Simulation and Study of Temperature Distribution in Living Biological Tissues under Laser Irradiation

Kawther Mohammad Shurrab, Moustafa Sayem EL-Daher

Higher Institute for Laser Research and Applications, Damascus University, Syria

Abstract

Introduction: With the rapid increase in use of lasers in medical treatments, it is important to understand the mechanisms of heat transfer in biological tissues in order to minimize damage to the tissues resulting from extra heat applied. The aim of this study is to investigate the temperature distribution in living biological tissues when laser irradiation is used in a treatment.
Methods: In this work a model was suggested to study the impact of several parameters such as (laser power, exposure time, laser spot size) on the temperature distribution within skin tissues when subjected to a laser source. A three-dimensional finite element thermal model of biological tissues was developed using bio-heat equation to describe heat transfer in living tissues.
Results: Temperature distribution within skin tissues subjected to laser heating is calculated in details using the Finite element method and a suggested model; the results are presented in figures and tables showing the effects of Laser spot size, power and exposure time on temperature distribution within treated tissue.
Conclusion: the results presented in this work are expected to be useful in optimizing Laser spot size, power and exposure time for a variety of laser applications medicine and surgery.

Keywords: temperature; laser; simulation, finite element method.

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Corresponding Author: Moustafa Sayem EL-Daher, PhD; Higher Institute for Laser Research and Applications, Damascus University, Syria; Tel: +963-1133924790; Fax: +936-112119896; Email: eldaherm@scs-net.org

Introduction

With the growing interest in Laser's applications in medicine, many medical practices have sought the help of physical models to insure safety and minimize risk levels involved in successful diagnosis and treatment of human diseases[1]. The various effects of laser interaction with biological tissues and thermal effects are of special importance, these effects are very complex and result from three distinct phenomena, namely, conversion of light to heat, transfer of heat and the tissue reaction, which are ultimately related to the temperature and exposure time. This interaction leads to denaturation or destruction of a volume of the tissue[2].

A key for understanding this interaction is through analysis of the mechanism of heat transfer in the biological tissues[3] Figure 1. The transfer of energy of the laser beam to the tissue molecules occurs randomly between the more and less energetic particles and results in a secondary heated volume which is bigger than the primary one[1].

Most human cells can withstand prolonged exposure to 40º C. At 45º C, cultured human fibroblasts die after about 20 minutes. However, the same cells can withstand more than 100º C if present for only 10^{-3} seconds, it is the combination of temperature and time that governs the thermal effects[4].

Methods

The skin tissues model under laser irradiation

In this work we propose two models to simulate the laser skin tissue interaction:

The first model: Figure 2 shows a schematic diagram

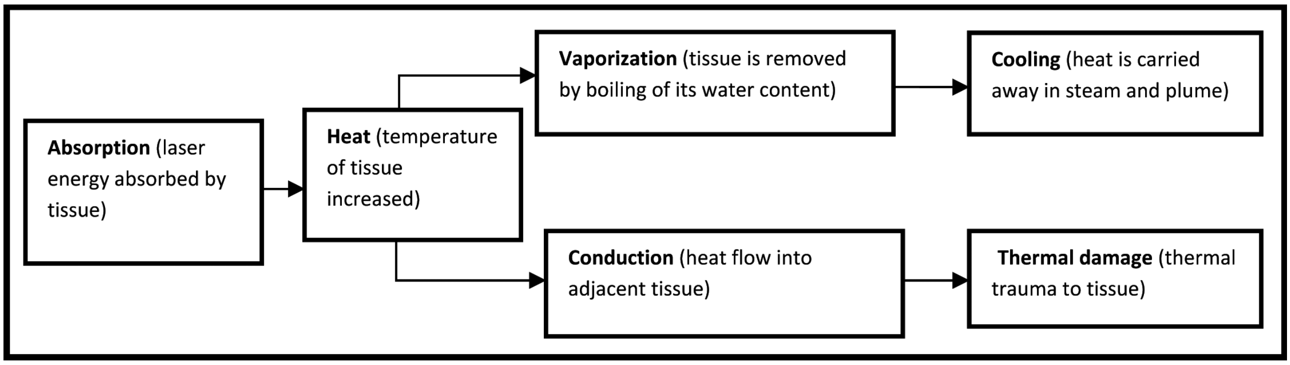

Figure 1. Where does the heat go?

of a laser-irradiated living tissue. The skin tissue model is assumed to be a cube of 4*4*1cm^3. A 1cm diameter tumor is located on the surface of the tissue.

