Effect of Cooling on Thermal Damage in Tissue Subjected to Laser Irradiation

Sudad E. Younis\textsuperscript{1}, Khalid Salem Shibib\textsuperscript{1}, May A. Abduljabbar\textsuperscript{1}

\textsuperscript{1} Laser and Optoelectronics Engineering Department-University of Technology-Iraq

Abstract. This work focuses on the finite element method (FEM) that has been used to study the effect of cooling on damage initialization in skin subjected to CO\textsubscript{2} laser. The bio-heat equation was used to simulate the temperature distribution in a skin. The result of this work was compared with the analytical solution of the same problem with good nearby results. From the result of this work, it was observed that increasing the convection heat transfer coefficient of the skin could increase the possible time required to cause damage during subjected the tissue to the laser. Also, it was found that the decrease in the environmental temp. can cause the same effect on the initialization of damage. This observation is very useful in treating skin through various laser medical procedures to avoid thermal damage.

Keywords. bio-heat equation, skin thermal damage, heat transfer coefficient, longwave laser

1. Introduction

Since its first invitation in the sixties of the last century, the laser is serving as an indispensable tool in many medical fields. As an example, the laser is used as a therapeutic tool in dermatology, skin resurfacing, cosmetic surgery [1-7], wound healings [8], nerve stimulation [9,12], dentistry [13], cancer therapy [14-17], measurement and diagnostic [18-21], ophthalmology [22]. One of the most disadvantages of using the laser as the heat source in medical processes is the thermal damage in tissue which is combined with many therapeutic procedures such as removing the tattoo, removing hair, and cutting tissues.

Due to the importance of this field in medicine, many works were devoted to the effect of cooling on tissue thermal damage. M. Jasiński [23] studied numerically the resulting thermal damage in biological tissue during subjected to the laser using a two-dimensional heat transfer equation with an internal heat source that modeled the heat generation due to laser exposure inside the tissue. Their result was based on the solution of the diffusion equation. I. C. Ibarguren et al [24] studied the histology of soft tissue subjected to different laser wavelengths. They found that the tissue subjected to Er, Cr: YSGG laser with water/air spray has minimum thermal damage less than that of CO\textsubscript{2} and diode lasers respectively. Li C et al [25] studied analytically the temperature distribution and the resulting thermal damage in multi-layer skin subjected to the laser. Also, the effect of convection heat transfer coefficient on the temperature distribution and subsequently on skin thermal damage was obtained. They also studied the pulse laser parameters’ effect on thermal damage. Y L Su et al [26] predict the thermal damage of the porcine liver subjected to the laser. They solved the bio-heat equation using ANSYS software to obtain the temperature distribution and the resulting thermal damage in the tissue. The resulting surface temperature is verified experimentally using infrared thermography. They also
studied the effect of different laser parameters on thermal damage. J. Ma et al [27], studied analytically in vivo 3D thermal damage in human tissue due to moving laser beam. The effect of moving speed, spot size, and phase lag of heat were studied.

In this work, the FEM was used to obtain the temperature distribution in human skin subjected to the laser by solving the bio-heat equation. The effect of increasing convection heat transfers that subjected to the skin was studied and it was found that increasing heat transfer coefficient delay the time at which damage may start in the tissue, and also the initial skin cooling was studied and it was found that pre-cooling of the skin before applying the laser severely reduced the aftermath time required to reach damage.

2. Theory

The surface human skin is studied and a longwave laser with Gaussian beam distribution is applied. The effect of cooling on starting tissue thermal damage is studied, also the advantages of skin precooling are shown numerically. Due to the symmetrical nature of the problem an axis-symmetry bio-heat equation is used to model the problem physically [10,28];

\[ \rho c \frac{\partial T}{\partial t} = k \nabla^2 T + \dot{Q} + Q_m + Q_p \]  

(1)

Where \( \rho, c, k \) are the density (kg/m\(^3\)), specific heat (J/kg.K), thermal conductivity (W/m.K) respectively, \( T \) is the temperature ( K). \( \dot{Q} \) is heat generation due to laser-tissue interaction (W/m\(^3\)), \( Q_m \), metabolic heat generation(W/m\(^3\)). \( Q_p \) is the perfusion heat transfer due to blood flow (W/m\(^3\))=\( Q_p w(T - T_b) \), note that the subscript b referred to blood and \( w \) referred to perfusion rate, see table 1.

