Thermal Science and Engineering Progress 7 (2018) 203–212

Contents lists available at ScienceDirect

Thermal Science and Engineering Progress

journal homepage: www.elsevier.com/locate/tsep

Evaluation of heat conduction in a laser irradiated tooth with the three-phase-lag bio-heat transfer model

S. Falahatkar[a], A. Nouri-Borujerdi[a,b,*], A. Mohammadzadeh[a], M. Najafi[a]

[a] Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Bio-heat equation
Laser therapy
Three-phase-lag
Periodic heat flux
Numerical method

ABSTRACT

In this study, a dental short pulse laser with a Gaussian beam profile was applied normally to the top surface of a mineral organ i.e. the human tooth for a root canal therapy. A numerical method of finite difference is adopted to solve the time-dependent heat transfer equation. The real boundary conditions of thermal insulation on the sharp segment of the root canal and periodic heat flux on the top boundary of the tooth were applied. The comparison of a three-phase-lag (TPL) bio-heat transfer model with other heat transfer studies has shown that this new bio-heat model (TPL) could accurately predict the thermal behaviour of a non-homogeneous structure such as the human tooth. It was observed that decreasing of the pulse time, increasing of the pulse number and laser spot radius are the logical approaches for dental pulp ablation in comparison with increasing of laser intensity or increment of continuous irradiation time. Based on the results of this investigation, an optimum dental laser with heat flux of 5 W/cm^2 that could make adequate temperature increments in the range of 5 °C to 8 °C inside the dental pulp after 30 s is suggested. The time of each pulse was 0.1 s, and eight times were iterated in the first ten seconds of treatment time while the laser radius was 3 mm.

1. Introduction

The enamel and dentin layers of a tooth are mostly made up of minerals which are susceptible to decay by saliva. If this problem is not treated in a timely manner, it can be infected. Sabaeian et al. [1] investigated the possibility of using a laser for dental caries removal. Chiang et al. [2] used the various types of lasers such as CO_2, ER:YAG and ND:YAG in dental equipment. The laser application is accompanied with thermal science in micro scale and low radiation time. Wight et al. analysed the thermal conductivity measurements on thin layers [3]. The laser can be considered to be a form of light amplifier – it provides for the enhancement of particular properties of light energy. Most low-level laser therapy or low – intensity laser therapy apparatus generates light in the red visible and near infrared bands of the electromagnetic spectrum, with typical wavelengths of 600–1000 nm. These devices have the low value of mean power such as (1–100mW), while the maximum power may be much higher than 100mW. Today, a lot of advanced equipment such as root canal therapy by laser is used in dentistry [4,5]. This technique can cause damage to the pulp or to the enamel and dentin [6]. The enamel and dentin of a tooth are solid tissues but the dental pulp layer is a soft tissue containing nerves [7].

The damage caused to the pulp by an increase of temperature can make one worry about the intensity of the laser. Table 1 lists the temperature rise for different types of thermal therapy [8–10]. Zhu et al. [11] developed a heat transfer model to estimate the temperature elevations in both, the tooth root and the surrounding tissue during the disinfection of the root canal surface by a laser. In this technique, the precise irradiation intensity or radiation heat flux must be carefully selected in order to avoid excessive heat generation in the tooth layers. Hence, the power density of the laser used must be safe against the strength of the pulp and tooth layers. Denise et al. [12] demonstrated that the enamel temperature rises 77 °C when the tooth is irradiated by laser intensity of 3 W/cm^2. Zhou et al. [13] performed a parametric study under conditions of various laser exposure times and tissue optical properties. They predicted laser energy threshold for causing irreversible damage to the tissue was about 50% higher when the bio-heat non-Fourier effect was neglected. The wave nature of heat propagation was experimentally investigated in processed meat by Mitra et al. [14]. They demonstrated that the hyperbolic heat conduction equation was an accurate model, on a macroscopic level, of the heat conduction process in such biological material. This model and the Fourier results compared based on the measured temperature distribution in the samples. There were significant deviations between the two approaches, especially during the initial stages of the transient

* Corresponding author at: Department of Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.
E-mail addresses: Falahatkar.sh@srbiau.ac.ir, anouri@sharif.edu (A. Nouri-Borujerdi).

https://doi.org/10.1016/j.tsep.2018.06.012
Received 9 December 2017; Received in revised form 23 April 2018; Accepted 27 June 2018
2451-9049/

Nomenclature

C	specific heat of tooth layers, (J/kg.°C)
H	heaviside function
i	integer number of mesh in ξ-direction
J	Jacobian matrix
j	integer number of mesh in η-direction
k	thermal conductivity, (W/m.°C)
k^*	rate of thermal conductivity, (W/m.°C.s)
L	Photon's path length, (cm)
m	identifies the sub-domains of tooth
N_P	Pulse Number
N_ξ	grid points in ξ mapping coordinate
N_η	grid points in η mapping coordinate
n	integer number of time step
q	rate of heat transfer (W)
q_0	initial heat flux, (W/m^2)
q_L	time dependent heat flux of laser, (W/m^2)
q_{mb}	source term of metabolic heating, (W/m^3)
q“	laser heat flux, (W/m^2)
r	radius, (mm)
T	temperature of tooth tissue, (°C)
t	time of simulation, (s)
tp	time of pulse duration, (s)
W_b	blood perfusion, (m^3/m^3 of Tissue. s)
z	height, (mm)