The second model: Figure 3, It models the localized transient heating caused by a laser beam that moves in circles over a skin model, the model simulate the substrate as a 3D object with these dimensions:

width: 4 x 4 cm^2
thickness: 1 mm

In the two models the laser beam strikes the tissue on the top surface. The bottom surface of the skin tissue, as shown in Figure 2 and Figure 3 is assumed to be located within the body core.

Mathematical Analysis

Analysis of the skin tissue model is performed using Comsol FEM Lab 3.2[5] which utilizes Finite Element Method to solve the bio-heat equation for the problem of heat transfer within skin tissues.

The temperature distribution resulting from laser irradiation of the treatment zone and other areas is governed by the bio-heat equation[6] which takes the following form:

$$\frac{\rho C_p \partial T}{\partial t} + \nabla \cdot \left(-k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)\right) = \rho_b C_b \omega_b \left(T_b - T\right) + Q_{met} + Q_{ext} \qquad (1)$$

Where ρ is the density (kg m^{-3}), Cp is the specific heat capacity (J kg^{-1} k^{-1}), is the thermal conductivity of local skin tissue (w m^{-1}k^{-1}), and Q is the heat source term (w m^{-3}) where heat can be generated through metabolism or from external sources. T is temperature (K) and t is time (s). Subscript b refers to blood. The properties for each tissue domain are obtained based on Table 1[7,8], please see appendix for nomenclature used in current work.

When the laser beam hits the skin surface, the laser energy is partially absorbed, scattered, and transmitted. Heat generation due to scattering is assumed to be negligible[9]; the specific absorption rate in the target skin