Tabell 1. Some physical properties of human skin [10].

| Type of Tissue     | Density kg/m\(^3\) | Specific heat J/kg.K | Thermal conductivity W/m.K | Perfusion rate Kg/s.m\(^3\) | Thickness \( \mu m \) |
|-------------------|---------------------|-----------------------|-----------------------------|-----------------------------|------------------------|
| Epidermis         | 1200                | 3590                  | 0.23                        | 0                           | 80                     |
| Dermis            | 1200                | 3300                  | 0.45                        | 1.35                        | 2000                   |
| Subsequent tissue | 1000                | 2675                  | 0.19                        | 1.35                        | 18000                  |
| Blood             | 1060                | 3770                  | -                           | -                           | -                      |

A convection and radiation heat transfer was assumed at the outer surface of the skin and an insulated boundary condition at the far in-depth dimension of the skin, then the surface boundary conditions of the skin can be modeled mathematically as:

\[ k \frac{\partial T}{\partial z} = h_{co} (T - T_{\infty}) + h_r (T - T_{\infty}) \]  

(2)

Where \( h_{co} \) is the convection heat transfer coefficient(W/m\(^2\).K) and for naturally cooled surface it was taken to be \( =2.7 \) W/m\(^2\).K[27], \( h_r \) is the radiation heat transfer coefficient (W/m\(^2\).K) = \( 4 \sigma \varepsilon (T + T_{\infty})^3 \) \[29\]. The environmental temperature \( (T_{\infty}) \) is assumed initially to be \( 25^\circ \) C unless other mentioned, while the emissivity \( (\varepsilon) \) of the skin is equal to 0.975[30,31] and \( \sigma \) is Stefan Boltzmann's constant.
To well model the problem with good accuracy, the radiation heat transfer is calculated also where the temperature through the solution could reach 60°C which is known to be an indication of the starting damage.

2.1 Heat source distribution

As the long-wavelength laser interacts with tissue (i.e. CO\textsubscript{2} laser), heat is generated which depends mainly on absorption coefficient $\mu_a(z) = 594 \text{ (m}^{-1})$ and the heat generation can be written as [10]

$$\dot{Q}(r, z, t) = \mu_a \left(1 - rf^2\right) I_0 \exp(-\mu_a z)$$

(3)

Where $rf$ is the reflectivity of tissue which is equal to zero at this wavelength and Beer-Lambert law can model the heat generation inside the tissue due to laser absorption. Waist diameter ($2w_o$) is taken to be 1 mm to standardize the model and for Gaussian beam distribution the induced localized power intensity is

$$I_o(r, z) = \frac{2p}{\pi w_o^2} \exp(-\frac{2r^2}{w_o^2})$$

(4)

Where $p$ is referred to the power of the laser in W. A really well-tested situation is assumed where all the power of the laser is absorbed by the skin and the effect of skin roughness and skin color is more obvious in shorter wavelengths (i.e in Nd: YAG or visible laser)

2.2 Thermal dose calculation

Saparteto et al [32], suggested a technique that used a numerical calculation to estimate the thermal dose in minute as shown in the following equation. This equation is known as the thermal dose equation and is calculating the dose at which the subsequent tissue temperatures can cause the damage. Many previous works calculate the dose of damage for various tissue types. For example for human skin the dose is known to be equal to 240 minutes [10,27];

$$\text{Thermal dose} = \sum R^{T - 43} dt \text{ where } R = 2 \text{ for } T \geq 43^\circ \text{C and } 4 \text{ for } T < 43^\circ \text{C}$$

(5)

Where $dt$ is the time interval in minutes at which instantaneous thermal dose is calculated. This equation is used for quantitatively and qualitatively describing the thermal effect on tissue.

2.3 Finite element formulation

Equation (1) is discretized in axis-symmetry dimensions $(r,z)$ and solved by following the Galerkin approach [10]. A total number of 65 triangular elements with 98 nodes were used following a proper grid model. In the highly expected temperature gradient zone a finer mesh is used and a courser mesh elsewhere, see figure 1 where a well-tested mesh was taken from references [10,33,34]. A computer program is written in Visual Basic program following FEM procedure to predict the temperature distribution through the skin from which the initialization of thermal damage could be obtained.

