On Phantom Experiments of the Photon Migration Model in Tissues

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Abstract: Light-tissue interaction is common in clinical treatments and medical research, therefore investigation of light path in irradiated tissues is of high importance. In this research, reflected light intensity measurements from different homogeneous phantoms, combined with numerical simulations, have been used for the investigation of phantoms absorption properties. Our results suggest a good fitting between the theoretical model and the random walk simulations, enabling the extraction of the lattice absorption parameter. Yet, as long as low scattering phantom experiments are concerned, the photon migration model does not provide an adequate description for the phantom absorption coefficient extraction.

Keywords: Photon migration, phantoms, light-tissue interaction, light path in irradiated tissues, absorption properties.

1. INTRODUCTION

Most optical-physiological diagnoses are based on the insertion of light, with known parameters, to a tested tissue, followed by the measurement of the reemitted light. Changes in the spectrum and intensity of the reemitted light, compared to the injected light, result from interactions of the irradiated light with the tissue components [1, 2].

Tissues can be physically characterized by their optical parameters. The optical properties of human tissues, such as the absorption coefficient μ_α, the scattering coefficient μ_s, and the anisotropy factor g, which represents the directionality dependence of light propagating inside the tissue, reflect the composition and the physiological dynamics of the tissue. Whereas μ_α is mainly related to tissue chromophores [3-5], μ_s and g reflect the form and concentration of the scattering components in the irradiated tissue [6, 7].

Each tissue contains many components in which scattering and absorption processes can occur. Multiple scattering results in more light absorption due to prolongation of the optical path-length. The extent of light absorption depends on the wavelength of light, tissue optical characteristics, such as the absorption coefficient, and the distribution of absorbers in the tissue through which it propagates.

Despite the complexity of light path through tissues, many applications were and are being developed based on tissue irradiation for clinical or diagnostic purposes [8-10]. Therefore, many researches present the influence of tissues' optical parameters on the light path inside. These include, e.g., the effect of anisotropic optical properties on the photon migration [11], the time of flight and photon path length [12] and the penetration depth in irradiated tissue [13-15]. A comprehensive study of different tissues, representing different spatial distribution of the tissues' optical components and their response to irradiated light, is still under investigation [16-19].

One of the most simple tools which has been theoretically proved useful for tissue's optical parameters investigation is the photon migration model by Bonner R.F. *et al*., [20]. This model enables one to study reflected light intensity measurements in several distances on the tissue surface, from which one can deduce tissue optical properties such as the absorption parameter μ.

The model simplest version is the homogeneous tissue [20] (see Fig. **1**), in which a single set of absorption and scattering parameters describes the lattice. The transverse coordinate is ρ=(x,y), and the positive z axis is pointing into the tissue. The tissue interface, z=0, is assumed to be a totally trapping surface. Radiation is injected into the tissue through the origin (0,0,0) and photons then randomly diffuse within the tissue. Photons eventually either reach the upper surface z=0, where they can be detected and disappear from the system [20, 21], or they go through an internal absorption. The intensity profile of the reflected radiation, Γ(ρ), was shown by Bonner R.F. *et al*. [20] to be given by:

$$\Gamma(\rho) \approx \frac{\sqrt{6\mu}}{\rho^2}\exp(-\rho\sqrt{6\mu}) \tag{1}$$

from which one can infer the value of the lattice absorption parameter, μ. This equation can be rewritten as:

$$\ln(\rho^2\Gamma(\rho)) = c - \rho\sqrt{6\mu} \tag{2}$$

where c is a constant, depending on the lattice absorption parameter μ. Hence, the slope of $\ln(\rho^2\Gamma(\rho))$ should yield μ of the irradiated sample.

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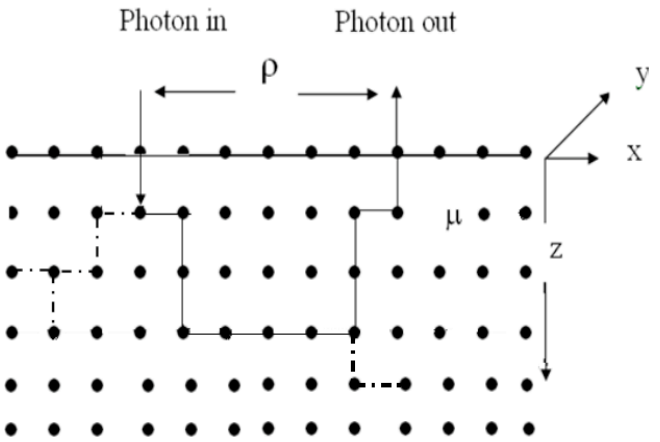


Fig. (1). A discrete lattice representing a homogeneous biological tissue in the photon migration model. The full line presents the trajectory of a reflected photon that arrived to the detector while the dashed line presents a trajectory of a photon that was absorbed within the lattice.

