Original Article

Study of Interaction of Laser with Tissue Using Monte Carlo Method for 1064nm Neodymium-Doped Yttrium Aluminium Garnet (Nd:YAG) Laser

Abbas Majdabadi[1], Mohammad Abazari[2*]

[1]Nuclear Science and Technology Research Institute, Laser and Optic Resrearch School, Tehran, Iran
[2]Faculty of Energy Engineering and Physics, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

Abstract:

Introduction: Liposuction using laser is now one of the most common cosmetic surgery. This new method has minimized the disadvantages of the conventional liposuction including blood loss, skin laxity and long recovery time. Benefits of the new liposuction methods which include less trauma, bleeding and skin tightening prove the superiority of these methods over the traditional mechanical methods. Interaction of laser with fat tissue has the vital role in the development of these new procedures because this interaction simultaneously results in retraction of skin layers and coagulation of small blood vessels so skin tightening and less bleeding is achieved.
Method: Laser lipolysis uses a laser fiber inserted inside a metal cannula of 1 mm delivering the laser radiation directly to the target tissue. Laser lipolysis has a wavelength dependent mechanism, tissue heating and therefor thermal effects are achieved through absorption of radiation by the target tissue cells, causing their temperature to rise and their volumes to expand. We used Monte Carlo (MC) method to simulate the photons propagation within the tissue. This method simulates physical variables by random sampling of their probability distribution. We also simulated temperature rise and tissue heating using Comsol Multiphysics software.
Conclusion: Because optimum and safe laser lipolysis operation highly depends on optical characteristics of both tissue and laser radiation such as laser fluence, laser power and etc. having physical understanding of these procedures is of vital importance. In this study we aim to evaluate the effects of these important parameters.
Results: Findings of our simulation prove that 1064 nm Neodymium-Doped Yttrium Aluminium Garnet (Nd:YAG) has good penetration depth into fat tissue and can reach inside the deeper layers of fat tissue. We see that this wavelength also resulted in good temperature rise; after irradiation of fat tissue with this wavelength we observed that tissue heated in permitted values (50-65°C), this is why this wavelength is widely used in laser lipolysis operations.
Keywords: laser; lipolysis; absorption; radiation.

Please cite this article as follows:
Majdabadi A, Abazari M. Study of Interaction of Laser with Tissue Using Monte Carlo Method for 1064nm Neodymium-Doped Yttrium Aluminium Garnet (Nd:YAG) Laser. J Lasers Med Sci 2015;6(1):22-7

Corresponding Author: Mohammad Abazari MSc; Faculty of Energy Engineering and Physics, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. Tel: +98- 9377326811; Fax: +98-2166414113; Email:alpazar@aut.ac.ir

Introduction

Lasers now have increasingly gain importance in various fields of human activities like industry, telecommunication and medicine. However their main and vital application as a medical device is a look of the future of new medical sciences`. Lasers are now extensively used in medical fields. Laser therapy is widely used in ophthalmology, cancer treatment, dentistry and cosmetic operations.

Nowadays laser assisted lipolysis, which uses a laser fiber inside a standard liposuction cannula to remove body excessive fat has become increasingly popular. The possibility of laser- assisted lipoplasty was first reported in 1992 by Apfelberg. Apfelberg reported laser-assisted liposuction with the YAG laser beam enclosed in a cannula[1]. In conventional liposuction procedures, with the use of metal micro cannula in mechanical back and forth movements, the adipocytes in fat tissue were mechanically removed, causing many undesired effects while many of them were critical drawbacks. Scars, excessive blood loss, skin flaccidity and long recovery time were the mostly reported problems in conventional methods[2]. The application of the novel method of laser lipolysis has eliminated these problems. This technique uses an optical fiber inserted inside a 1 mm cannula, needing a smaller incision, resulting in less bleeding and scars. Interaction of laser radiation with skin tissue results in skin tightening and elimination of the former problems of skin flaccidity and laxity. There are fewer traumas in laser lipolysis procedure due to the small cannula size which results in faster recovery time. One of the most important advantages of this new method is the coagulation of small blood vessels by the laser light resulting in less blood loss during the procedure[3].

Laser lipolysis, also called laser lipoplasty, is now widely used in Europe and Latin America and has recently been introduced in Japan and the United States[4]. Laser lipolysis now is among the most popular cosmetic operations, with 400,000 operations in 2006 only in North America[5].

