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Simulation Study for the Penetration Depth of Red and Near Infrared Light in Muscle Tissue

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Abstract

Light dosimetry is an important procedure in photodynamic therapy for tumor kill without harming the healthy tissue. For correct dosimetry, the penetration depth of the light into the tissue is one of the important parameters. In this study, fluence and penetration depth for the wavelengths of 650 nm and 830 nm in the muscle tissue have been investigated using Monte Carlo simulations. It is found that the decrease in the fluence of the 650 nm with the increase in depth is sharper than that of 830 nm. In addition, the penetration depth of muscle tissue for the wavelengths of 650 nm and 830 nm are found to be 1.57 and 3.23, respectively, which are reasonably agree with the experimental ones (1.47 and 3.72) reported in the literature.

Key words: Simulation, Penetration depth, Tissue optics, Photodynamic therapy

1. Introduction

Electromagnetic radiation of different wavelengths, including the ones in red and near infrared regions of the spectrum, is increasingly applied in medical diagnostic and treatment. Photodynamic therapy (PDT), for example, is a cancer treatment technique, which requires the use of tumor-localizing photosensitizing agent and light of a wavelength specific to activation characteristics of the photosensitizer [1]. The wavelength of light used in PDT is predominantly in the wavelength range between 600 nm and 850 nm, which is called “phototherapeutic window” [2]. Light dosimetry is an important procedure in PDT to ensure tumor kill by avoiding damage to the healthy tissue. For correct dosimetry, it is crucial to assess the optical properties of tissue [3]. More specifically, the penetration depth of the phototherapeutic light into the tissue and deposited energy via the optical absorption are important parameters for the determination of correct dose in PDT.

Propagation of the light in a biological tissue is known to be complex. When the light enters the tissue, it is either scattered or absorbed depending on not only the wavelength of the light but also the optical characteristics of the tissue. The interaction of the light with the biological tissues can be analyzed via several models, one of which is diffusion model [4-5]. In addition, Monte Carlo method is alternatively used to simulate photon transport in tissues since 1983, when it was first introduced by into the field of light tissue interactions [6].

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The optical properties of a tissue are usually described in terms of various parameters, including the scattering coefficient (μ_s), the absorption coefficient (μ_a), refractive index (n) and the scattering anisotropy factor (g). The scattering (absorption) coefficient is defined to be the product of microscopic scattering (absorption) cross-section and the particle density of scatters (absorbers) in units of cm^{-1}. Moreover, g factor is defined as the mean cosine of deflection angle due to a scattering event. All of these parameters are wavelength dependent and detailed information on them can be find in [7] and references there in.

In this study, fluence and penetration depth for the wavelengths of 650 nm and 830 nm in the muscle tissue have been investigated using Monte Carlo simulation. The simulation results have been compared with measurements performed by a different group in order to test the reliability of the models used in the simulations.

2. Simulation Method

Monte Carlo simulations for interactions of the light with the modelled muscle tissue have been performed using GEANT4 [8] architecture for medically oriented simulations (GAMOS) [9] together with the Tissue Optics plug-in [10]. Although, the plug-in modified package was developed specifically for simulation of light transport due to the Čerenkov effect, its flexibility makes it also extensible to more conventional biomedical optics simulations [10].

By utilizing the plug-in, the muscle tissue has been modeled to have a simple geometry, which is a cubic box with sides of 5 mm. Optical parameters of the muscle tissue defined in the simulations have been determined on the basis of literature values. The parameters corresponding to the wavelengths of 650 nm and 830 nm are given in Table 1.

Table 1. Optical parameters of the muscle tissue [11]

Wavelength (nm)	μ_s (cm^{-1})	μ_a (cm^{-1})	N	g
650	88	1.03	1.37	0.9
830	70	0.30	1.37	0.9

Simulations have been performed for 650 nm and 830 nm wavelengths separately. For each run, 1 million photons, which are considered to be emitted from a pencil-beam source, have been injected normally upon the modelled muscle tissue. In order to analyze the interaction more efficiently, the modeled tissue has been subdivided into cubic voxels with sides of 0.1 mm and the fluence has been recorded for each individual voxel. The results are discussed in the following section.

3. Results and Discussion

Two dimensional distributions of the fluence of 650 nm light throughout the muscle tissue model (5 mm x 5 mm) are illustrated in Figure 1 for different depths (tissue surface, 1 mm, 2 mm and 3 mm deep from the surface) separately. Since the photons have been injected upon the modelled muscle tissue in a single direction, the energy of the photons are deposited only at a small area. However, light is scattered in the tissue during its propagation. That's way, the area of the cross section that the photons reach gets larger for deeper sides of the tissue. Although the similar situation is valid also for 830 nm, how much the light is scattered or at which depth the light can penetrate is heavily depend on the wavelength.

