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Non-Fourier effect of laser-mediated thermal behaviors in bio-tissues: A numerical study by the dual-phase-lag model

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ABSTRACT

Pulsed laser has been widely used for the thermotherapy of skin diseases. In this process, non-Fourier heat conduction has to be considered because of its small time scale. After optical transmission and energy deposition were obtained by Monte Carlo method, the dual-phase-lag (DPL) model was employed and solved by using a three-level finite difference method to characterize non-Fourier heat conduction by focusing on the thermal lag during the interaction of pulsed laser with biological tissues. The following main conclusions are obtained. Substantial discrepancies exist among the temperature responses of biological tissues with and without considering the non-Fourier effect. In the DPL prediction, nonlinear temperature increases as laser pulse heating is performed, and the appearance of the highest temperature exhibits lagging behaviors. This is mainly dominated by the relaxation parameter of heat flux vector (τ_q). The lag later appears about 2.8 times the pulses when τ_q is equal to the pulse duration. τ_q and τ_T, which are respectively the relaxation parameters of heat flux vector and temperature gradient, can decrease the calculated temperature, whereas τ_T can equalize the temperature gradient at tissue interface. In the DPL model, the thermal relaxation times of the material do not stand for τ_q and τ_T, which are inherently related to the physical time scale.

1. Introduction

Fourier's law, known as the basic law of heat conduction, is derived from a phenomenological viewpoint. Heat conduction is physically manifested as diffusion, and thermal disturbance likely propagates at an infinite speed [1], that is, no time delay occurs between heat flux and temperature gradient formation. At a microscopic level, heat conduction is accomplished through successive collisions of energy carriers, such as electrons, photons, phonons, and lattices [2]. This process occurs at small temporal and spatial scales. Assuming that all carriers move with a collision time of femtosecond to picosecond at Fermi velocity, such as 10^6 m/s to 10^3 m/s for electrons and phonons [1,2], we can obtain the mean free length of the space where thermal equilibrium is defined in nanometers. Therefore, Fourier's law seems inapplicable when the physical scale of time or space is small and comparable to the collision time or mean free path [3]. This phenomenon characterizes micro- and nano-scale heat transfer that can be applied to various fields, such as ultra-short pulsed laser processing and large-scale integrated circuit manufacturing [4]. In a physical system, small space scale is an absolute notion, whereas small time scale is a relative concept compared with the collision time or relaxation time of a given material.

Laser has been widely used for various medical applications, for example, laser-mediated therapies for dermatosis, such as port wine stain (PWS). In laser-mediated therapy for PWS, which is a vascular skin disease caused by congenital vascular malformation [5], laser energy is selectively absorbed by blood (mainly hemoglobin) to form coagulation, and thus the malformed capillaries can be thermally destroyed. In such applications, temperature distribution and variation should be precisely predicted to accurately control thermal damage and provide an enhanced curative effect. Although the time scale is longer than the collision time of electrons, the non-Fourier effect of laser therapy may occur because biological tissues are composed of bio-macromolecules, which may function as energy carriers with a relatively longer collision or relaxation time than the pulse duration. In general, laser pulses with millisecond or nanosecond durations are used for the treatment of vascular dermatosis, such as PWS, compared with nanosecond or picosecond pulses for pigmented dermatosis [6]. Therefore, laser-mediated thermal behaviors in bio-tissues can be regarded as a good example in studies on non-Fourier effects.

Heat transfer problems that cannot be depicted by Fourier's law are termed non-Fourier heat conduction. Different theories on

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Nomenclature

$\mathbf{q}$	heat flux vector (W/m^2)	$\boldsymbol{g}$	anisotropy factor
T	temperature (K)	$\boldsymbol{n}$	refractive index
$\mathbf{r}$	position vector	E_d	energy density (J/cm^3)
k	thermal conductivity (W/m/K)	A	deposition of photon weight
S	heat source (W/m^3)	E	incident laser fluence (J/cm^2)
ρ	material density (kg/m^3)	r_s	radius of the laser spot (cm)
C_p	specific heat capacity (J/kg/K)	N	number of the launched photons
α	thermal diffusivity (m^2/s)	dV	the local volume
t	flow time (s)	Q_b	the source term effect of hemoperfusion
x, y, z	coordinates and directions	Q_m	the source term effect of metabolism
c_i (i = 1,...,7)	equation coefficients	Q_e	the source term effect of external heating
c_{ij} (i = 1,2,3; j = 1,2)	equation coefficients	T_0	initial temperature (K)
t_p	laser pulse duration (s)	T_w	the interface temperature (K)
τ_T, τ_q	relaxation parameter (s)	T_f	ambient temperature (K)
l	depth of thermocouples (mm)	h	natural convection coefficient ($W/m^2/K$)
$\boldsymbol{\mu_a}$	absorption coefficient (cm^{-1})	n	interface normal vector
$\boldsymbol{\mu_s}$	scattering coefficient (cm^{-1})		

