Turkish Journal of Physics

Volume 43 | Number 3 Article 8

1-1-2019

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TÜBİTAK

Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2019) 43: 286 – 292

doi:10.3906/fiz-1902-8

Determination of fluence rate distribution in a multilayered skin tissue model by using Monte Carlo simulations

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Received: 12.02.2019 • **Accepted/Published Online:** 10.05.2019 • **Final Version:** 12.06.2019

Abstract: Information on light–tissue interaction is important for clinical applications of lasers. The Monte Carlo technique is one of the commonly used methods to simulate photon propagation and to describe energy absorption in biological tissues. In this study, fluence rate distributions of 633 nm and 830 nm light inside a multilayered skin tissue model have been investigated by using two different simulation software programs: GAMOS tissue optics plug-in and MCML. Results of the plug-in for the fluence rate distributions are in very good agreement with the ones from MCML for both of the wavelengths. This shows that GAMOS tissue optics plug-in can be utilized in simulation studies on the interaction of light in the phototherapeutic window within multilayered tissue models.

Key words: Laser–tissue interaction, Monte Carlo simulation, fluence rate

1. Introduction

The understanding of laser–tissue interaction is crucial for both diagnostic and therapeutic applications of light in medicine. When light travels in tissue, it can be absorbed by chromophores such as hemoglobin and water. In addition, it can be scattered due to differences in the refractive index between intracellular and extracellular fluids and various subcellular components such as mitochondria or nuclei, as well as varying tissue densities. Therefore, knowledge of absorption and scattering properties of tissues must be known in diagnostic and therapeutic applications [1]. The light propagation inside biological tissue is usually characterized by several optical parameters, which are mainly refractive index (n), absorption coefficient (μ_a), scattering coefficient (μ_s), and anisotropy factor (g). The absorption coefficient is defined as the probability of light absorption within biological tissue, and it gives information about the concentration of the light-absorbing molecules, called chromophores, in the tissue. The scattering coefficient, which is defined as the probability of scattering of light within the tissue, depends on the shape, size, and concentration of the scattering molecules. In addition, the g factor is the mean cosine of the deflection angle due to the scattering of photons, and it is a measure of how much the direction differs after scattering from the light-absorbing and light-scattering molecules. All of these parameters are wavelength-dependent and detailed information on them can be found in [2] and the references therein.

Since biological tissues generally have a complex structure, analytical investigation of the light scattering and absorption inside the tissue is not easy. Therefore, a variety of computational methods have been developed in order to analyze the light propagation inside tissue. Radiative transport theory [3,4], the Kubelka–Munk

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model [5], the multiflux model [6], the adding-doubling method [7], and diffusion approximation [8,9] are among the most widely used ones in previous studies. In addition to such methods, the Monte Carlo technique has been used to simulate photon transport and to describe light distribution in biological tissues. This method, which was first introduced for the field of light–tissue interactions in 1983 by Wilson and Adam [10], is a statistical model, and light propagation in the tissue can be accomplished by initiating, moving, and terminating photons using this method. Photon propagation is are expressed in the method as probability distributions that describe the step size of photon movement between two interactions and the deflection angles in a scattering event. Because of its statistical nature, calculating the propagation of a large number of photons is necessary to achieve more accurate results. Many different physical quantities can be scored after each step in the simulation simultaneously.

One of the most active topics in the field of biomedical optics is the investigation of light propagation in skin tissue. Skin tissue consists of several layers with inhomogeneous and complicated structures, and the light can be scattered and absorbed as it propagates inside the tissue [11]. Therefore, it is very important to determine the optical properties of multilayered skin tissue and to investigate how deeply the light can penetrate. There are many studies in the literature on the multilayered modelling of skin tissue by Monte Carlo simulation (see, for example, [12–16]). As the wavelength increases into the visible and near-infrared optical region of the spectrum, light can penetrate more deeply. Penetration depth of visible light in skin tissue is known to have values generally in the range from 1 mm to 3 mm, which includes the epidermis, dermis, and subcutaneous layers of skin tissue [17]. This range of penetration ensures that it is possible to treat diseases in these layers by using phototherapy.

