laser-tissue interactions modelling the internal heat source resulting from the laser irradiation results from the solution of the diffusion equation. In Figure 3 the temperature distribution in the irradiated tissue is shown [6]. The generalized dual-phase lag equation is used here and the problem is solved using the finite difference method.

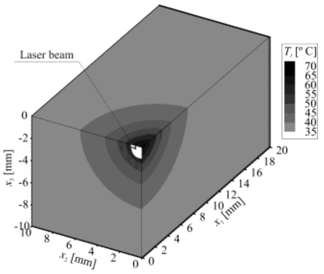

Figure 3: Temperature distribution [6]

4. Freezing of biological tissue

In Figure 4 the domain of biological tissue subjected to the action of cylindrical cryoprobe is shown [7]. Temperature distribution is described by dual-phase lag equation supplemented by appropriate boundary and initial conditions. The model of the freezing process is based on the introduction of a parameter called 'a substitute thermal capacity' to the dual-phase lag equation. The problem has been solved using the explicit scheme of finite difference method developed for hyperbolic equation. Figure 5 illustrates the temperature distribution in being frozen tissue [7].

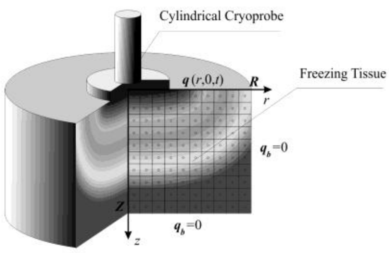

Figure 4: Domain considered [7]

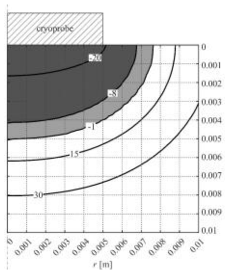

Figure 5: Temperature distribution after 90 seconds

5. Identification problems

The body surface temperature is controlled by the blood perfusion, local metabolism and the heat exchange between skin and environment. The appearance of tumor can lead to the increase of a local blood perfusion and a capacity of metabolic heat source and in this case the temperature of skin surface can also increase. This abnormal temperature (Figure 6) can be used in order to predict the location and size of tumor region (Figure 7) [8]. The non-invasive diagnosis using skin surface temperature measurements requires the solution of inverse bioheat transfer problem [8].

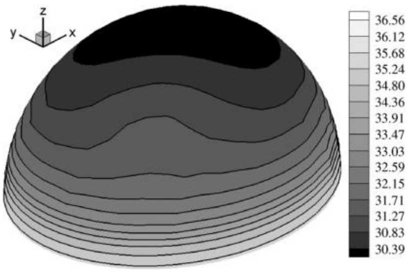

Figure 6: Temperature distribution on the skin surface [8]

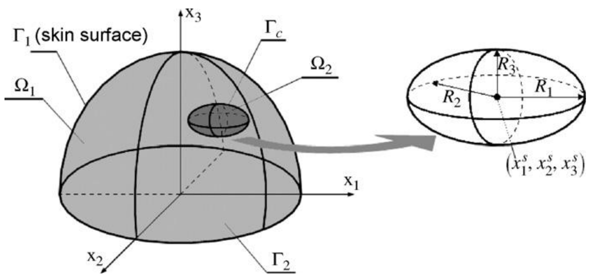

Figure 7: Tissue with a tumor [8]

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