The interaction of the laser with the tissue is achieved through absorption of the laser energy by the receptive chromophores, thus producing sufficient heat to cause the desired thermal damage. The heat acts on fatty cell, the extracellular matrix and the microcirculation to produce cellular damages, which facilitate the liposuction through fewer traumas and bleeding[6].

The mechanism governing laser lipolysis is selective tissue heating. The laser energy is delivered directly into treated tissue by using a flexible laser fiber. The laser energy converts into heat energy when absorbs by the target adipocytes causing their volume to expand and cell membrane damages. This results in liberating the cellular contents into the extracellular volume which can subsequently be removed via suction cannula[7].

Laser lipolysis has a wavelength dependent mechanism, with tissue heating and desired thermal effects caused by interaction of laser with tissue. However wavelength is the most predominant factor in this procedure. Selective laser heating can be achieved by utilizing an optical wavelength where the absorption by the target tissue is greater than the surrounding region. Specifically for fat treatments the absorption of lipids at vibration band near 915, 1210 and 1720 nm exceeds that of water[8]. Absorption of laser radiation by tissue cells depends extremely on wavelength. High absorption coefficient will conclude to large accumulation of heat and intense temperature rise at the target tissue. Absorption and scattering coefficients of various tissues, depend on wavelength, and are the most important factors in tissue heating, radiation diffusion and penetration depth. High absorption coefficient causes large quota of incident radiation absorb in shallow layers and this give rise to low penetration of radiation into deeper layers of target tissue.

Nowadays there are many different wavelengths available for medical purposes, each of which has their own optical characteristics. Laser tissue interaction, as mentioned above, depends strongly on wavelength; therefor proper selection of wavelength is of vital importance. Each tissue has its own physical and optical properties that result in its dominant absorption for a specific wavelength. Thus proper wavelength selection results in selective treatment of that tissue.

Methods

Now many laser wavelengths have developed for medical purposes. Among them are 920, 980, 1064, 1320 and 1444 nm each of which has their own optical characteristics. Among these wavelengths 920nm has the smallest absorption coefficient in fat tissue and so penetrates the deeper layers of tissue. On the other hand 1320 and 1440nm have largest absorption coefficient in fat tissue causing smaller penetration depth inside fat tissue. These wavelengths are suitable for superficial treatment of such tissues.

1064 nm Neodymium-Doped Yttrium Aluminium Garnet (Nd:YAG) lasers is now widely used in laser lipolysis. Many researches have proved the efficacy of this wavelength in laser lipolysis and fat removal operations[4,9]. The absorption coefficient of fat tissue in this wavelength has a medium value of about $80_{\mu m\text{-}1}$, which results in good penetration depth into the fat tissue. In this paper we determine the penetration depth of this wavelength into the target tissue by using the famous Monte Carlo method and we also evaluate temperature rise of the fat tissue for this wavelength by using Comsol Multiphysics software.

Description of the absorption and scattering characteristics of laser radiation in numerical way can be done by Monte Carlo method. This method is a stochastic one and relies on statistical procedures, its accuracy depends on the number of random numbers and so numerous quantities of photons have to be simulated[10]. However it is extensively used in the problems of laser-tissue interaction. Accuracy of this method has proved with experimental evidences[10].

In the Monte Carlo simulation, the laser beam is represented as a stream of a large number of laser “photons” each having a specific and well defined coordinate, direction and energy weight W[3,11]. In this method we randomly take sampling of variables from their probability distributions[11]. In this manner each random number represents one photon, perpendicularly incidents on the tissue surface. Initial positions of the photons are set to the origin of the coordinate system. We attribute an initial weight of w=1 for each photon. This weight regularly decreases once photon reaches a photon-tissue interaction site. In order to propagate photons inside the tissue we must determine the polar and azimuthal angles of photon direction. The polar angle of photon direction inside the tissue is obtained by random sampling from the probability distribution of the cosine of the deflection (polar) angle[10,12,13]. Azimuthal angle uniformly distributed in (0, 2) and sampled by using a random number. Photons interact with the tissue repeatedly until their weight fall below the predefined threshold value (e.g w< 0.001). Photons below this weight will terminate in an unbiased manner[14].

