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# Analysis of thermal damage to laser irradiated tissue based on the dual-phase-lag model

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ABSTRACT

The use of lasers in medical applications has dramatically increased over the past half century. For treatment quality, the control of thermal damage is absolutely necessary. Living tissue is highly non-homogenous, and the effect of local non-equilibrium on the thermal behavior should be accounted. Therefore, this work uses the dual-phase-lag model to analyze thermal response for estimating thermal damage in laser-irradiated biological tissue. The transport behavior of laser light in the tissue is assumed as highly absorbed and strongly scattered, respectively. Thermal damage is assessed with the rate process equation. The effects of blood perfusion and metabolic heat generation on thermal response and thermal damage are explored. The reliability of the present results has been evidenced through comparison with the literature. The results show the DPL bio-heat transfer equation with the effect of blood perfusion, even with the space-dependent source term, can be reduced to the Fourier bio-heat transfer equation for $\tau_q = \tau_T$.



## 1. Introduction

Over the past half century, the applications of laser in the medical treatments, such as laser hyperthermia, coagulation, and surgery, have been increasing. Responses of biological tissues to laser irradiation are various. Among of them, thermal interaction is the most important, since temperature rising due to thermal effects is the ultimate factor to produce thermal damage. For lack of knowledge about thermal response, clinical doctors usually cannot control accurately the laser power or treatment times, maybe induce the target tissue additional hot injury or lack of thermal dose. Thermal damage in a living tissue was considered as a chemical reaction. Welch [1] has used a chemical rate process equation to quantify it based on protein denaturation. The Arrenius equation was used to evaluate the damage parameter, and been followed by many researchers [2,3]. It further shows that the protein denaturation depends on the tissue temperature. In order to predict the thermal damage, it is required to investigate the thermal response caused by the laser energy deposition. As a result, rational analysis of thermal transport is relatively important to improve the treatment efficiency and for safety.

The Pennes bio-heat transfer equation is commonly used to simulate thermal behavior in biological bodies for simplicity and validity. However, it was developed on the basis of the Fourier law which depicts an infinitely fast propagation of thermal signal. In accordance with the contents of the literature [4,5], thermal behavior in nonhomogenous media needs a relaxation time to accumulate enough energy to transfer to the nearest element. The living tissues are highly nonhomogenous, and the velocity of heat transfer in tissues should be limited. The correct description of thermal behavior in biological tissues is an absolute necessity for fundamental knowledge on heat transfer in living tissues. Mitra et al. [6] did the experimental study in processed meat and reported the thermal relaxation time for such material is of the order of 15 s. As a result, to solve the paradox of instantaneous responses of thermal disturbance occurred in the Pennes bio-heat transfer equation, the non-Fourier models of bio-heat transfer were proposed for the investigation of physical mechanisms and the behaviors in thermal propagation in living tissues [7–9].

In order to consider the effect of micro-structural interactions in the fast transient process of heat transport, Tzou [10] introduced a phase lag for temperature gradient absent in the thermal wave model. The corresponding model is called the dual-phase-lag (DPL) model. Antaki [9] has used the DPL model to interpret heat conduction in processed meat treated as a composite material that is a heterogeneous compacted mixture of meat particles and water. At the same time, the phase lag times of heat flux and temperature gradient were predicted from the measurement data in the literature [6] for processed meat. Liu and his co-workers [11,12] did an extension study for exploring whether the DPL thermal behavior exists in tissue. They estimated the phase lag times in accordance

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**Nomenclature**

| | |
|---|---|
| $c$ | specific heat of tissue, J/kg· K |
| $c_b$ | specific heat of blood, J/kg· K |
| $f$ | parameter defined in Eq. (20) |
| $g$ | anisotropy factor. |
| $H$ | new dependent variable, $H = T - T_b$ |
| $\widetilde{H}$ | Laplace transform of $H$ |
| $k$ | thermal conductivity, W/m· K |
| $K$ | parameter defined in Eq. (21) |
| $\ell$ | distance between two neighboring nodes, m |
| $n$ | total number of nodes |
| $p$ | parameter defined in Eq. (22) |
| $q_0$ | laser density, W/m$^3$ |
| $q_m$ | metabolic heat generation, W/m$^3$ |
| $q_r$ | spatial heating source, W/m$^3$ |
| $R_d$ | diffuse reflectance of light at the irradiated surface |
| $s$ | Laplace transform parameter |
| $t$ | time, sec |
| $T$ | temperature of tissue, °C |
| $T_b$ | arterial temperature, °C |
| $T_i$ | initial temperature of tissue, °C |
| $w_b$ | perfusion rate of blood, m$^3$/s/m$^3$ |

*Greek symbols*

| | |
|---|---|
| $\delta$ | effective optical penetration depth |
| $\lambda$ | parameter defined in Eq. (19) |
| $\mu_a$ | absorption coefficient |
| $\mu_s$ | scattering coefficient. |
| $\mu_s'$ | reduced scattering coefficient |
| $\rho$ | density, kg/m$^3$ |
| $\tau_q$ | phase lag of the heat flux |
| $\tau_T$ | phase lag of the temperature gradient |
| $\phi_{in}$ | incident laser irradiance |
| $\varphi$ | function |
| $\Omega$ | damage parameter |