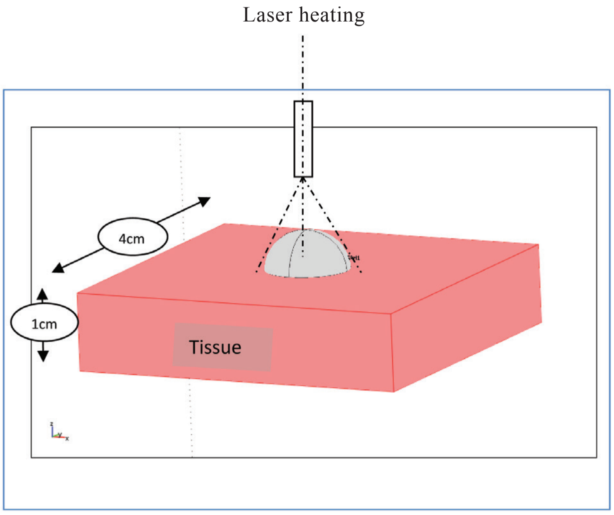

Figure 2. A schematic of a laser-irradiated skin tissue

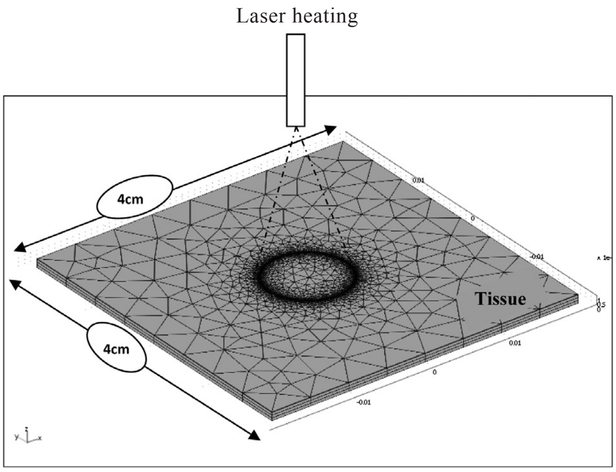

Figure 3. Moving laser heats a skin tissue

Table 1. Properties of living tissue

Description	Constants	Value
Density of tissue	rho_blood	1000 kg/m^3
Specific heat of blood	C_blood	4200 J/(kg.k)
Arterial blood temperature	T_blood	310.15 K
Thermal conductivity of skin	K_skin	0.2 w/(m.k)
Density of tissue	rho_skin	1200 kg/m^3
Specific heat of skin	C_skin	3600 J/(kg.k)
Blood perfusion rate of skin	W_b_skin	3e-3 1/s
Thermal conductivity of tumor	K_tumor	0.5 w/(m.k)
Density of tumor	rho_tumor	1050 kg/m^3
Specific heat of tumor	C_tumor	3600 J/(kg.k)
Blood perfusion rate of tumor	W_b_tumor	6e-3 1/s
Metabolic heat source	Q_met	400 w/m³
Temperature	T_0	310.15 K
Heat transfer coefficient	h_conv	10 w/(m^2.k)
External temperature	T_inf	296.15 K
Absorption coefficient	μ_a	500cm^{-1}

can be expressed as follows[10]:

$$Q_{ext} = \left(\frac{\mu_a * P}{A_s}\right) * e^{-\mu_a * r} \quad (2)$$

Where Q_{ext} is the external heat source term (w m^{-3}), ρ is the density (kg m^{-3}), μ_a is the absorption coefficient (cm^{-1}), A_S is the laser spot area (mm^2), and r is the propagation length of laser light (cm). Since the diameter of the tumor is 1cm; the irradiated diameter is set to be 1cm. for the area not exposed to a laser irradiation, the specific absorption rate is set to be 0.

The initial and boundary conditions:

Immediately before application of the laser source (t=0), the tissues are assumed to be at a uniform temperature T=37ºC. During the thermal process (t>0), the boundary condition at the skin surface is given by[11]

$$n\cdot(K\nabla T) = q\cdot + h(T_{inf} - T) \quad \text{at } y=0 \quad (3)$$

At the bottom of the domain, the temperature is assumed to be same as the body core temperature[12]

$$T=T. =37^\circ C \text{ at } y=L \quad (4)$$

Where L is the distance between skin surface and body core.

$$\text{At } x=0, \quad \frac{\partial T}{\partial x}=0, \qquad \text{At } z=0, \quad \frac{\partial T}{\partial z}=0 \quad (5)$$

Results

The bio-heat equation has been solved iteratively using the finite element method; the calibrated models were employed to study several parameters (laser power, time, laser spot size) and their impact on the temperature distribution within the skin tissue[2].

The results are verified with results obtained by previous studies on human eye and breast tumor treatment, There was a little deviation in our results as shown in Table 2.

Temperature distribution and laser spot size

The laser spot size impacts the degree of heat conduction within the patient's skin. As the laser spot size increased from 2mm to 5mm there was relatively more noticeable temperature increase. A time 0.5s and power 0.5 Watts have been used to obtain results shown in the Table 3.

4-2 Temperature distribution and laser power

The increase of laser power from 0.5w to 2.5w affected the temperature distribution within the skin. A time of 0.5s and laser spot sizes have been used to obtain results shown in Table 4.

From Table 4, we can notice that the most suitable temperature is at 350k where the laser spot size is 5mm, exposure time is 0.5s and laser power is 0.5w, while the human cells can withstand prolonged exposure to 333k as shown in the Figure 4 and Figure 5.

The results of second model show as we used 5mm, 0.5w and 0.5s that the maximum temperature reached is 335ºK which did not cause thermal damage as shown in Figure 6 and Figure 7.