2.4 Modulation

A program written in Visual Basic program has been used to calculate the temperature distribution through the skin. The first run of the program is used to calculate the initial temperature distribution through the skin where natural convection is assumed at the surface of the skin with initial temperature distribution of 37°C. The running time required to reach the steady-state is about 310 s where the surface temperature of the skin reaches 33.5°C, see figure 2(a, b). This temperature distribution is taken to be the initial condition as the cooling agent was tested through the program. Different values of convection heat transfer were tested and the time required to reach thermal damage was recorded. Three values of environmental temperature were tested; once it is applied with laser appliances and in the second studied condition, the cooling is applied initially before the appliances of laser radiation till the skin temperature reaches 20°C and the time required to reach damage is recorded.
3. Result and Discussion
The FEM of the bio-heat equation was used to obtain the temperature distribution in the skin of the human body. To ensure the accuracy of the result obtained with the built program, it is tested with the same problem solved analytically by reference [22] and it was found that the maximum difference doesn’t exceed 4%. A longwave laser beam was used to initialize damage in the skin while the skin is subjected to different cooling loads. The cooling load can be achieved either by decreasing the environmental temperature or by increasing the heat transfer coefficient to show the effect of cooling on the initialization of damage. The program is tested to predict the initial temperature distribution in the skin. The time required to reach steady-state temperature distribution in the skin is found to be about 310 s as mentioned before and the steady-state initial temperature distribution is shown in fig.2. Assume the program is started with an initial temperature of 37°C. The skin temperature could reach about 33.5 °C which matches the usual skin surface temperature. It is assumed that the heat transfer coefficient is that for natural convection (i.e. 2.7 W/m².K) and the environmental temperature is 25°C.
These initial temperature distributions are used as starting values for the temperature in the skin assume that the z-coordinate of the skin surface is as shown in figure 2(a, b). The used thermal properties and the metabolic heat generation together with the different skin layers’ thickness are shown in tab.1[10]. In the subsequent discussion, the effect of cooling and pre-cooling on tissue is discussed.

3.1 Increase the convection cooling.

Three-level environmental temperatures were tested 15°C, 20°C, 25°C while the convection heat transfer coefficients were varying from natural convection to higher levels as shown in figure 3(a, b, c). Those figures show the effect of cooling on the time required to initializing damage at different power levels. The solid line indicates the time required to reach damage at the environmental temperature of 25 °C. The long-dashed line indicates the time required to reach damage at the environmental temperature of 20°C and the small dashed line indicates that time at 15 °C environmental temperature. It is shown that the heat transfer coefficient increased the time required to initialize damage is increased too which can be explained by the fact that the amount of heat that was transferred out of tissue increased, its effect on tissue is decreased which means that as the amount of accumulated heat in the tissue decreased then the time required to cause damage is increased. These facts also explain the increase in time required to reach damage as the environmental temperature decreased which is shown in figure 3(a, b, c). It is also shown that more convection heat transfer is needed to delay the time of initialization damage as power increased (i.e., more heat must be extracted to delay damage).

3.2. Precooling of tissue

The effect of initial cooling of tissue before exposed to laser is studied. The result is shown in figure 4. The skin is initially subjected to a stream of cold air at a temperature of 15 °C and the velocity of the air stream is increased so that the heat transfer coefficient is increased from 150 W/m².K to 400 W/m².K as indicated in figure 4. At each value of heat transfer coefficient, the time required for the surface of the skin to reach 20°C is calculated and it is found that as the heat transfer coefficient increased or the environmental temperature decreased, the time required to reach the required temperature (i.e., 20 °C) is reduced which is explainable since the amount of heat that extracted from the skin is increased as heat transfer coefficient increased (or a reduction in the environmental temperature). It is also shown that the time required for the skin to reach damage after laser exposure is increased as the heat transfer coefficient increased (or reduce in the environmental temperature).
which can be explained by the fact that the accumulated heat in the tissue which is responsible for thermal damage, is decreased as the cooling increased.
Figure 3. The effect of heat transfer coefficient on time needed to reach damage at different power levels a) 3W b) 4W c) 5W. The solid line indicates an environmental temperature of 25 °C, the long-dashed line indicates environmental temp. of 20°C, the small dashed line for an environmental temperature of 15°C.

