Short Communication

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Thermal Effects of Laser-osteotomy on Bone: Mathematical Computation Using Maple

Asghar Gholami[1], Molood Baradaran-Ghahfarokhi[1,2], Marjan Ebrahimi[3], Milad Baradaran-Ghahfarokhi[4,5]

[1]Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran, [2]Medical Student's Research Center, School of Medicine, Isfahan University of Medical Sciences, Isfahan, Iran, [3]Department of Physics, Khorasgan (Isfahan) Branch, Islamic Azad University, Isfahan, Iran, [4]Department of Medical Physics and Medical Engineering, School of Medicine, Isfahan University of Medical Sciences, Isfahan, Iran, [5]Department of Medical Radiation Engineering, Faculty of Advanced Sciences and Technologies, Isfahan University, Isfahan, Iran

Submission: 01-06-2013 Accepted: 28-07-2013

ABSTRACT

In recent years, interest in medical application of lasers especially as a surgical alternative is considerably increasing due to their distinct advantages such as non-contact intervention, bacteriostasis, less traumatization, minimal invasiveness, decreased bleeding and less heat damage. The present study aimed to evaluate the temperature changes and the consequent released thermal stress in cortical bone caused by an Erbium:yttrium aluminum garnet (Er:YAG) laser (Fideliss 320A, Fotona Inc., Deggingen, Germany) during osteotomy, using mathematical computation by means of Maple software, version 9.5 (Maplesoft, a division of Waterloo Maple Inc., Canada). The results obtained here were compared with the experimental measurements using Er:YAG laser in the osteotomy clinics. A bone slab with thickness of 1 mm was simulated in Maple software. Then, an Er:YAG laser emitting 100 μs pulses at a wavelength of 2940 nm were modeled. Two different clinical settings of the Er:YAG laser with 200 mJ and 400 mJ energies, both with 100 μs exposure and 500 μs silence were studied. To investigate the temperature distribution in the cortical bone, the time-dependent heat conduction equations were defined and solved in the Maple software. Finally, by defining the heat distribution function in the Maple, thermal stress in the bone was investigated. Results of the computations showed that, on the bone irradiated area (center of the bone surface) the maximum temperature rise was 0.8°C and 1.6°C, for 200 mJ and 400 mJ Er:YAG laser exposure, respectively. The temperature rise reached to its minimum at radial distances of 1.2 cm from the point of irradiated area for 200 mJ laser while it was 1.5 cm for 400 mJ laser. For 200 mJ laser the maximum derived radial (σ_{rr}), axial (σ_{zz}) and azimuthally ($\sigma_{\theta\theta}$) stress components were 0.20, 0.16 and 0.08 MPa, respectively. While, for 400 mJ laser the maximum derived σ_{rr}, σ_{zz} and $\sigma_{\theta\theta}$ stress components were 0.39, 0.31 and 0.16 MPa, respectively. These results confirm that use of 100 μs Er:YAG laser pulses with 500 μs silence at 200 and 400 mJ energies minimizes thermal tissue damage for the laser osteotomies, without continued water cooling (irrigation) on the exposed area.

Key words: *Erbium:yttrium aluminum garnet laser, laser-osteotomy, Maple software*

INTRODUCTION

In recent years, interest in medical application of lasers especially as a surgical alternative is considerably increasing.[1] Considering distinct disadvantages of the burrs and saws such as extensive heat deposition, broadening of cuts, mechanical traumatization, the deposition of metal shavings and bacterial contamination, lasers offer several significant advantages. Compared with other conventional surgical procedures the laser distinct advantages in surgery are non-contact intervention, bacteriostasis, less traumatization, minimal invasiveness, decreased bleeding and less heat damage.[2]

The first serious attempts on using lasers to replace the burr is reported by Horch *et al*. who have extensively studied the potential use of lasers for osteotomy procedures.[3,4] It has been stated that, excessive heat is the major source of damage in bony tissues during bone osteotomy.[5] Eriksson and Albrektsson described the critical temperature of 47°C for bone. Moreover, they also noted that temperature elevation between 44°C and 47°C may already lead to tissue necrosis.[6,7] It should be noted that, heat and necrosis have a directly proportional relationship[6,8] and increased areas of necrosis result in tissue breakdown and impairment of wound healing.[7,8] If the zone of necrotic bone exceeds a certain limit, the body is no longer able to easily remove the devitalized tissues. In this regard, investigators have shown that reduction of heat, shortens healing periods and allows a faster integration of osteosynthesis.[9]