Results

In this article we use the reputed transport theory to numerically simulate photon-tissue interaction by using the Monte Carlo method. All of physical and optical properties of the 1064nm Nd: YAG laser have been used in this paper. The power of laser was set on 10 watt, absorption and scattering coefficients of this wavelength are $80_{\mu m\text{-}1}$ and 1150 $_{\mu m\text{-}1}$ for fat tissue. The beam radius of the laser radiation sets on 200 µm. Program of this simulation was written in Matlab and has run for 1,000,000 of random numbers (photons). In order to have better understanding of the problem, we set up a grid system, with the typical dimensions of the fat cells, i.e. 100 µm, we recorded the absorbed weight of the photons in these grid elements.

The penetration depth of the mentioned wavelength for the power of 10 watt has been presented in Figure 1. Monte Carlo simulation of the photon penetration depth

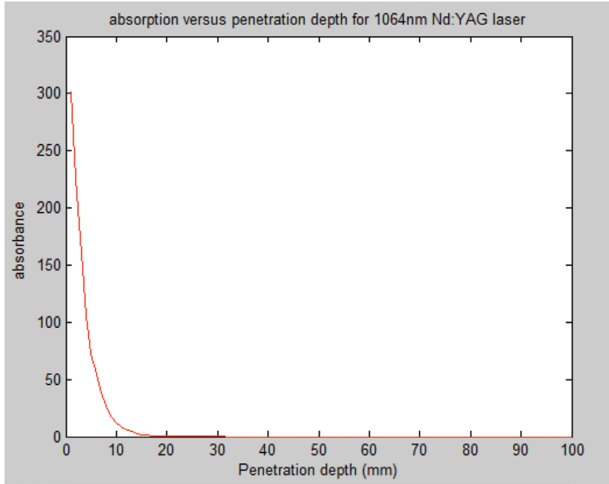

Figure 1. Penetration depth of 1064nm wavelength inside the fat tissue.

shows the mean penetration depth of 3.1 mm for 1064nm wavelength. Comparison with wavelength 1440 nm, having larger absorption coefficient in fat, proves the deeper penetration of 1064nm in fat tissue (Figure 2).

Fluence of the laser radiation is one of the most important parameters in laser lipolysis. Fluence in definition is the energy per unit of area with the dimension of (joule/m^2). We examined the effects of laser fluence in three different ways; first for the fixed beam radius of 200 µm we increased the power of laser. We changed the power from the initial value of 10 to 20 and 30 watt. This resulted in increasing the fluence. Increasing the power of the laser correspond to increasing the photon weight, so we assign the weight of w=1, 2, 3 for the powers of 10, 20 and 30 watt respectively. Results of the Monte Carlo simulation for this state, presented in Figure 3, show a small increase in photon penetration depth. Findings of the simulation show penetration depth of 3, 3.2 and 3.3 mm for powers of 10, 20 and 30 watt respectively. The results of simulation indicate that increasing the power of laser to achieve deeper penetration isn’t reasonable; it leads to the sharp raise in temperature within the tissue and causes undesired effects.

For evaluation of the effects of fluence on penetration depth, this time we increased both power and beam radius of laser radiation in such a way that fluence remains constant. To do this we set the fluence of (1/12560 joule/m^2) as fixed criterion for laser fluence. In the next step we increased laser power to 20 and 40 watt and we increased the beam radius to 282.84 and 400 µm respectively. The results of Monte Carlo simulation for this state have been presented in Figure 4. We found from this simulation that increasing the power and beam radius simultaneously for a fixed fluence leads to interesting results; we saw that