In this study, fluence rate distributions of the light with two different wavelengths (633 nm and 830 nm) inside a multilayered skin tissue model have been investigated by using the Monte Carlo technique. For this purpose, two different simulation software programs have been used and the results from the first code are tested with those from the second one, which is well known in the field of biomedical optics.

2. Materials and methods

Geant4/GAMOS Monte Carlo (MC) architecture [18,19] has been used with an extra package for stochastic modeling and investigation of emerging biomedical applications of the Cherenkov effect [20]. Since Geant4 was originally designed as a simulation architecture for high-energy physics research, it is based on the Class Library for High Energy Physics (CLHEP), working on a predefined set of unit classes. Therefore, it has been widely used to simulate radiation of energies higher than $\sim$250 keV with matter (see, for example, [21,22]). However, thanks to the tissue optics plug-in, it can be used to simulate the transport of radiation-induced optical photons, such as that due to the Cherenkov effect, inside the medium. Moreover, the results of validation simulations of the plug-in encourage its use it for more conventional biomedical optics simulations [20].

Secondly, the Monte Carlo modeling of photon transport in multilayered tissues (MCML) algorithm [23], which has been written in C programming language, has been used for modeling and understanding photon transport in skin tissue. It is possible to define multiple planar layers, each with its own optical properties and thickness, by using MCML. It models the propagations of photons that are assumed to be in the form of a very narrow light beam perpendicular to the tissue surface. MCML is commonly used in simulation studies for the interaction of light with multilayered tissue models, and it gives very successful results [24,25].

In this study, skin tissue has been considered to consist of three layers: epidermis (0.3 mm), dermis (1.2 mm), and subcutaneous fat (3 mm). A schematic view of the skin tissue model is illustrated in Figure 1.

The simulations' input parameters, which are absorption coefficient (μ_a), scattering coefficient (μ_s), anisotropy scattering factor (g), refractive index (n), and thickness (d), have been specified for each layer and wavelengths of 633 nm and 830 nm based on the values available in the literature (see Table). For every run, g and n have been accepted to have constant values of 0.8 and 1.4, respectively, regardless of the wavelength and tissue type [26].

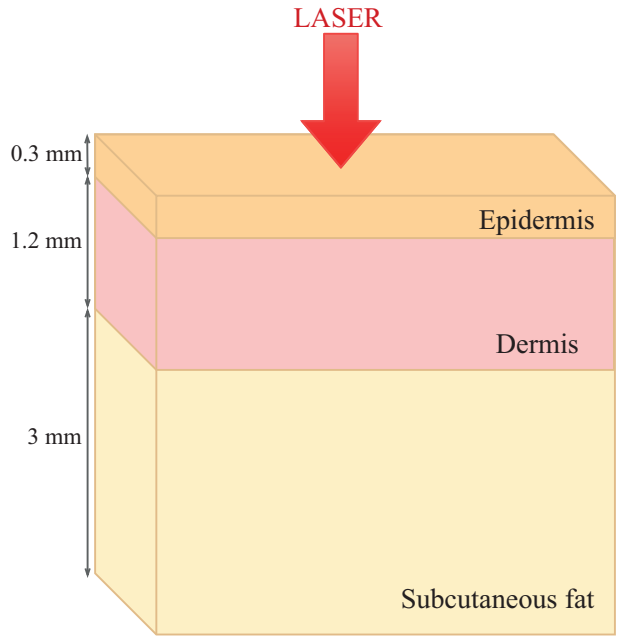

Figure 1. Schematic view of the tissue model.

Table. Optical parameters of skin tissue [26].

		633 nm	830 nm
Epidermis	μ_a (cm^{-1})	0.26	0.14
	$\mu_s^{'}$ (cm^{-1})	23.80	17.80
Dermis	μ_a (cm^{-1})	0.15	0.11
	$\mu_s^{'}$ (cm^{-1})	14.95	10.75
Subcutaneous fat	μ_a (cm^{-1})	0.14	0.10
	$\mu_s^{'}$ (cm^{-1})	12.70	9.80

Monte Carlo simulations have been performed separately for 633 nm and 830 nm. The same geometry and parameters have been used in both GAMOS tissue optics plug-in and MCML software. For each case, the simulation codes have been run such that the photons have been considered to be emitted from a collimated beam source as shown in Figure 1. The modeled tissues have been subdivided into cubic voxels that have sides of 0.1 mm and the fluence rate for each individual voxel has been recorded. Simulation results are compared and discussed in the following section.