Temperature Distribution and time exposure

For different rates of exposure time, the temperature increased as shown in Table 5

Table 2. The results of the study when compared to previous study

Temperature distribution	Our study	The previous study	The references
Breast tumor treatment	327K	315K	[13]
Human eye	340K	338K	[14,15]

Table 3. Effect of laser spot size on the temperature distribution within the skin tissue

	Laser spot size			
	2mm	3mm	4mm	5mm
Power (w)	2.5	2.5	2.5	2.5
Q _ext (w/m^3)*e10	0.99	0.44	0.25	0.16
Time (s)	0.5	0.5	0.5	0.5
Max temperature (k)	1600	890	640	525

Table 4. Effect of laser power on the temperature distribution within the skin tissue

	Laser spot size											
	2mm			3mm			4mm			5mm		
Power (w)	2.5	1	0.5	2.5	1	0.5	2.5	1	0.5	2.5	1	0.5
Q _ext (w/m^3)*e10	0.99	0.40	0.20	0.44	0.18	0.09	0.25	0.10	0.05	0.16	0.06	0.03
Time (s)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Max temperature (k)	1600	840	555	890	550	430	640	440	375	525	390	350

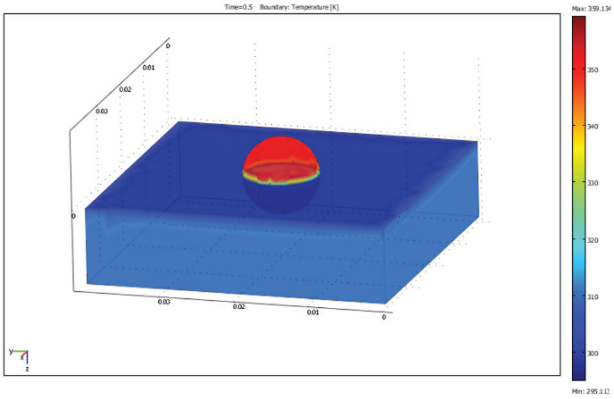

Figure 4. The yellow color is at 335k which caused less damage

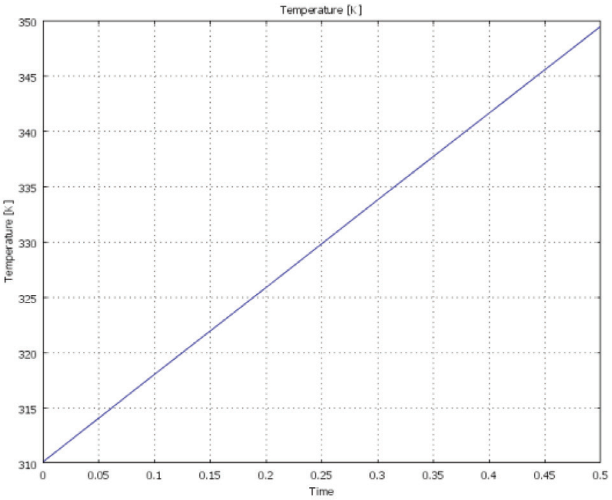

Figure 5. Temperature distribution with time (P=0.5w), the highest temperature at 350k

Table 5. Effect of time variations on the temperature distribution within the skin tissue

	Laser spot size		
	5mm		
Power (w)	0.5	0.5	0.5
Q _ext (w/m^3)*e10	0.03	0.03	0.03
Time (s)	0.5	1.0	1.5
Max temperature (k)	350	390	430