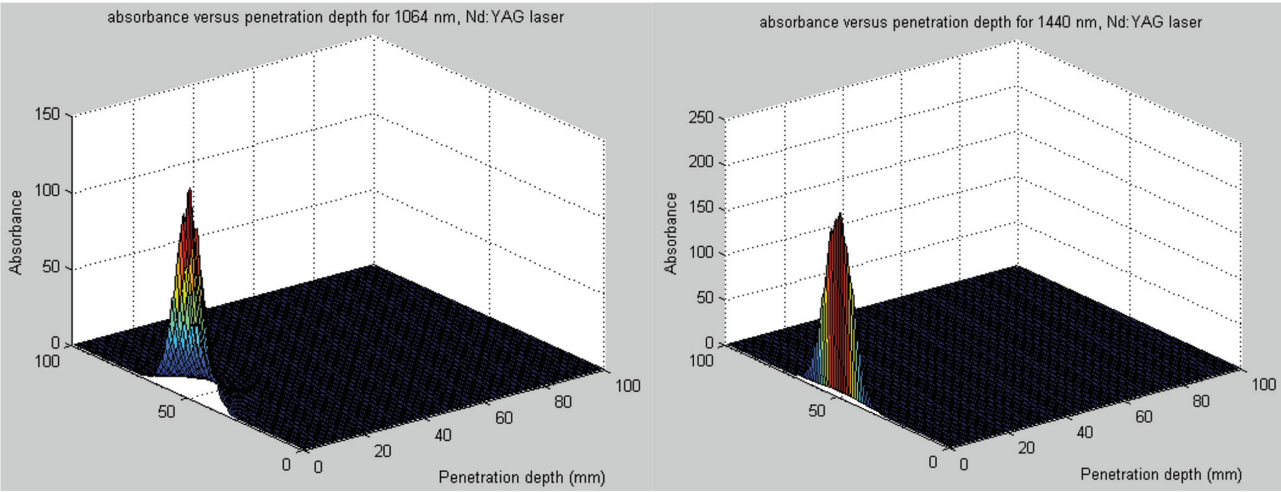

Figure 2. Comparing the penetration depth for wavelength of 1064nm and 1440 nm.

penetration depth increases, the penetration depth is 3, 3.1 and 3.15 mm for the beam radiuses of 200, 282.84 and 400 µm respectively.

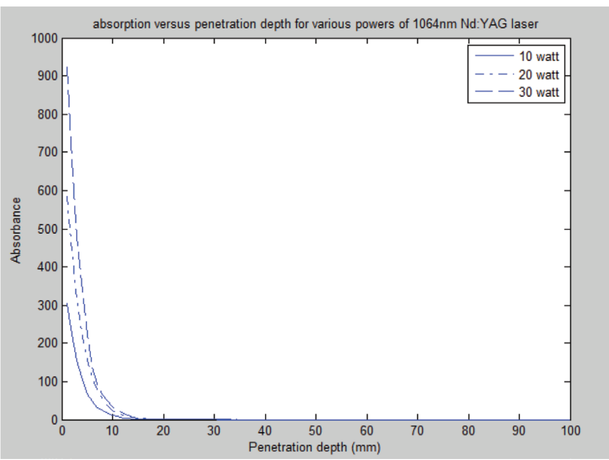

Figure 3. Comparing the penetration depth of 1064nm wavelength for various powers of Nd:YAG laser.

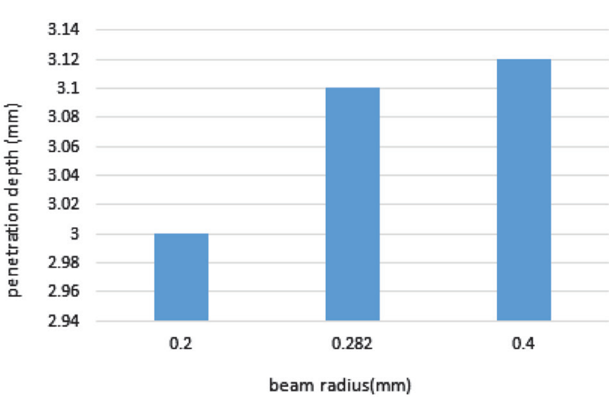

Figure 4. Penetration depth of 1064 nm wavelength for various beam radiuses in fixed fluence.

Examination of the effects of laser fluence in a third way has been done by increasing the beam radius for the fixed power of 10 watt. For this purpose we increased the radius of beam from the initial value to 282.84 and 346.4 µm. In this manner laser fluence decreases and we saw that penetration depth decreases this time too. We saw that penetration depth for the beam radiuses of 200, 282.84 and 346.41 µm is 3, 2.95 and 2.9 mm respectively. However one must note that increasing the beam radius give rise to wider laser beam, causing large volume of tissue being under direct laser radiation. But this has a negative effect and results in decreasing of laser efficacy.

We now present the simulation of tissue heating and temperature rise after the radiation of the 1064nm Nd:YAG laser. Absorption of light in tissue causes a local elevation in temperature. Tissue heat transfer due to the deposited light is described by the bioheat transfer equation[4]. Simulation of tissue heating has been done in Comsol Multiphysics. This software simultaneously solves the Bioheat equation and radiative diffusion equation. Comsol have some predefined physical modules solving the governing physical equations for those modules. Heat transfer module, including Bioheat equation, is one of those modules. Those of physical differential equations that aren't predefined in Comsol modules are anticipated in weak form equations, covering more extensive and general equations. In order to solve these two equations simultaneously, we define these equations in two separate spaces in Comsol and substitute the solution of the radiation diffusion equation as external heat source into bioheat equation. In this simulation, physical properties of fat tissue including specific heat, conductivity and mass density were employed for the analysis. We set the time steps at 0.1 s and the initial temperature at 30.4°C. By choosing proper elements and meshing of the elements we obtained stable solutions for this simulation.