Address for correspondence:
Dr. Milad Baradaran-Ghahfarokhi, Department of Medical Physics and Medical Engineering, Isfahan University of Medical Sciences, Isfahan 81746 - 73461, Iran. E-mail: mbaradaran@edc.mui.ac.ir

However, safety and the efficacy of the laser depend on applied laser parameters as well as on the tissue characteristics.[10] Erbium:yttrium aluminum garnet (Er:YAG) laser are widely used for osteotomy procedures. The Er:YAG laser, with the wavelength of 2.94 μm, has demonstrated promising results with bone tissue due to maximum coincides with water absorption in the bone.[11]

Majoran *et al*. found that, heat diffusion for Er:YAG-laser at a short pulse length (50-300 μs) is negligible.[11,12] Moreover, clinical trials studying laser drilling in dentine with Er:YAG laser light at a pulse length of 100 μs did already confirm the tissue preserving the character of the laser parameters.[13]

To avoid temperature rise in hard tissue structures, the pulse duration has to be set close to the thermal relaxation time of the tissue respective of ablation thresholds.[2] It can be assumed that the thermal relaxation time for bone is best estimated at a range between 20 μs and 80 μs.

The aim of this study was to evaluate the temperature changes and the consequent released thermal stress in cortical bone slices caused by an Er:YAG laser during osteotomy, using mathematical computation by means of Maple software, version 9.5 (Maplesoft, a division of Waterloo Maple Inc., Canada). The results obtained here were compared with the experimental measurements using Er:YAG laser in the osteotomy clinics.[2]

According to the best of our knowledge, the use of such computation with methodology described here on laser systems for clinical applications on human bone has not been reported so far.

The use of computational methods for the study of anatomical organs can yield information that is difficult or impossible to obtain experimentally. Therefore, at this study computational method was used to assess the changes in temperature during laser-osteotomy.

MATERIALS AND METHODS

Study method was in accordance with the experimental work on the measurements of temperature changes in cortical bone slices during osteotomy procedure.[2] A bone slab with thickness of 1 mm was simulated using Maple software. Table 1 gives the thermo-mechanical characteristics of the cortical bone for the calculations.

Then, an Er:YAG laser (Fideliss 320A, Fotona Inc., Deggingen, Germany) emitting 100 μs pulses at a wavelength of 2940 nm was modeled. The laser was considered with a built-in 650 nm and 1 mW target beam. At the point of incidence of the laser beam, the diameter of the irradiated area was set to be approximately 1.1 mm. At this work 2 different clinical settings of the Er:YAG laser with 200 mJ and 400 mJ energies, both with 100 μs exposure and 500 μs silence were studied.

Table 1: Thermo-mechanical characteristics of the cortical bone

Parameter	Value
Young's modulus (E) (GPa)[14]	14.8
Poison ratio (ν)[15]	0.2
Density (kg/m^3)[15]	1900
Thermal expansion (mm/°C)[16]	27.5±3.9×10^{-6}
Thermal contraction (mm/°C)[16]	27.2±5.2×10^{-6}
Thermal conductivity (W/mK)[17]	0.54
Specific heat (J/kg °K)[1]	1260

Water cooling was neglected from this study. However, for clinical applications, one can calculate the water flow rate using results of the temperature changes and the consequent released thermal stress in the bone slice.

To investigate the temperature distribution in the cortical bone, the time-dependent heat conduction equations were defined and solved in the Maple software.

The equation of the heat distribution function can be calculated as follows: [10]