*Subscripts*

| | |
|---|---|
| $i$ | node number |
| $j$ | number of sub-space domain |

with the experimental data and gave the further evidence to the dual phase lag thermal behavior in muscle tissue from cow. Xu et al. [13,14] presented a system discussion to the DPL effects on the biothermomechanical behavior of skin tissue. Liu and Chen [15] predicted the thermal behavior in a two-layer concentric spherical tissue with constant heat source. Liu et al. [16] employed the DPL model of bio-heat transfer to analyze the bio-heat transfer problem in a tri-layer composite. Zhou et al. [17] investigated thermal damage to biological tissues caused by laser irradiation with the DPL model. Zhang [18] and Afrin et al. [19,20] presented another feature of the DPL bio-heat transfer with the definition of separate temperatures for solid and fluid constituents of tissue. These papers have done a lot of discussions for the physical meanings and the applicability of DPL mode.

This work employs the DPL model of bio-heat transfer to simulate the thermal response in the laser irradiated tissue for the estimation of thermal damage. The phase lag times $\tau_q$ and $\tau_T$ are the characteristic of the dual-phase-lag model, and their values significantly affect the simulated results [15,17,21]. There are mathematical difficulties in solving the DPL model of bio-heat transfer. As a result, the different conclusions are presented in the relevant literatures [10,13,16,17]. In pure heat conduction media, Tzou [10] derived that the DPL model can reduce to Fourier's law for $\tau_q = \tau_T$, but Xu et al. [13] obtained the different results. Zhou et al. [17] concluded that the DPL bio-heat conduction equation with the effect of blood perfusion can be reduced to the Fourier bio-heat conduction equation only if both $\tau_q$ and $\tau_T$ are zero. Liu et al. [16] reviewed the above controversy with a bio-heat conduction problem with boundary pulse heating. They showed that the DPL model can be reduced to the Fourier heat conduction theory in a pure conduction medium where $\tau_T$ is equal to $\tau_q$ and that the DPL model of bio-heat transfer can be reduced to the classical model of bio-heat transfer for $\tau_q = \tau_T$, even with the effect of blood perfusion, if the thermal effect of metabolic heat generation can be neglected. However, the heating source considered in the literatures [13,17] is space-dependent, not boundary heating.

The form of heating source may change the effects of lag times on the thermal behavior in living tissues. Therefore, this work regards the transport behavior of laser light in the tissue as highly absorbed and strongly scattered, respectively. The hybrid numerical scheme [22–23] based on the Laplace transform and the modified discretization technique is proposed to solve the DPL equation of bio-heat transfer. The influences of lag times, blood perfusion rate, and heating strength on the thermal response and thermal damage are investigated. It would be further investigated whether the DPL bio-heat conduction equation with the effect of blood perfusion can be reduced to the Fourier bio-heat conduction equation only if both $\tau_q$ and $\tau_T$ are zero. Also, the reliability of the present results would be evidenced through comparison with the contents of the literatures and discussion.

## 2. Problem formulation

In order to solve the paradox occurred in the classical heat flux model and to consider the effect of micro-structural interactions, the DPL model was suggested [10] with

$$\vec{q}(t+\tau_q) = -k\nabla T(t+\tau_T) \tag{1}$$

where $T$ is the temperature, $k$ is the heat conductivity, $q$ is the heat flux, and $t$ is the time. $\tau_T$ and $\tau_q$ mean phase lag time for temperature gradient and heat flux.

Eq. (1) is, usually, developed in the first-order Taylor series expansion [10,17]. Thus, it is rewritten as

$$\left(1+\tau_q\frac{\partial}{\partial t}\right)\vec{q} = -\left(1+\tau_T\frac{\partial}{\partial t}\right)k\nabla T \tag{2}$$

In a local energy balance, the energy conservation equation of bio-heat transfer is described as

$$\rho C\frac{\partial T}{\partial t} = -\nabla\cdot\vec{q} + w_b\rho_b c_b(T_b - T) + q_m + q_r \tag{3}$$

where $t$ is time. $\rho$, $c$, and $T$ denote density, specific heat, and temperature of tissue. $c_b$ and $w_b$ are, respectively, the specific heat and perfusion rate of blood. $q_m$ is the metabolic heat generation and $q_r$ is the heat source for spatial heating. $T_b$ is the arterial temperature.

Substituting (2) into the energy conservation (3) leads to the DPL equation of bio-heat transfer with constant physiological parameters as the following:

$$\left(1+\tau_T\frac{\partial}{\partial t}\right)k\nabla^2 T = \left(1+\tau_q\frac{\partial}{\partial t}\right)\left[\rho c\frac{\partial T}{\partial t} - w_b\rho_b c_b(T_b - T) - q_m - q_r\right] \tag{4}$$