Figure 4. The effect of cooling on time to reach tissue damage in tissue subjected to laser; dashed line for time to reach damage, solid line time required to reach 20 °C before subjected to laser, laser power 5W, environmental temperature 15 °C.
4. Conclusions

A numerical modulatio was presented to study the effect of cooling on tissue thermal damage in tissue subjected to a laser. In this study, the CO₂ laser was used as a therapeutic tool in dealing with human skin. The heat transfer coefficient together with environmental temperature was used as outer boundary conditions in tissue subjected to CO₂ laser as an internal heat source. The FEM was used to obtain the temperature distribution inside the irradiated tissue. The result was compared with an analytical solution of the same problem with acceptable accuracy. The effect of increasing cooling on the treated tissue was tested and it was found that the increase in cooling could delay the time at which damage may occur also it was found that pre-cooling of skin surface before subjecting the laser irradiation led to an increase in the allowable time without the possibility of damage.

5. References

[1] Marc RA, Avram MM and Paul M 2014 Laser and Light Source Treatments for the Skin Jaypee Brothers Medical Publishers.

[2] Choudhary S, Elsaie M L, Leiva A and Nouri K 2010 Lasers for Tattoo Removal: A review, Lasers in Medical Science 25 (5):619-27.

[3] Jiyong Cho, Binbin Prasad, Jung Kyung Kim 2018 Near-infrared laser irradiation of a multilayer agar-gel issue phantom to induce thermal effect of traditional moxibustion, J. of Innovative Optical Health Sciences 11(6); pp:1-12

[4] Thongsima S, Zurakowski D and Manstein D 2010 Histological Comparison of Two Different Fractional Photo-Thermolysis Devices Operated at 1.550 nm Lasers Surg Med 42; 32-37.

[5] Maranda E L, Nguyen A H, Lim V M, Hafeez F and Jimenez J J 2016 Laser and Light Therapies for The Treatment of Nail Psoriasis J. Eur Acad Dermatol Venereol 30; 1278-1284.

[6] Tong L, Wei G and Cheng JX 2009 Gold Nanorods As Contrast Agents for Biological Imaging: Optical Properties, Surface Conjugation, and Photothermal Effects Photochem and Photobiol 85: 21-32.

[7] Shibib K S and Munshid M A 2010 Thermal Behavior of Tissues Having Different Porosities During Continuous CO₂ Laser Irradiation, Thermal sciene 14 (1): 49-56.

[8] Waibel J S, Gianatasio C, Rudnick A and Siegel A 2018 Use of Lasers in Wound Healing: How to Best Utilize Laser Technology to Prevent Scar Formation Current Dermatological Reports 7 :303–310.

[9] Shibib K S 2013 Finite Element Analysis of Cornea Thermal Damage Due to Pulse Incidental Far IR Laser Lasers in Medical Science 28: 871–77.

[10] Shibib K S 2010 Thermal Damage Due to Incidental Continuous CO₂ Laser Irradiation on Human Skin Thermal science 14 (2): 451-58.

[11] E. Vecchio, L.Bassez, K. Ricci, C. Tassorelli, E. Liebler and M. de Tommaso, 2018 Effect of Non-invasive Vagus Nerve Stimulation on Resting-State Electroencephalography and Laser-Evoked Potentials in Migraine Patients: Mechanistic Insights, Front. Hum. Neurosci. 12,pp.366

[12] C. Machad ,Y. Machado M. Chinchilla, H. Foyaca-Sibat, Vagal Nerve 2019 Stimulation With Low Level Lasers Of Two Different Frequencies, Assessed By QEEG Internet Journal of Neurology 21(1):1-9

[13] Schelle Fl, Polz S and Halouli H 2014 Ultrashort Pulsed Laser (USPL) Application in Dentistry: Basic Investigations of Ablation Rates and Thresholds on Oral Hard Tissue and Restorative Materials J Lasers Med Sci 29: 1775-83.

[14] Lin J T, Hong Y L and Chang C L 2010 Selective Cancer Therapy Via IR-Laser-Excited Gold Nanorods Proc. SPIE 7562-75620R.