$$\Delta T(z,t)=\left\{\sum_{m=0}^{\alpha}\left\{\frac{2}{l}\left(\frac{ml\pi\left(\cos(m\pi)e^{-l\alpha}-1\right)}{l^2\alpha^2+m^2\pi^2}\right)\left[-\frac{Q_0\tau_1}{\tau_2\alpha^2K}+\right]\right\}\right.$$
$$\sin\left(\frac{m\pi}{l}z\right)+\sum_{n=1}^{\alpha}\frac{2Q_0\sin\left(\frac{n\pi\tau_1}{\tau_2}\right)K\alpha^2\tau_2^2}{n\pi\left(\alpha^2K^2\tau_2^2+n^2\pi^2\rho^2c^2\right)}$$
$$\left\{\frac{2}{l}\left(\frac{l^2\alpha\left(1-\cos(m\pi)e^{-l\alpha}\right)}{l^2\alpha^2+m^2\pi^2}\right)\right.$$
$$\left[-\frac{Q_0\tau_1}{\tau_2\alpha^2K}+\sum_{n=1}^{\infty}\frac{2Q_0\sin\left(\frac{n\pi\tau_1}{\tau_2}\right)K\alpha^2\tau_2^2}{n\pi\left(\alpha^4K^2\tau_2^2+n^2\pi^2\rho^2c^2\right)}\right]$$
$$\left.\cos\left(\frac{m\pi}{l}z\right)\right\}e^{-\frac{m^2}{\rho c}t}e^{\frac{-2r^4}{\omega^4\rho}}$$
$$+\left\{\frac{\tau_1Q_0e^{\alpha z}}{\tau_2\alpha^2K}-\sum_{n=1}^{\infty}\frac{2Q_0e^{\alpha z}\sin\left(\frac{n\pi\tau_1}{\tau_2}\right)}{n\pi\left(\alpha^4K^2\tau_2^2+n^2\pi^2\rho^2c^2\right)}\right.$$
$$\left.\left[K\alpha^2\tau_2^2\cos\left(\frac{n\pi}{\tau_2}t\right)-n\pi\rho c\tau_2\sin\left(\frac{n\pi}{\tau_2}t\right)\right]\right\}e^{\frac{-2r^4}{\omega^4p}} \quad (1)$$

Finally, by defining the heat distribution function in the Maple, thermal stress in the bone was investigated using below equations.[18]

$$\sigma_{rr} = \frac{\alpha_T E}{1-v}\left(\frac{1}{r_b^2}\int_0^{r_o} rTdr - \frac{1}{r^2}\int_0^{r} rTdr\right) \tag{2}$$

$$\sigma_{\theta\theta} = \frac{\alpha_T E}{1-v}\left(-T + \frac{1}{r_b^2}\int_0^{r_b} rTdr + \frac{1}{r^2}\int_0^{r} rTdr\right) \tag{3}$$

$$\sigma_{zz} = \frac{\alpha_T E}{1-v}\left(-T + \frac{2}{r_b^2}\int_0^{r_b} rTdr\right) \tag{4}$$

Where σ_{rr}, σ_{zz} and $\sigma_{\theta\theta}$ are the radial, axial and azimuthally stress components respectively, E is the young's modulus; ν is the Poisson ratio and α_T is thermal expansion coefficient.

RESULTS

Results of the computations showed that, on the bone irradiated area the maximum temperature rise was 0.8°C and 1.6°C, for 200 mJ and 400 mJ Er:YAG laser exposure, respectively. The temperature rise reached to its minimum at radial distances of 1.2 cm from the point of irradiated area for 200 mJ lasers, while it was 1.5 cm for 400 mJ lasers.

Figure 1 shows the distribution of temperature rise on the cortical bone surface for both 200 mJ and 400 mJ Er:YAG laser at different radii from the irradiated area.

Considering the bone depth from the irradiated area, for 200 mJ laser the temperature rise reached to its minimum value at 0.05 mm. While, for 400 mJ laser the mentioned depth was 0.08 mm, significantly higher than 200 mJ laser. Figure 2 gives the distribution of temperature rise on the cortical bone irradiated area for 200 mJ and 400 mJ Er:YAG laser at the bone irradiated area to depth of 0.5 mm from the irradiated area.

Figure 3 illustrates the bone temperature rise following an 100 μs pulse of the 200 mJ and 400 mJ Er:YAG laser at different radii and depths from the irradiated area.