Subscripts

amb	ambient
b	blood
L	laser
mb	metabolic
P	pulse

Greek letters

α	thermal diffusivity, (m^2/s)
β	rate of Thermal diffusivity, (m^2/s^2)
ξ	mapping coordinate of r-direction
η	mapping coordinate of z-direction
μ_a	absorption coefficient, (cm^{-1})
υ	thermal displacement, (°C.s)
ρ	density of tooth layers, (kg/m^3)
ρ_b	density of blood, (kg/m^3)

conduction process. The measured values were found to match the theoretical non-Fourier hyperbolic predictions very well. Many researchers applied finite difference scheme to the numerical solution of the DPL non-Fourier equation [15–17].

Despite the previous studies about the bio-heat equation based on Fourier or common non-Fourier methods, the present work has developed a new non-Fourier bio-heat conduction model under a transient pulse laser irradiation. The model is based on the three-phase-lag bio-heat transfer equation to predict the temperature elevation and heat penetration in the tooth.

2. Physical model and bio-heat equation

2.1. The dual-phase-lag bio-heat transfer

A 3-D model of the first premolar tooth with a maximum height of Z = 12 mm, maximum radius of R = 4 mm, and initial temperature of T_0 = 37 °C is considered. The premolar tooth has a single root canal with uneven boundaries, (see Fig. 1). The dental pulp is entrenched into the gingiva at a height of 7 mm. Conditions under which the incident laser radiation is collimated at an angle of 90° relative to the top surface of the tooth are investigated.

A pulse laser is used with Gaussian distribution. In total 8 pulses are used for a duration of 0.1 s and an intensity of 5 W/cm^2, (Fig. 2). The time between two consecutive pulses is 0.9 s. The heat transfer in the living tissue is accompanied by metabolic heat generation and blood perfusion. The bio-heat energy balance equation with blood perfusion and metabolic heat generation is given by [18,19]:

$$\rho c\frac{\partial T}{\partial t} = -\nabla.\, q + \rho_b C_b W_b (T_b - T) + q_{mb} \tag{1}$$

Table 1
Temperature rise during thermal therapy [8–10]

Type of Thermal Therapy	Temperature Rise [°C]
Laser assisted tooth ablation	2.3–24.7
Laser assisted caries prevention	1.2–4
Bleaching (without light/laser assisted)	0.1–1.1
Bleaching (with light/laser assisted)	1.1–16
Polymerization of dental restorative material	2.9–7.8

Combining the above equation and the classical Fourier's law with eliminating the heat flux q leads to the parabolic bio-heat conduction or Fourier bio-heat transfer (Pennes) equation for tissue temperature. The parabolic diffusion equation implies an infinite speed of propagation of the thermal wave through the tissue medium which is not correct in reality, but it propagates with a finite speed. The thermal wave model of Non-Fourier heat conduction assumes that the temperature gradient always precedes the heat flux. Tzou [20] proposed a dual-phase-lag (DPL) model that allows either the temperature gradient to precede the heat flux vector or the heat flux vector to precede the temperature gradient.

$$\vec{q}\,(r, z, t + \tau_q) = -k\nabla T(r, z, t + \tau_T) \tag{2}$$

Where τ_q is the phase lag time for the heat flux vector, and τ_T is the phase lag time for the temperature gradient. The local heat flux is the result of the temperature gradient at the same position when the phase lag time of heat flux is more than phase lag of temperature gradient. But if $\tau_q < \tau_T$, the heat flux at the early stage is main reason for make the temperature gradient. If the first order approximation of Eq. (2) is used to replace the Fourier's law of conduction, the DPL bio-heat equation becomes:

$$\tau_q\frac{\partial^2 T_m}{\partial t^2} + \left[1 + \lambda\tau_q\frac{W_b\rho_b C_b}{\rho_m C_m}\right]\frac{\partial T_m}{\partial t} = \alpha_m\left[1 + \tau_T\frac{\partial}{\partial t}\right]\nabla^2 T_m + \lambda\frac{W_b\rho_b C_b}{\rho_m C_m}(T_b - T) + \lambda\frac{q_{mb}}{\rho_m C_m} \tag{3}$$

Where, index m and parameter λ identify the particular sub-domains of the tooth. For the tooth pulp $m = 1$ and λ = 1 while for enamel and dentin $m = 2$ and λ = 0. The above equation reduces to Pennes bio-heat equation if $\tau_q = \tau_T = 0$. In the absence of a phase lag time for temperature gradient ($\tau_T = 0$), Eq. (3) is reduced to the thermal wave hyperbolic model. In this study, the blood temperature and metabolic heat source are constant.

2.2. The Three-Phase-Lag Bio-Heat equation

The tooth decay is accompanied with the structural failure caused by the maladjustment of the material properties along the tooth layers. Based on the proposed new approach, the elastic properties of the tooth