[15] Huang X H, El-Sayed I H, Qian W and El-Sayed M A 2009 Cancer Cells Assemble and Align Gold Nanorods Conjugated to Antibodies to Produce Highly Enhanced, Sharp, and Polarized Surface Raman Spectra: A Potential Cancer Diagnostic Marker Nano Lett 7: 1591-97.
[16] Shibib K S, Munshid M A and Lateef H A 2017 The Effect of Laser Power, Blood Perfusion, Thermal and Optical Properties of Human Liver Tissue on Thermal Damage in LITT Laser in Med. Science 32(9):2039-46.

[17] AbdulRazzaq MJ, Mohammed AZ, Abass AK, and Shibib KS 2019 A new approach to evaluate temperature distribution and stress fracture within solid state lasers , Optical and Quantum Electronics, 51(9):1-10

[18] Shibib K S and Shaker D 2019 Inverse Heat Transfer Analysis in Detecting Tissue Optical Properties Using Laser Laser in Med. Science, 34(8):1671-1678.

[19] Shibib KS, Tahir M M and Mahdi MA 2014 Analytical treatment of transient temperature and thermal stress distribution in CW end pumped laser rod: Thermal response optimization study , Thermal Science 18(2):pp.399-408

[20] Younis S I, Qatta H I, Abdul Razzaq M J and Shibib K S 2020 Thermal Conductivity and Specific Heat Evaluation of Tissue Using Laser Materials Science Forum 1002:303-310.

[21] Wienke S and Gerhard C 2018 Lasers in Medical Diagnosis and Therapy IOP Publishing Ltd ISBN: 978-0-7503-1275-2, London, UK.

[22] Mardin C Y, Tornow R P and Kruse F E 2010 Lasers in Ophthalmology Physics Procedia 5: 631–636.

[23] Jasiński M 2018 Modelling of Thermal Damage Process in Soft Tissue Subjected to Laser Irradiation Journal of Applied Mathematics and Computational Mechanics 17(2): 29-41.

[24] Cercadillo-Ibarguren I, España-Tost A, Arnabat-Domínguez J, Valmaseda-Castellón E, Berini-Aytes L and Gay-Escoda C 2010 Histologic Evaluation of Thermal Damage Produced on Soft Tissues by CO₂, Er,Cr:YSGG and Diode Lasers Med Oral Patol Oral Cir Bucal. 115 (6): 912-8.

[25] Li C, Lin S and Wan Y 2020 Prediction of Temperature Field and Thermal Damage of Multilayer Skin Tissues Subjected to Time-Varying Laser Heating and Fluid Cooling by a Semi-Analytical Method Mathematical Problems in Engineering 2020: 1-15.

[26] Su Y L, Chen K T, Chang C J and Ting K 2015 Experiment and Simulation of Bio Tissue Surface Thermal Damage During Laser Surgery Proc. IMechE Part E: J Process Mechanical Engineering 231(3).

[27] Ma J, Yang X, Sun Y and Yang J 2019 Thermal Damage in Three-Dimensional Vivo Bio-Tissues Induced by Moving Heat Sources in Laser Therapy Sci Rep 9, 10987.

[28] S. Kumar, R. S. Damor, and A. K. Shukla 2018 Numerical study on thermal therapy of triple layer skin tissue using fractional bio-heat model, International Journal of Biomathematics, 11(4):pp1-24

[29] McQuiston F C, Parker J D and Spitler J D 2000 Heating, Ventilating, and Air conditioning, 5th edition. John, Wiley & Sons.

[30] Ghadban M Y , Shibib K S and Abdulrazzaq MJ 2020 Analytical model of transient thermal effects in microchip laser crystal AIP Conference Proceedings 2213, 020179

[31] LeCarpentier G L, Motamedi M, McMath L P, Rastegar S and Welch A J 1993 Continuous-Wave Laser Ablation of Tissue: Analysis of Thermal and Mechanical Events IEEE transactions on biomedical engineering 40(2):188-200.

[32] Sapareto S A and Dewey W C 1984 Thermal Dose Determination in Cancer Therapy Int. J. Radiat. Oncol.Biol. Phys. 10(6):787-800.

[33] Shibib K S, M.A. Minsuid, and M. M. Tahir 2009 Finite Element Analysis of Spot Laser of Steel Welding Temperature History, Thermal science 13(4):134:150

[34] Shibib KS , Munshid M A, Abdul rayyak MJ and Salman L H 2017 Transient Analytical Solution of Temperature Distribution and Fracture Limits in Pulsed Solid-State Laser Rod, Thermal science .21(3):1213-22

9