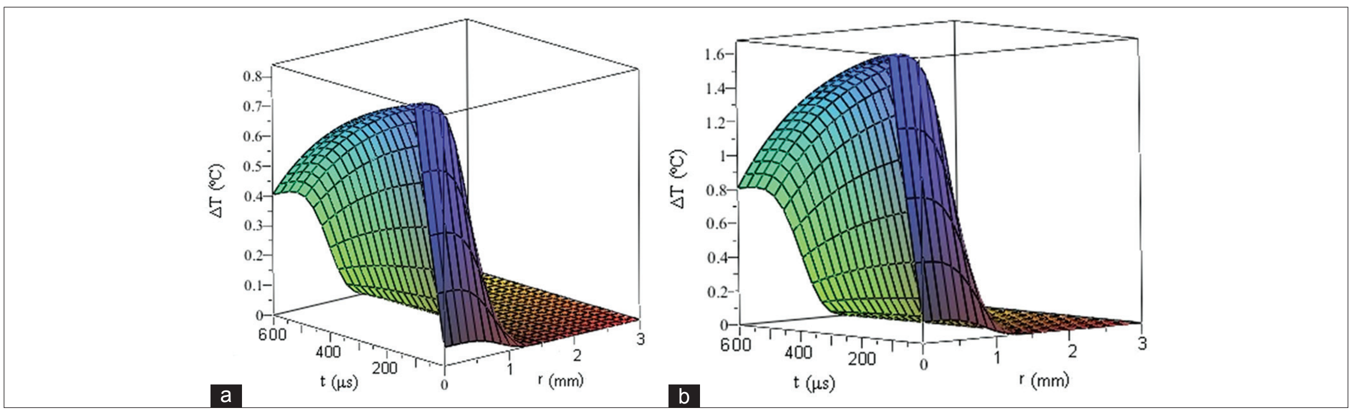

Figure 1: Distribution of temperature rise on the cortical bone irradiated area for, (a) 200 mJ and, (b) 400 mJ Erbium:yttrium aluminum garnet laser at different radii from the irradiated area

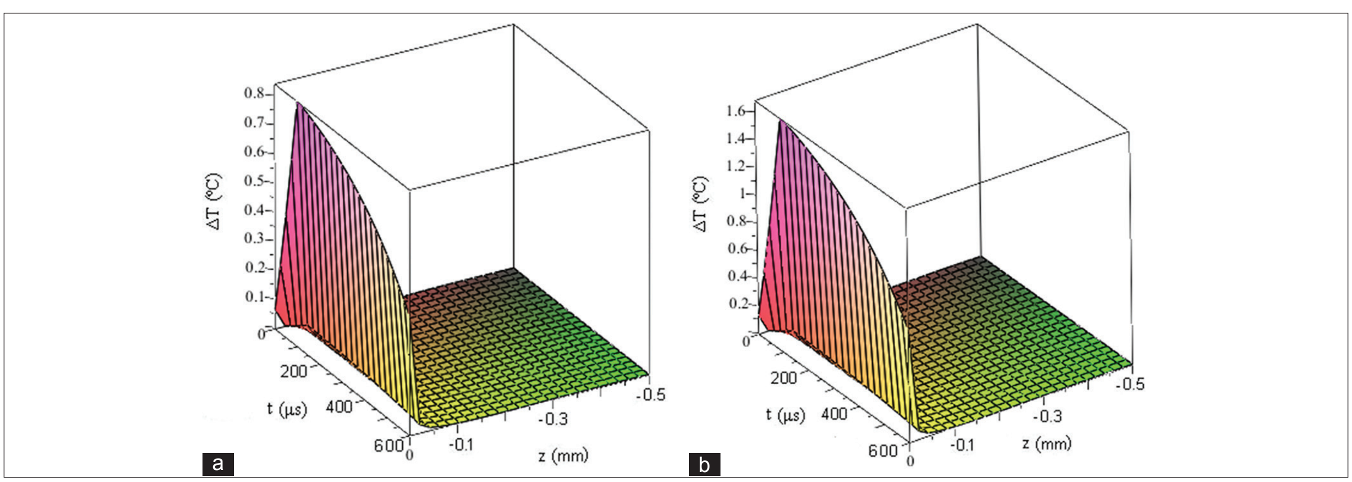

Figure 2: Distribution of temperature rise on the cortical bone irradiated area for, (a) 200 mJ and, (b) 400 mJ Erbium:yttrium aluminum garnet laser at different depths from the irradiated area

Considering the consequent derived thermal stress due to laser exposure, it was found that for 200 mJ laser the maximum derived radial (σ_{rr}), axial (σ_{zz}) and azimuthally ($\sigma_{\theta\theta}$) stress components were 0.20, 0.16 and 0.08 MPa, respectively. While, for 400 mJ laser the maximum derived σ_{rr}, σ_{zz} and $\sigma_{\theta\theta}$ stress components were 0.39, 0.31 and 0.16 MPa, respectively. Figures 4 and 5 show the derived σ_{rr}, σ_{zz} and $\sigma_{\theta\theta}$ stress components for 200 and 400 mJ laser, respectively, at different depths and radii from the exposed area.