3. Results and discussion

The simulation results for the fluence rate values inside the multilayered skin tissue model is shown in Figure 2 for the wavelengths of 633 nm and 830 nm as a function of depth.

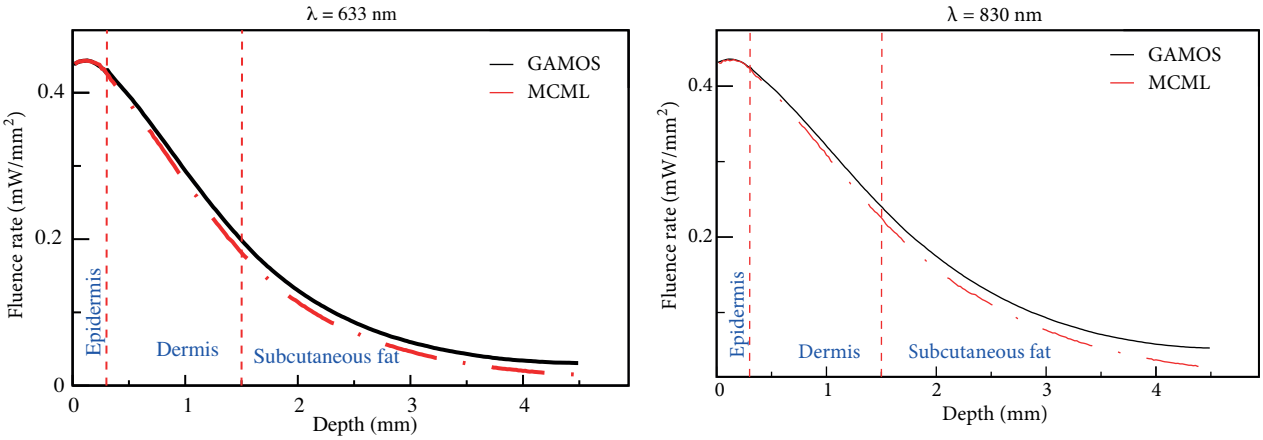

Figure 2. Fluence rate distribution of 633 nm and 830 nm light in multilayered skin tissue as a function of depth.

It can be obviously seen from the figure that the simulation results of the GAMOS tissue optics plug-in for both of the wavelengths are in very good agreement with the ones from the MCML code. Both of the software programs agree that the fluence rate within the skin tissue increases up to a depth of ∼0.2 mm, and then drops rapidly as the depth inside the tissue increases. However, decrease in the fluence rate at 633 nm is sharper than that at 830 nm, indicating that 830 nm light can penetrate deeper than 633 nm. This situation can be attributed to the relatively higher absorption and scattering coefficients of skin tissue for 633 nm compared to those for 830 nm. As the absorption coefficient increases for a kind of tissue, the average energy of the photons at a specific depth inside the tissue decreases. This is because the increased absorption rate causes a reduction in the number of photons at a specific depth. As a result, average photon path length and optical penetration depth are relatively smaller in tissues with higher absorption coefficients. Although a greater scattering coefficient causes larger path lengths of the photons, it results in decreased optical penetration depth.

It is known that melanin and water are the main constituents affecting the absorption and scattering coefficients of the skin tissue. Since melanin and water have high absorption rates for the wavelength of 633 nm, the light at this wavelength cannot penetrate deeper into the skin tissue. On the other hand, light with a wavelength of 830 nm, which is in the near-IR region, has a lower absorption rate for such chromophores compared to that for the visible wavelength of 633 nm.

Two-dimensional distributions of the optical fluence rate obtained by using the GAMOS tissue optics plug-in for wavelengths of 633 nm and 830 nm are illustrated in Figure 3. As can be seen from this figure, 830 nm light has penetrated more deeply and has spread more widely in the skin tissue compared to 633 nm. This finding based on Figure 3 supports the inference made above by looking at Figure 2.