In Figure 4 we present the results of Comsol simulation for tissue heating for the power of 15 watt of Nd:YAG laser. This figure shows that temperature of the tissue increased to 339.687 k which is sufficient to trigger the desired thermal effects. In fact the thermal interval of (50-65°C) is the essential temperature for laser lipolysis[3]. Higher temperatures result in hyperthermia, bruising and ecchymosis[3].

The temperature profile of the tissue after the irradiation of 15 watt 1064nm Nd:YAG laser is presented in Figure 5. We inserted the laser fiber through a micro cannula into the depth of 1cm of the fat tissue. The dimensions of fat tissue were 10×10×3 cm. this figure shows that the

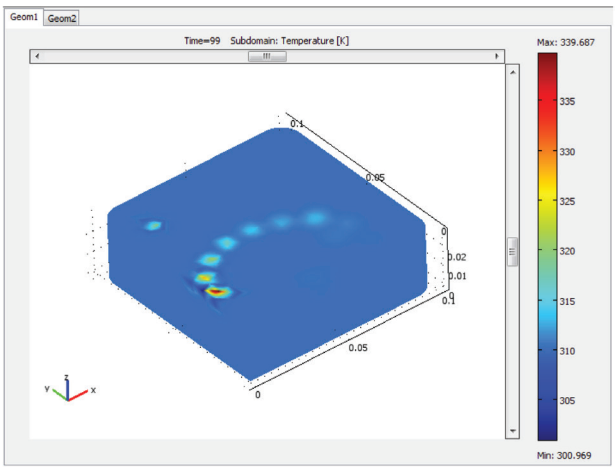

Figure 5. Simulation of temperature rise in fat tissue following the radiation of 1064 nm Nd:YAG laser.

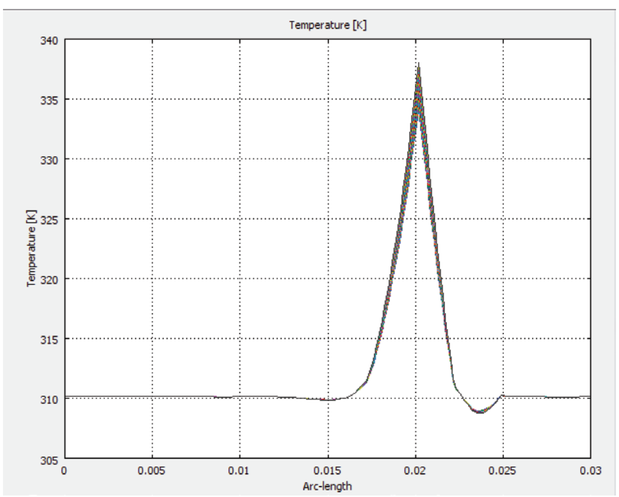

Figure 6. Temperature of the fat tissue at location of the laser fiber.

temperature of the tissue at the laser beam location reaches its maximum value of 340 k. Temperature profile easily have a Gaussian profile due to the Beer-Lambert law of attenuation of radiation[3,10].

Discussion

Numerous studies show that two parameters are of vital role in laser lipolysis: The first is wavelength since the interaction between laser and tissue is achieved through the absorption of the laser radiation by the tissue cells, causing adequate amount of heat produced and consequently the desired thermal effects[5,8]. Second is fluence of radiation that determines dose of energy per area. Wavelength, as mentioned above, has the main role in the interaction of laser with tissue. The penetration depth of laser beam inside the tissue is strongly determined by the wavelength through absorption and scattering coefficients. Our simulations show that 1064 nm wavelength have mean absorption coefficient and so penetrate deeper layers of fat tissue compared to 1320 nm and 1444 nm wavelengths, having larger absorption coefficient by fat tissue.