DISCUSSION

In this study, the temperature changes and the consequent released thermal stress in cortical bone slices caused by an Er:YAG laser during osteotomy was evaluated using

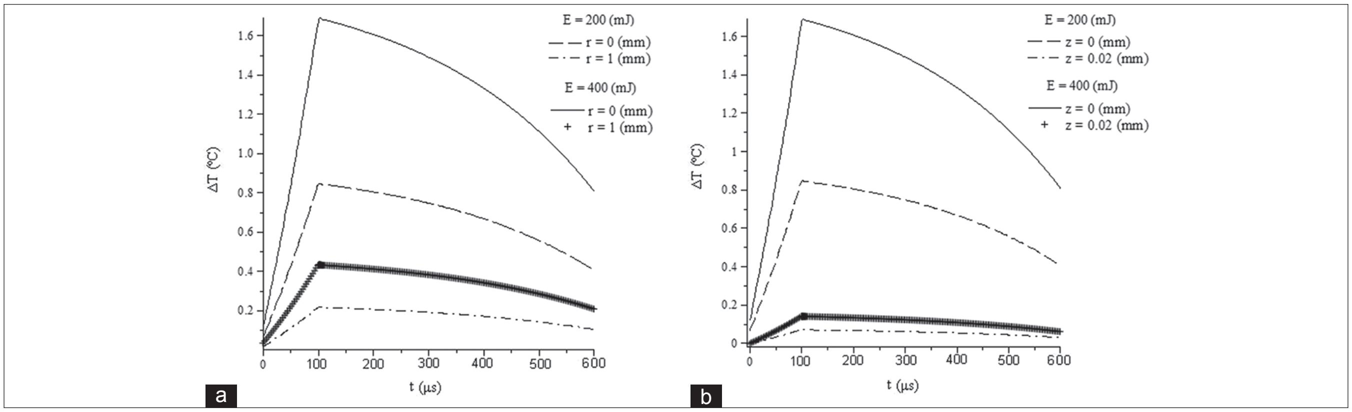

Figure 3: Bone temperature rise following an 100 μs pulse of the 200 mJ and 400 mJ Erbium: yttrium aluminum garnet laser at different radii, (a) and depths, (b) from the irradiated area

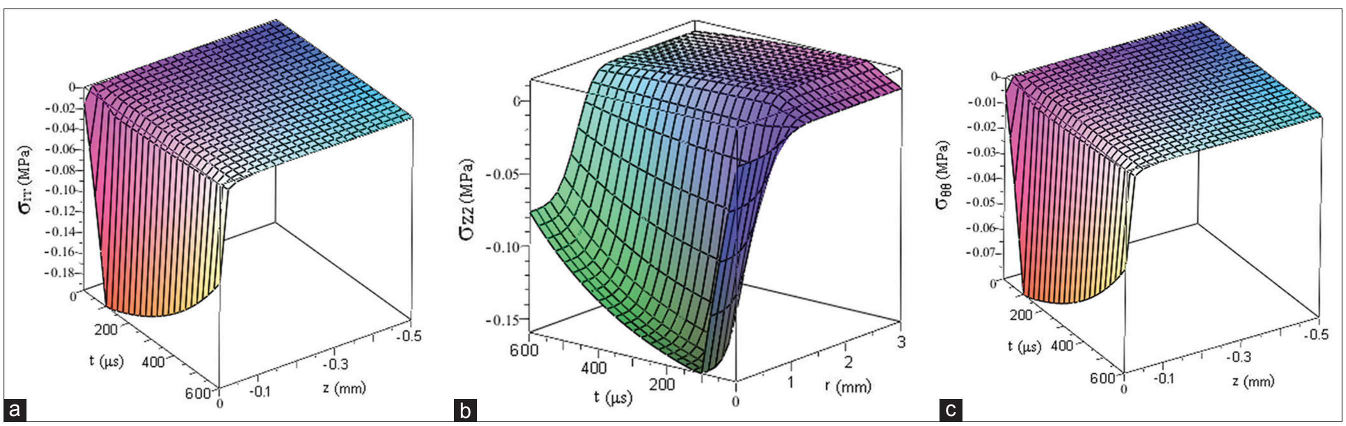

Figure 4: Derived (a) σ_{rr}, (b) $\sigma_{zz,}$ and (c) $\sigma_{\theta\theta}$ stress components for 200 mJ laser at different depths and radii from the exposed area (minus value refers to bone contraction)