non-Fourier effect have been proposed, including thermomass theory [7], thermal particle theory, and thermal wave theory [1–3]. According to thermomass theory, thermal potential stimulates heat with mass, and heat flows like a liquid. However, this principle has yet to be completely elucidated. In thermal particle theory, heat conduction is described as collisions of energy carriers by simulating their thermal and physical motions [2]. Reliable results can be obtained by simultaneously tracking a large number of particles representing energy carriers in a one-time step, but this process entails costly computation. The feasibility of this theory consequently requires a small spatial scale. In thermal wave theory, two models are generally used: the original Cattaneo–Vernotte (CV) model [2] independently postulated by Cattaneo and Vernotte and the subsequently developed dual-phase-lag (DPL) model developed by Tzou [3,8]. Two macro parameters, τ_q and τ_T, respectively denoting the lagging behaviors of heat flux vector and temperature gradient, are introduced to describe the non-Fourier effect macroscopically. The DPL model can also be developed on the basis of the two-step microscopic model, in which heat conduction between electrons and lattices is considered [2,3]. Thus, this model can deal with problems on macro and micro scales. Considering these features and advantages, we applied thermal wave theory to examine the non-Fourier effect during laser-tissue interactions.

With the introduction of τ_q and τ_T, heat conduction equation becomes hyperbolic or undergoes dual-phase lagging, in contrast to the parabolic-type governing equation under Fourier's law. Various numerical methods have been presented to resolve the non-parabolic heat conduction equation. Zhou et al. [9] provided a 2D axisymmetric thermal wave model of bio-heat transfer by using a highly accurate oscillation-free total variation diminishing method to investigate laser-induced damage in biological tissues. Dai et al. [10] developed a three-level finite difference method to solve the DPL heat transport equation in 3D spherical coordinates. A combination study of non-Fourier heat conduction with thermal phonon theory has also been performed [11]. Other numerical algorithms with highly accurate but complex finite difference schemes have also been developed with an alternating direction implicit method [12–15]. Considering computational complexity and accuracy, a full 3D finite difference method with three-level discretization in time and second-order accuracy of non-uniform structured grid was employed. The accuracy and stability of the numerical scheme was validated by Dai et al. [10].

In summary, this study aimed to develop a numerical method to resolve non-Fourier heat conduction with discrete heat sources by pulsed laser heating and to investigate the non-Fourier effect theoretically by simulating heat conduction during the pulsed laser irradiation of skin tissues. This paper is organized as follows. Section 2 presents a numerical model of hyperbolic heat conduction. Section 3 validates the numerical model and provides an experimental study on non-Fourier phenomenon. Section 4 mathematically describes the laser therapy for PWSs, including PWS tissue modeling, light propagation, and heat transfer during pulsed laser irradiation. Section 5 illustrates in detail the effects of the relaxation parameters on non-Fourier heat conduction in the PWS tissue model. Section 6 summarizes the main conclusions.

2. Numerical models for hyperbolic heat conduction

According to non-Fourier heat conduction, the precedence of heat flux or temperature gradient may resemble the chicken-and-egg problem. In 1995, Tzou [3] introduced τ_q and τ_T in the DPL model to describe the time delay between heat flux and temperature gradient. Thus, heat flux ($\mathbf{q}$) and temperature gradient (∇T) can be considered both the cause and the effect. This model can be mathematically expressed as follows [2,3]:

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

where τ_q and τ_T characterize the phase lag behavior of $\mathbf{q}$ and ∇T at location $\mathbf{r}$ within the material possessing the thermal conductivity of k. The heat flux vector and temperature gradient in Eq. (1) should be observed locally instead of the whole thermal system. At $\tau_T > \tau_q$, heat flow initially occurs and subsequently causes the temperature gradient. At $\tau_T < \tau_q$, heat flow is induced by the temperature gradient established at an earlier time [3]. At $\tau_T = 0$, Eq. (1) is converted to the original thermal wave model, that is, the CV model. Fourier's law assumes that $\tau_T = 0$ and $\tau_q = 0$.

By substituting the local energy conservation equation into the divergence form of Eq. (1), we can obtain the governing equation of the hyperbolic DPL model with temperature representation:

$$\frac{\partial T}{\partial t} + \tau_q \frac{\partial^2 T}{\partial t^2} = \alpha \cdot \left[\nabla^2 T + \tau_T \frac{\partial}{\partial t}(\nabla^2 T) + \frac{1}{k}\left(S + \tau_q \frac{\partial S}{\partial t}\right)\right], \tag{2}$$

where α is the thermal diffusivity $\alpha = k/(\rho C_p)$ and S is the heat source (W/m^3) within a unit volume of the material with density ρ and specific heat capacity C_p. The Taylor expansion of Eq. (1) at time t is defined as follows: