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Development of Temperature Distribution and Light Propagation Model in Biological Tissue Irradiated by 980 nm Laser Diode and Using COMSOL Simulation

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Abstract

Introduction: The purpose of this project is to develop a mathematical model to investigate light distribution and study effective parameters such as laser power and irradiated time to get the optimal laser dosage to control hyperthermia. This study is expected to have a positive impact and a better simulation on laser treatment planning of biological tissues. Moreover, it may enable us to replace animal tests with the results of a COMSOL predictive model.

Methods: We used in this work COMSOL5 model to simulate the light diffusion and bio-heat equation of the mouse tissue when irradiated by 980 nm laser diode and the effect of different parameters (laser power, and irradiated time) on the surrounding tissue of the tumor treatment in order to prevent damage from excess heat

Results: The model was applied to study light propagation and several parameters (laser power, irradiated time) and their impact on light-heat distribution within the tumor in the mouse back tissue

The best result is at laser power 0.5 W and time irradiation 0.5 seconds in order to get the maximum temperature hyperthermia at 52°C.

Conclusion: The goal of this study is to simulate a mouse model to control excess heating of tissue and reduce the number of animals in experimental research to get the best laser parameters that was safe for use in living animals and in human subjects.

Keywords: Laser irradiation; Diode laser; Optical-thermal; Experimental animal; Temperature distribution; Light propagation.

Introduction

The purpose of this project is to develop a mathematical model to investigate light distribution and study effective parameters such as laser power and irradiated time to get the optimal laser dosage to control hyperthermia.[1] This study is expected to have a positive impact and a better simulation on laser treatment planning of biological tissues. Moreover, it may enable us to replace animal tests with the results of a COMSOL predictive model.[2]

Heat-Tissue Interaction

When laser light absorption is converted into heat, the temperature of tissue increases and that could lead to thermal damage in the surrounding tissue.[3] The deposition of laser energy in the tissue depends on many parameters. To choose treatment parameters properly and to predict the outcome of the photo thermal effect, a reliable tissue model and simulation method is needed.[4] Temperature is the governing parameter of all thermal laser-tissue interactions. Depending on the tissue temperature, different effects are observed. For example, denaturation of enzymes and looseness of membranes occur at 40-45°C, coagulation, necrosis and protein denaturation occur around 60°C, drying out occurs at 100°C, carbonization occurs at 150°C, and, finally, pyrolysis and vaporization occurs at above 300°C.[5] Among those temperatures, 45°C is a characteristic temperature used frequently in photodynamic therapy. Although a range of temperature from 57 to 61°C is cited as the shrinkage temperature of collagen, increasing the tissue temperature to 100°C induces boiling of tissue water. Therefore, for prediction of the thermal response, a model for temperature distribution inside the tissue must be derived.[6]

Light-Tissue Interaction

The depth that laser light penetrates tissue depends upon the optical properties of the tissue, which vary with wavelength. The spectrum of medical laser ranges from 193 nm to 10.6 µm, since the absorption and scattering of

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any tissue vary with wavelength; there are differences in penetration depth of the radiation. Light at either 193 nm or 2.96 µm is absorbed in the first few μm of tissue owing to amino acid absorption in the ultraviolet and water absorption in the infrared.[7] In contrast, collimated light from 600 nm to 1.2 µm can penetrate several millimetres in tissue and the associated scattered light several cm. Within this red and near IR wavelength window there is a lack of strongly absorbing tissue chromophores. As the collimated beam passes through tissue, it is exponentially attenuated by absorption and scattering. Heat is generated wherever collimated or diffuse light is absorbed.[8]

Radiant energy will interact with tissue in 4 ways:

1. A portion of the incident beam may be reflected off the surface without penetration or interaction of the light energy with the tissue.
2. A portion of light may be transmitted through the tissue, attenuated as if transparent to the laser beam.
3. Some of the light may be absorbed into a component of the tissue and the energy will be transferred to the tissue.
4. The remaining light may penetrate the tissue and be scattered without producing a notable effect on the tissue.[9]

Mathematical Mouse Tissues Model Under Laser Irradiation

The goal of our simulation is to study optical-thermal laser tissue interaction to control the experiments that use mouse by focusing on light distribution, get a desired irradiation time and laser power.

Figure 1 shows mouse modeled in 2D is approximated with an ellipsoid assumed to be [0.35, 0.07 m]. A 0.01 m diameter tumor is located on the back surface of the mouse. The light source is diode laser 980 nm incident on the top surface of the tumor in the mouse back tissue; treatment fiber diameter is 400-micron in direct contact with intended target. The bottom surface of the model is located within the body core of mouse.

Mathematical Analysis

Analysis of the mouse tissue model is performed using COMSOL5, which utilizes Finite Element Method to solve the light diffusion and bio-heat equations to describe light propagation and heat transfer within a biological tissue and the induced photo-thermal effects. The geometry studied divided into a finite element mesh with computer software that makes it possible to numerically solve partial differential equations.[10-12]

The diffusion equation is:

$$-\nabla D(r,t)\nabla\Phi(r,t)+\frac{1}{c'}d/dt\Phi(r,t)+\mu_a\Phi(r,t)=S(r,t) \qquad (1)$$

The Helmholtz representation in COMSOL5 of the diffusion is given by:

$$\nabla(-c\nabla u)+au=f \qquad (2)$$

Where:

- c = D = $1/(3(\mu_a+\mu_s')$, The diffusion coefficient
- $u=\Phi$, fluence rate at position r
- $a=\mu_s$, absorption coefficient
- μ_s, scattering coefficient
- $f=S$, laser source

The absorption coefficient μ_a is defined in per unit length (cm-^{1}) that defines the probability that a photon is absorbed over a distance. The scattering coefficient μ_s is defined in per unit length (cm-^{1}) that describes the probability that a photon is scattered (changes direction) over a distance. The source term f is defined in (W).[13] The fluence rate value at the boundary is set to be zero, we suppose that the physical equivalent of a perfect absorbing tissue surrounding the region of study.

The bio-heat equation is:

$$\frac{\rho C_p\partial T}{\partial t}+\nabla\cdot\left(-k\left(\frac{\partial^2T}{\partial x^2}+\frac{\partial^2T}{\partial y^2}+\frac{\partial^2T}{\partial z^2}\right)\right)=\rho_b C_b\omega_b\,(T_b\text{-}T)+Q_{met}+Q_{ext} \qquad (3)$$

Where ρ is the density (kg m^{-3}), C_b is the specific heat capacity (J kg^{-1} k^{-1}), k is the thermal conductivity of local skin tissue (W m^{-1} k^{-1}), and Q is the heat source term (W m^{-3}) where it can be heat generated through metabolism or from external sources. T is temperature (K) and t is

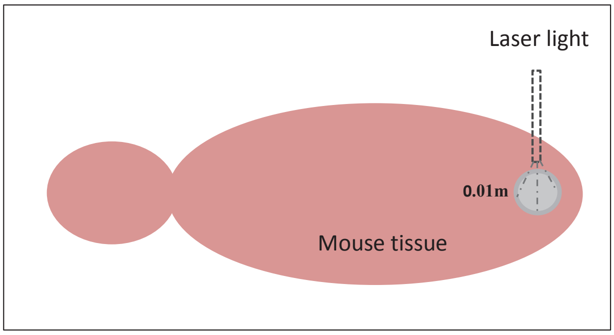

Figure 1. A Schematic of a Laser Irradiated Mouse Skin Tissue.

Table 1. Properties of Living Tissue

Description	Constants	Value
Absorption coefficient	μ_a	37.5 m^{-1}
Scattering coefficient	μ_s	17400 m^{-1}
Diffusion coefficient	D	3.17e-4
Source term	P	0.5 W
Spot size	A	16e^4 micron
Specific heat of tissue	C_p	3600 J/kg*K
Density of tissue	ρ	1200 kg/m^3
Thermal conductivity tissue	k	0.2 W/m*K
Specific heat of tumor	$C_{p\text{-tumor}}$	3600 J/kg*K
Density of tumor	$\rho_{\text{-tumor}}$	1050 kg/m^3
Thermal conductivity tumor	$k_{\text{-tumor}}$	0.5 W/m*K
Initial temperature	T_o	37°C (310.15 K)
Surrounding air temperature	28°C	300.15 K

time of irradiation (s). Subscript *b* refers to blood. The properties for each tissue domain are obtained based on Table 1.[14,15] The heat generation of beam irradiation is:

$Q(r,z) = \mu_a * I$

$$Q(r,z)=\mu_a * I_\circ(1-R)*\exp-(\mu_a+\mu_s)z \qquad (4)$$

Where Q(r,z) (w/cm^3) is the heat source at the coordinate (r,z), z (cm) is the depth at which the irradiance occurs, r (cm) is the radial position, I_o (W/cm^2) is the intensity of the incident light striking the surface, *R* is the total reflectance of the skin sample; μ_a (cm^{-1}) is the absorption coefficient, μ_s (cm^{-1}) is the scattering coefficient.

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=37°C. At the bottom of the domain, the temperature is assumed to be the same as the body core temperature.[15]

Results

The model was applied to study light propagation and several parameters (laser power, irradiated time) and their impact on light-heat distribution within the tumor in the mouse back tissue.

Temperature Distribution and Laser Power

The change of laser power from 0.3 W to 1.5 W affected the temperature distribution within the mouse skin. An irradiated time of 0.5 seconds has been used to obtain results shown in Table 2.

Temperature Distribution and Time Exposure

For different rate of exposure time from 0.5 seconds to 2 seconds, laser power 0.5 W, the temperature of treated skin increased when time increase as shown in Table 3.

Light Propagation and Laser Power

The change of laser power from 0.3 W to 1.5 W affected the light propagation within the mouse skin, as shown in Table 4.

Table 2. Effect of Laser Power on the Temperature Distribution Within the Mouse Tissue

Power (W)	0.3	0.5	1	1.25	1.5
Irradiated Time (s)	0.5	0.5	0.5	0.5	0.5
Max temperature (°C)	48	52	75	85	95

Table 3. Effect of Time Varying on the Temperature Distribution Within the Mouse Tissue

Power (W)	0.5	0.5	0.5	0.5
Irradiated Time (s)	0.5	1	1.5	2
Max temperature (°C)	52	73	94	110

Table 4. Effect of Laser Power on the Light Distribution Within the Mouse Tissue

Laser Power (W)	0.3	0.5	1	1.25	1.5
Max of light diffusion in the center of the tumor treatment	0.007	0.012	0.016	0.024	0.03

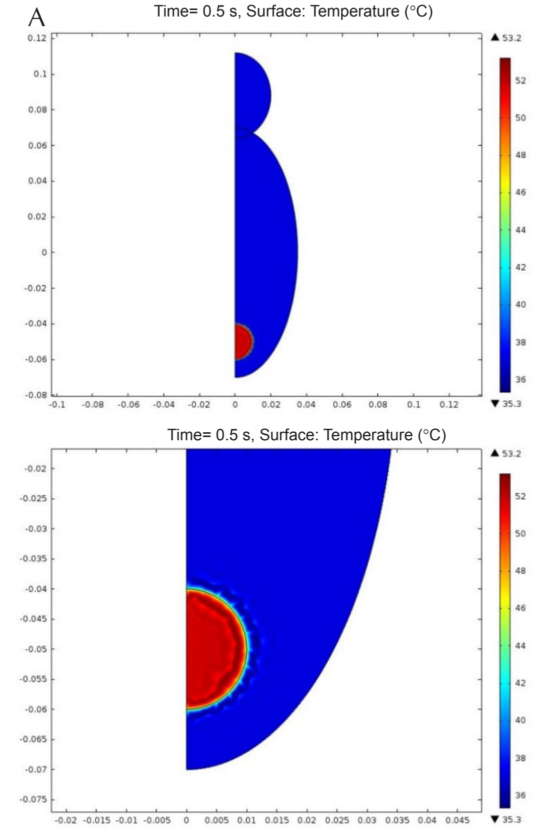

Figure 2. (A) Full Mouse Model, (b) Zoom of Tumor in the Back of Mouse. Temperature distribution with irradiated time (P = 0.5 W), maximum temperature in the center of the tumor is 52°C.

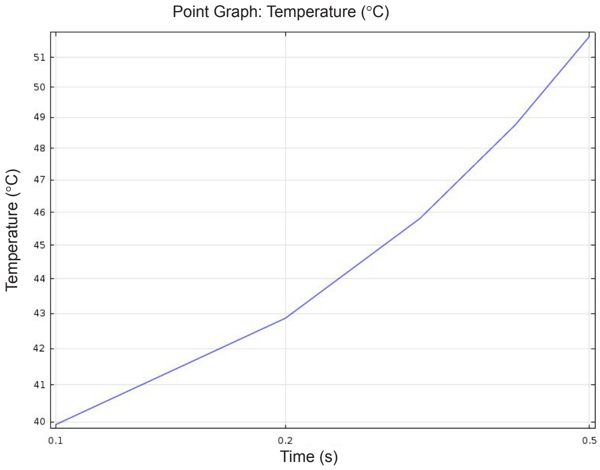

Figure 3. Temperature Distribution With Irradiated Time (P = 0.5 W, t = 0.5 s), the maximum temperature at 52°C (the temperature of treated skin increased when time increases).

Discussion

The aim of our study is to investigate light and heat distribution in treatment of living biological tissues when irradiated by a 980 nm laser diode at the tumor on the

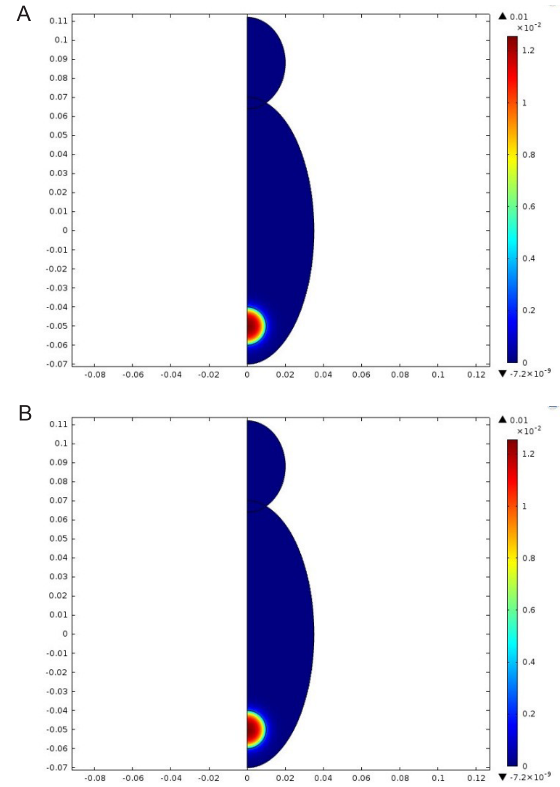

Figure 4. (A) Full Mouse Model, (B) Zoom of Tumor in the Back of Mouse. Light distribution within tumor in the back of mouse tissue, maximum light propagation in the centre of the tumor (P = 0.5 W, T_o = 37°C).

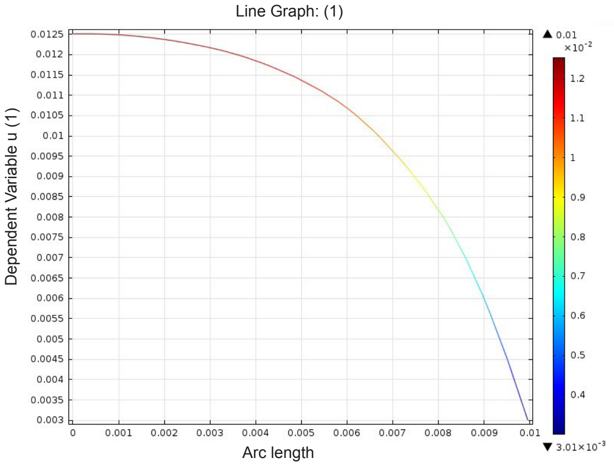

Figure 5. Maximum of Light Diffusion Within the Center of the Tumor Treatment.

back of mouse skin. To choose the appropriate laser parameters for conducting the experiment we used in this work COMSOL5 model to simulate the light diffusion and bio-heat equation of the mouse tissue and the effect of different parameters (laser power, and irradiated time) on the surrounding tissue of the tumor treatment in order to prevent damage from excess heat. The best result is at laser power 0.5 W and time irradiation 0.5 seconds in order to get the maximum temperature hyperthermia at 52°C as shown in Figures 2 and 3 as well as Figures 4 and 5 for light propagation.

Summary

COMSOL Multiphysics was used to design preliminary tests and the best parameters of 980 nm diode laser were used as a supportive tool on tumor hyperthermia in the back of mouse tissue. The goal of this study is to simulate a mouse model to control excess heating of tissue and reduce the number of animals in experimental research to get the best laser parameters that was safe for use in living animals and in human subjects.

Ethical Considerations

Not applicable.

Conflict of Interests

The authors declare that there is no conflict of interest.

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