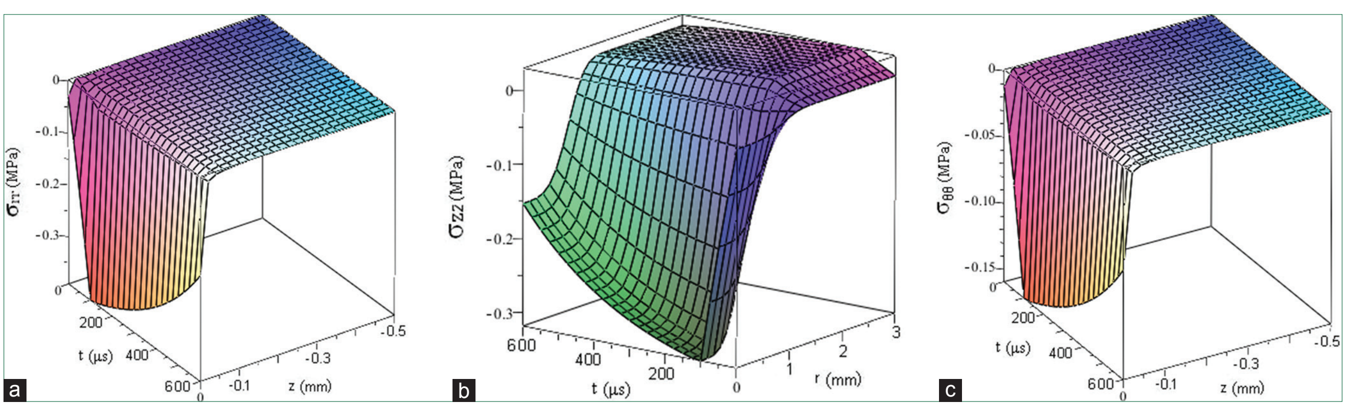

Figure 5: Derived (a) σ_{rr}, (b) σ_{zz} and (c) $\sigma_{\theta\theta}$ stress components for 400 mJ laser at different depths and radii from the exposed area (minus value refers to bone contraction)

Maple mathematical computation. The analysis was performed based on the previous work on the experimental measurements of temperature changes in cortical bone slices during osteotomy procedure.[2]

The results showed that, for a 100 μs pulse of 400 mJ Er:YAG laser, the temperature rise at the exposed area is 1.6°C [Figure 1a]. This was in a good agreement with the measured value of 2.0°C using a digital thermometer placed on the bone during Er:YAG laser osteotomy at a same settings. However, for 200 mJ laser, the discrepancy between the computed and measured value was relatively higher (up to 1.2°C). The discrepancy was mainly due to uncertainties in the experimental measurements and also the used thermo-mechanical characteristics in the simulations. Since thermo-mechanical characteristics of the cortical bone is related to age and diseases, material uncertainty might cause considerable effect on the simulated model.[19]

As can be seen from Figures 4 and 5, derived consequent thermal stress was less than 0.4 MPa for a 100 μs pulse, significantly below than the bone yield stress of 40.9-100.5 MPa. However, it should be noted that for continues exposure or pulse duration of >100 μs the derived value reaches a larger value. Generally, the stress behavior of bone is related to the mechanical properties of the mineral phase, the aspect ratio of the mineral platelets and the mechanical properties of the organic matrix.[19]

Gerold Eyrich, measured the temperature rise and potential thermal damage to tissue during ablation of bone using an Er:YAG laser, equipped with a water-cooling spray. The results of his work revealed the mean temperature rise of 2.0°C on the bone irradiated area. While, in this work, heat conduction equation was solved for the similar bone slice dimensions and the temperature rise at the exposed area was calculated to be 1.6°C [Figure 1a], which was in a good agreement with Gerold Eyrich measurements.[2] Recently, Elahi and Farsi, simulated the temperature distribution in dentin under pulse Er:YAG laser radiation. In accordance to our work, they have solved heat conduction equation and consequently they have obtained the temperature distribution in dentin. Based on their results, on the dentin irradiated area the maximum temperature rise was 3.7°C, for 300 mJ Er:YAG laser exposure, which have very good consistency with the experiment. It should be noted that, compared with our work, the main differences was the defined thermo-mechanical characteristics of the cortical bone and dentin for the calculations.[10] Lee *et al*. presented a new thermal model for bone drilling with applications to orthopedic surgery. Their new model combined a unique heat balance equation for the system of the drill bit and the chip stream, an ordinary heat diffusion equation for the bone and heat generation at the drill tip, arising from the cutting process and friction. In accordance to our results, they found that, the maximum temperature rise depends strongly on the osteotomy radius and depth [Figure 3a and b].[1]