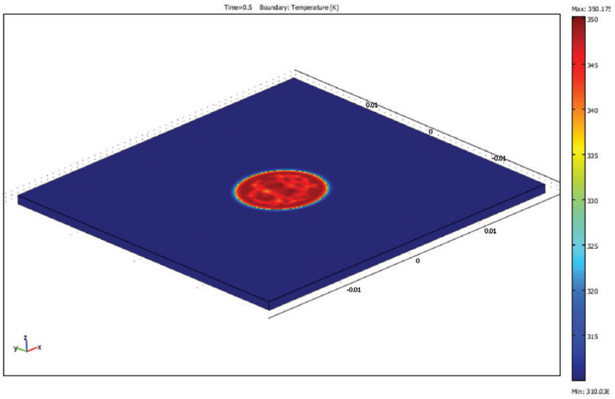

Figure 6. The yellow color is at 335k which caused less damage

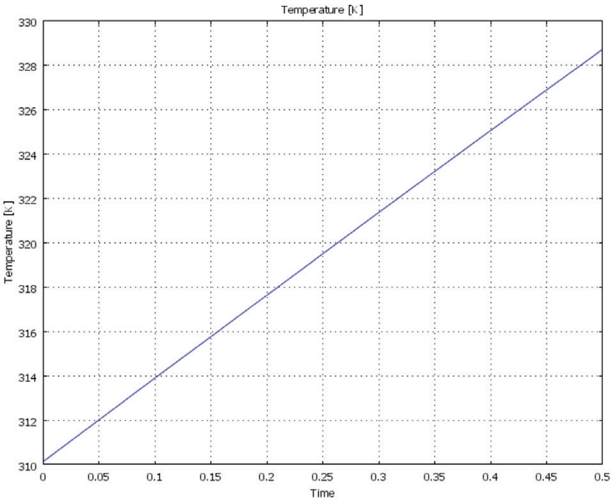

Figure 7. Temperature distribution with time (P=0.5w), the highest temperature at 329k

Discussion

The aim of the study was to investigate the temperature distribution in treatment of living biological tissues when subjected to a laser irradiation at the skin. We used in this work Finite Element Method (FEM) models to simulate the temperature distribution of the skin tissue. In the model constructed, three dominant parameters (laser power, time, spot size laser) are found to affect temperature distribution greatly. From our study we find that laser irradiation can make temperature increase to very high values when we increase the three parameters as shown in Tables 3, 4 and 5, and the best results are obtained at laser spot size 5mm, power 0.5w and time

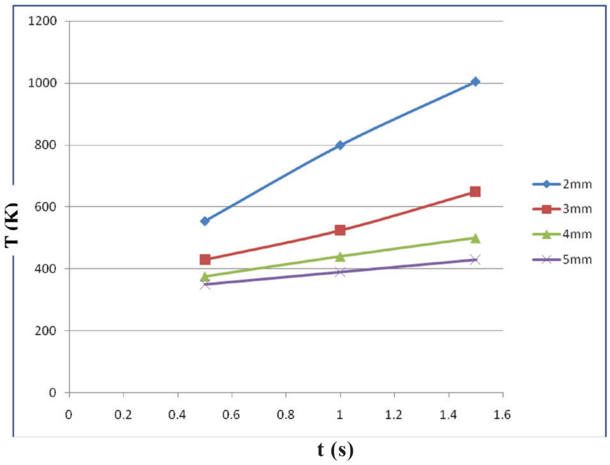

Figure 8. Temperature distribution with time with different laser spot sizes

0.5s to prevent the skin burn as shown in Figure 8.

Summary

In conclusion, two proposed models were used to study temperature distribution of the skin tissue when subjected to laser source. The results show that for the laser heating of skin treatment with different three parameters (laser power, time, and spot size laser), the temperature of skin tissue after heating is increased greatly.

The presented model provides a tool to study the relationship between thermal effect and (laser power, time, and spot size laser). The goal of this study is to control the temperature distribution in skin treatment by laser heating source. The future extension of this research would be the study of the thermal damage in different shapes of skin and tumor with more different parameters of laser source.

Appendix

	Nomenclature	
δ_{ts}	time-scaling coefficient	
ρ	the density	kgm^{-3}
C_p	the heat capacity	$Jkg^{-1}k^{-1}$
κ	the thermal conductivity	$W\ m^{-1}\ k^{-1}$
Q	the heat source	w/m^3
q	the heat Flux	w/m^2
d	depth at 50%penetration	μ_m
Ma	absorption coefficient	cm^{-1}
E	Energy	J
	Flounce	J/cm^2
P	Power	w
I	Power density	w/cm^2
	Spot size	mm
T_r	Thermal relaxation time	S

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