This model, and its later versions, were intensively discussed in the literature [13, 22-24]. Researchers have proposed different methods to determine quantitatively absorption and reduced scattering coefficients, by using spatially [24, 25] and/or temporally resolved measurements [26-29]. Diffusion theory or Monte Carlo simulations have been commonly used to relate the measured light intensity to the optical parameters [16, 30-32]. Still, an adequate relation between experimental results and the theoretical approaches of the photon migration model is not well established yet.

Our aim, in this current study, is to use Eq. 2 and suggest an experimental method for the extraction of irradiated phantom optical properties. In the current study we present simulations of reflected light intensity from homogeneous lattices owning different absorption properties. In addition, a non invasive optical technique for reflected light intensity measurements is presented. As irradiated samples we used solid phantoms with different absorption properties. The reflected intensity was measured in several source-detector distances (ρ) and was analyzed using Eq. 2 in order to deduce the absorption parameter of the irradiated phantom.

2. MATERIALS AND METHODOLOGY

2a. Simulation of Reflected Light Intensity Profile from a Lattice

Simulations of photon migration within a lattice, representing a biological tissue, were performed in order to substantiate and extend the experimental results. The main assumptions of the simulations correspond to the photon migration model [20], as follows:

(1) Photons were represented as random walkers, migrating within a semi-infinite three-dimensional medium;

(2) Photons were injected, without reflection, into a single point on the lattice plane z=0, while the positive direction of z was into the surface. The first location of a photon was (0,0,1);

(3) The probability for a photon to survive at each lattice step was exp(-μ);

(4) The mean scattering length was taken to be one lattice unit;

(5) When photons return to the surface z=0 they were emitted from the system.

In each lattice surface point (x,y,0), the number of photons reaching the point was counted. The simulation displayed the radial distribution of reflected photons around the injection point to perform a simulated Γ(ρ) and $\ln(\rho^2\Gamma(\rho))$ graphs. Different absorption parameters were simulated (μ=0.01, 0.04, 0.1, 0.2) and the absorption parameters were calculated from the graphs' slopes, using Eq. 2.

2b. The Irradiated Sample

Solid phantoms, with different absorption coefficients, were prepared in order to simulate skin tissues with different optical properties. The phantoms were prepared using Indian Ink 0.1%, as an absorbing component, Intralipid (IL) 20% (Lipofundin MCT/LCT 20%, B. Braun Melsungen AG, Germany), as a scattering component [33] and agar powder, in order to convert solution into gel. The phantom was prepared in cell culture plates (90 mm) and was cooled in vacuum conditions (to avoid bubbles). Three phantoms with different absorption coefficients were prepared. Each phantom was prepared using 2 ml of IL 20% and increasing volumes of Indian ink 0.1%: 1, 1.5 and 3 ml. The absorption coefficients were: μ_a= 0.0064, 0.0096 and 0.0192 mm^{-1} respectively, which were chosen according to the skin optical properties presented by Dam J.S. *et al.* [34].

2c. The Experimental Set-Up

A non invasive optical technique was designed and built (*NEGOH-OP TECHNOLOGIES*, Israel) for reflected light intensity measurements. The set-up included a laser diode, as an excitation source, with a wavelength of 650 nm. As photo detectors, we used four portable photodiodes, where each photodiode was deposited in a different distance ρ on the sample surface in order to enable Γ(ρ) measurements (see Fig. **2**). The irradiation was carried out using an optic fiber with a diameter of 125 μm. Each photodiode had a width of about 0.3mm (300μm). The distance between the light source and the first photodiode was ~1 mm. A continuum reflected light intensity measurement was enabled using a micrometer plate on which the phantom was deposited. The reflected light intensity was collected from ~200 source-detector distances, with a distance of 20 μm in between. Thus, the initial ρ was 1mm (the distance between the light source and the first photodiode), the second ρ for the first photodiode was 1.02 mm, the third was 1.04 mm and so on. The maximal ρ that the fourth photodiode arrived was ~9 mm since the entire array (of length ~5mm) moved 200 steps of 20 μm each. The maximal distance in which the signal to noise ratio was high enough to give an appropriate decaying character was 5 mm. The reflected intensity was collected using a digital scope (*Agilent Technologies, Mso7034a, Santa Clara, CA*) and the data was processed using the MATLAB program.