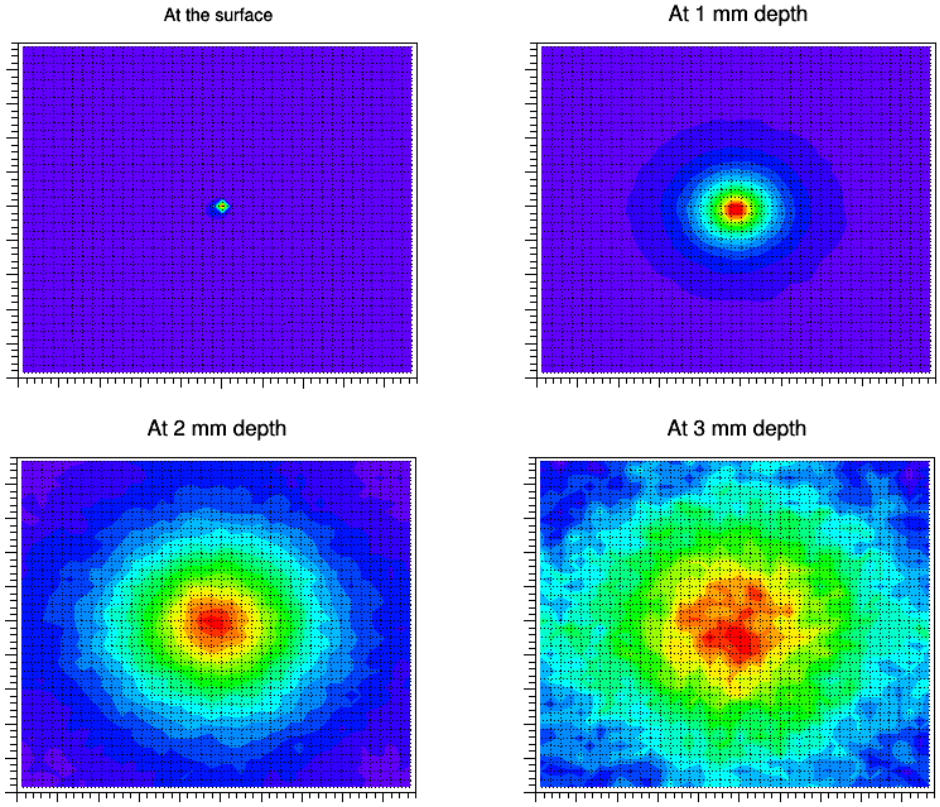

Figure 1. Two dimensional distribution of fluence in muscle tissue for the wavelengths of 650 nm

It is clear that increase in the scattering coefficient results in an increased scattering and, therefore, low penetration. Similarly, as the absorption coefficient increases, the average penetration depth of the photons decreases because the energy of the photons at a deep position decreases. As it is given in Table 1, both of the scattering and the absorption coefficients of the muscle tissue for 650 nm wavelength are greater than that for 830 nm. Based on this information, 830 nm light is expected to penetrate deeper than the one with 650 nm in muscle tissue. The simulation results for the fluence of the 650 nm and 830 nm in tissue are given in Figure 2 as a function of depth. As it can be seen from the figure, decrease in the fluence of the 650 nm is sharper than that of 830 nm, which indicates that 830 nm light can penetrate deeper than 650 nm.

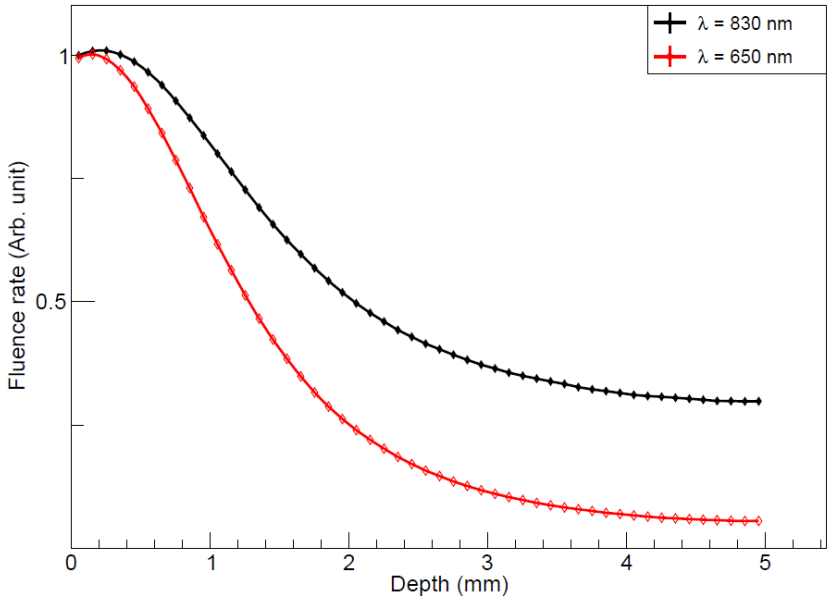

Figure 2. Fluence distributions of 650 nm and 830 nm light in muscle tissue as a function of depth.

The depth at which the intensity of the light inside the tissue falls to 1/e (~37%) of its value at the surface is defined as penetration depth. In this study, penetration depths of muscle tissue for the wavelengths of 650 nm and 830 nm are obtained to be 1.57 mm and 3.23 mm respectively. The measurements made by another group yielded that penetration depths for the wavelengths of 632.8 nm and 835 nm are 1.47 and 3.72 in muscle tissue [12]. It can be said that the simulation results of this study are quite compatible with the experimental ones, even though simulated depth for 650 nm (830 nm) is 7% greater (13% smaller) than the measured one for 632.8 nm (835 nm). The slight difference between the results could be attributed to simulation model and the measurement technique. However, the use of same simulation package for different tissue types is planned for the future in order to check the success of the models used in the simulations for different conditions.

4. Conclusions

In this study, fluence and penetration depth for the wavelengths of 650 nm and 830 nm in the muscle tissue have been investigated using Monte Carlo simulation. For this purpose, GEANT4 architecture for medically oriented simulations (GAMOS) together with the Tissue Optics plug-in has been utilized. It is obtained that the fluence of the 650 nm light decrease with the increase in depth more dramatically than 830 nm. As a consequence of this, the penetration depth of muscle tissue for the wavelength of 650 nm is found to be 1.57 where that of 830 nm is 3.23. These results are reasonably agree with the experimental ones (1.47 and 3.72 respectively) reported in the literature for the wavelengths of interest.

Acknowledgments

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