At this study, different combinations of power were considered to evaluate the temperature changes and consequent thermal stress. However, it is also extremely difficult to determine a precise value, due to the individual difference between bone samples, e.g., maturity of bone, degree of mineralization, distribution of bone components (collagen), density of bone, orientation of layers and etc., For simplicity, only an average value of the thermo-mechanical properties of bone was introduced, taking into account for the analysis.

These results could be used as a guideline in numerous clinical applications in bone osteotomy, especially in designing a water coolant, ι.ε., water flow rate. However, the feasibility of the method depends on accurate geometry construction, precise boundary condition definition and suitable thermo-mechanical characterization.[1]

As stated earlier, to prevent thermal damage to adjacent tissue layers, the rise in bone tissue temperature may not exceed 47°C, nor persist for a duration longer than 1 min on 44°C.[20,21] Results of this study confirm that, use of 100 μs Er:YAG laser pulses with 500 μs silence, without continued water cooling on the exposed area, minimizes thermal tissue damage for the laser osteotomies.

In this work, a simple model has been considered wherein the viscoelastic nature, hierarchical organization and local variations in mineral content of bone tissue have not been taken into account. Moreover, the orientation of the mineral and organic has not been considered. We have assumed that the mineral and organic are isotropic. We have also neglected the complicated shape, orientation and distribution of the micro-porosity.

CONCLUSION

In this paper, thermal effects and the consequent released thermal stress in cortical bone slices caused by an Er:YAG laser during osteotomy was evaluated using mathematical computations. These results confirm that use of 100 μs Er:YAG laser pulses with 500 μs silence at 200 and 400 mJ energies minimizes thermal tissue damage, without continued water cooling on the exposed area. The results obtained were compared with the experimental measurements and a good agreement was found.

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How to cite this article: Gholami A, Baradaran-Ghahfarokhi M, Ebrahimi M, Milad Baradaran-Ghahfarokhi M. Thermal Effects of Laser-osteotomy on Bone: Mathematical Computation Using Maple. J Med Sign Sens 2012;3:195-262-8.

Source of Support: Nil, **Conflict of Interest:** None declared

BIOGRAPHIES

Asghar Gholami received his B.Sc. and M. Sc. degrees in Electronics Engineering from Isfahan University of Technology, Isfahan, Iran, in 1993 and 1996, respectively, and Ph.D. degree in Electrical Engineering from Ecole Supérieure d'Electricité (Supélec), France, in 2003. He was awarded a post-doctoral fellowship by Supélec University in 2007. As a post-doctoral fellow he worked on the Modeling, Simulation and Characterization of Next-Generation Multimode Fibers. He has published several research papers in this area. He is currently Assistant Professor at the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran.

E-mail: Gholami@cc.iut.ac.ir

Molood Baradaran-Ghahfarokhi is currently M.Sc. student of Electronics Engineering at the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran. Her research interests include Medical Applications of Lasers and Radiofrequency Radiation. She has published several research papers in these areas.

E-mail: M.baradaran@ec.iut.ac.ir

Marjan Ebrahimi received the B.Sc. degree in Atomic Physics from Islamic Azad University, Shahreza (Isfahan) Branch, Isfahan and M.Sc. degree in Laser Physics from Shiraz Payam-e-Noor University, Shiraz, Iran. Her research interests include Medical Applications of Lasers and Biomedical Engineering.

E-mail: Marjan_ebrahimi1000@yahoo.com

Milad Baradaran-Ghahfarokhi was born in Isfahan, Iran, in 1983. He received the B.Sc. degree in Mechanical Engineering and M.Sc. degree in Medical Radiation Engineering from Shiraz University, Shiraz, Iran. He is currently Ph.D. student of Medical Physics at Isfahan University of Medical Sciences, Isfahan, Iran. His research interests include biomechanical Finite Element Modeling, Monte Carlo simulation, 4D radiotherapy, radiation shielding design and manufacturing and non-ionizing radiation.

E-mail: Milad_bgh@yahoo.com