The findings of our simulation show that increasing the fluence will result in increasing penetration depth. Surprisingly we see that at fixed fluence, simultaneous increasing of both power and beam radius will result in increasing the penetration depth also. However this increasing in penetration itself isn't considered to have a positive effect and will result in lower efficacy. We also examine the effects of decreasing fluence on penetration depth by increasing the radius of laser beam for a fixed power. The increase of beam radius yields to large area of the tissue to be under direct laser radiation. We see that penetration depth of laser radiation inside the tissue decreases this time. However this effect in penetration itself isn't a good point and we need to always have a specific fluence with well-defined power and beam radius.

Simulation of tissue heating has been done in Comsol Multiphysics. Our simulation for 1064 nm wavelength of the Nd:YAG laser in power of 15 watt confirmed tissue heating and temperature rise. The tissue had been under laser radiation for about 100 seconds until the entire tissue to be irradiated uniformly. After this time we saw that tissue temperature had reached 339.687 k or 66.537°C. Most researchers are unanimous on the temperatures in range of 50-65°C as efficient and safe temperatures[3,7,4]. Temperatures less and more than this range do not lead to the desired thermal effects.

Laser lipolysis is a new technique still under development. There are numerous studies exploring the applicability of other techniques and other wavelengths in this field. It has been proved that 1064 nm Nd:YAG laser is a good choice for laser lipolysis. This wavelength has a good penetration depth so is suitable for laser lipolysis. More studies are needed to introduce better wavelengths and more efficient methods. However these results confirm that 1064nm wavelength is one of the best options available for laser lipoplasty. This wavelength has good penetration depth into the tissue, and medium absorption of this wavelength by tissue causes moderate temperature elevation in tissue.

Numerical simulation of the procedures governing laser-tissue interaction can provide better understanding of this procedures and helps in predicting the amount of heats that accumulates within tissue and so predicting the thermal effects and damages. Simulation of interaction of laser with tissue provides large research opportunities in this field.

References

1. Ichikawa K, Tanino R, Wakaki M. Histologic and photonic evaluation of a pulsed Nd:YAG laser for ablation of subcutaneous adipose tissue. Tokai J Exp Clin Med. 2006; 31: 136-40.
2. Youn J. Ablation Efficiency Measurements for Laser-Assisted Lipolysis Using Optical Coherence Tomography. Lutronic Corporation. February 2009
3. Lukac M, Vizintin Z, Zebkar J. QCW pulsed Nd:YAG 1064 nm laser lipolysis. J Laser Health Acad. 2010; 1: 24-34.
4. Mordon S, Wassmer B, Reynaud J, Zemmouri J. Mathematical modeling of laser lipolysis. BioMed Eng Online. 2008; 7:10.
5. Bruce K, Mcbean J, Cheung JS. The new laser liposuction for men. Dermatol Ther. 2007; 20: 448-51.
6. Badin AZ, Gondek LB, Garcia MJ, Valle LC, Flizikowski FB, de Noronha L. Analysis of laser lipolysis effects on human tissue samples obtained from liposuction. Aesthetic Plast Surg. 2005; 29: 281-9.
7. DiBernardo B, Reyes J, Chen B. Evaluation of tissue thermal effects from 1064/1320-nm laser-assisted lipolysis and its clinical implications. J Cosmet Laser Ther. 2009; 11: 62-69.
8. Shah J, Thomsen S, Milner TE, Emelianov SY. Ultrasound guidance and monitoring of laser-based fat removal. Lasers Surg Med. 2008; 40: 680-7.
9. Goldman A. Submental Nd:YAG laser- assisted liposuction. Lasers Surg Med. 2006; 38: 181-4.
10. Niemez M. Laser- tissue interactions, fundamentals and applications. Springer; third edition: Page 15-36.
11. Wang L, Jacques S, Zheng L. MCML- Monte Carlo modeling of light transport in multi-layered tissues. Comput Methods Programs Biomed. 1995; 47: 131-46.
12. Prahl S, Keijzer M, Jacques S, Welsh AJ. A Monte Carlo model of light propagation in tissue. Dosimetry Laser Radiat in Med Biol. 1989; 5: 102-11.
13. Guo Z, Aberb J, Garetz B A, Kumar S. Monte Carlo simulation and experiments of pulsed radiative transfer. J Quantitative Spectroscopy Radiative Transfer. 2002; 73: 159-68.
14. Saidi P, Sadeghi M, Tenreiro C. Variance reduction of Monte Carlo simulation in nuclear engineering field. Theory of Applications of Monte Carlo simulations 2013 chapter 7: 153-72.