It is obvious that different optical parameters for different wavelengths cause different fluence rate distributions inside the multilayered skin tissue model. Even if 830 nm light can penetrate into deeper regions of the tissue, both 633 nm and 830 nm light can pass through the layers of the epidermis, dermis, and subcutaneous fat. That is why 830 nm light can be used effectively for the treatment of diseases in deeper parts of these layers even though 633 nm is more convenient for the ones in shallower regions.

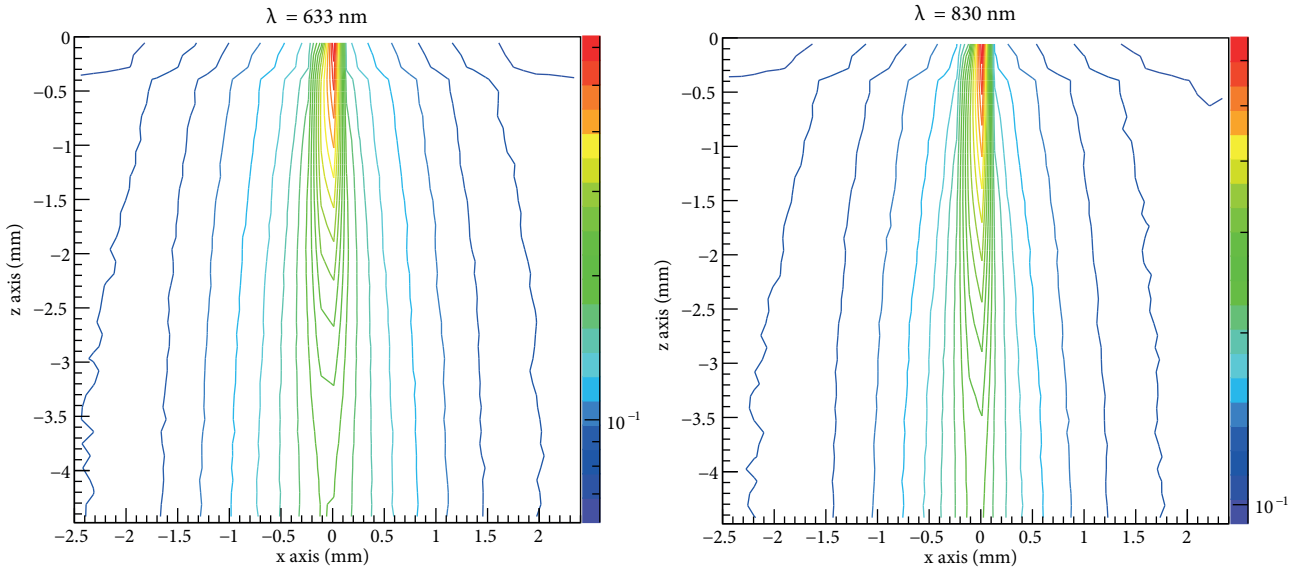

Figure 3. Two-dimensional fluence rate distributions of 633 nm and 830 nm light in multilayered skin tissue.

4. Conclusion

In this study, fluence rate distributions of 633 nm and 830 nm light inside a multilayered skin tissue model have been investigated by using the Monte Carlo technique. Two different simulation software programs, the GAMOS tissue optics plug-in and MCML, have been utilized for this purpose. Results of the plug-in for the fluence rate distributions of 633 nm and 830 nm light are in very good agreement with those from MCML. By using both of the software programs, it has been found that the fluence rate inside the skin tissue model is increased up to the depth of ∼0.2 mm, and then it drops rapidly as the depth increases. It is known that GAMOS gives accurate results for simulations of the interaction of relatively higher energy radiation with matter since it uses the libraries of Geant4. This study shows that the tissue optics plug-in is also quite successful in simulating the interaction of light with tissue in phototherapeutic window within multilayered tissue models. Therefore, it can be concluded that GAMOS tissue optics plug-in can be utilized for more conventional biomedical optics simulations.

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