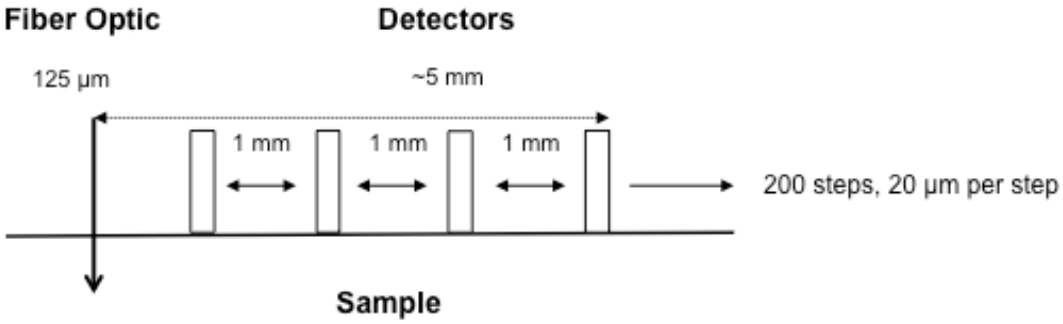


Fig. (2). A schematic description of the experimental set-up for linear reflected light intensity measurements. The laser diode wavelength was 650 nm. The photodiodes were in close contact with the phantom surface. The micrometer plate moved ~200 steps of 20 µm each, enabling continuous measurements of the spatial reflectance from the phantom from 1 mm up to 9 mm from the laser diode position.

3. RESULTS

3a. Simulations

Simulations of reflected light intensity from lattices with different optical properties were performed, according to the description in section *2a.* Photons penetrate into the lattice and advance randomly in it. In each lattice point, the photon is either being absorbed, with a probability of (1-exp(-µ)), or is survived and scattered to one of its six nearest neighbors (x±1, y±1, z±1) with a probability of exp(-µ). Simulations were performed assuming several absorption coefficients. The lattice surface dimensions were (2000 X 2000) lattice points. The logarithmic graphs of the reflected light intensity are shown in Figs. (**3a** and **3b**).

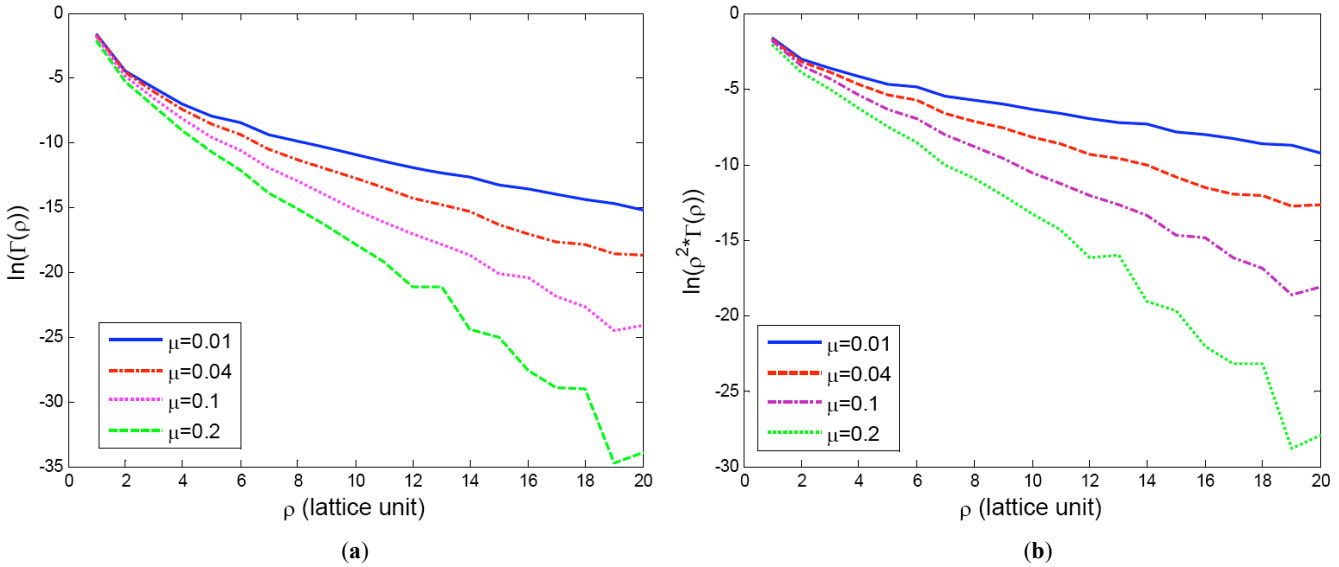
The simulation results present the predicted dependence of the reflected light intensity profile on the lattice absorption parameter: the higher is the value of the absorption parameter the sharper is the decay of the reflected light intensity profile. This is in agreement with Eq. 1, where the absorption parameter (µ) is presented in the exponential decay term. Moreover, the slopes in Fig. (**3b**) calculated according to Eq. 2, fit well the simulation lattice absorption parameters: 0.01, 0.04, 0.1, and 0.2. The absorption parameters, calculated from each graph slope, were: 0.015± 0.004, 0.052±0.005, 0.115±0.005, 0.26±0.02 respectively. These simulation results suggest that the approximated term of $\ln(\rho^2\Gamma(\rho))$ is adequate for the absorption parameter deduction of irradiated scattering and absorbing media.

Our next step was to experimentally measure the reflected light intensity profile from phantoms with different absorption coefficients in order to extract the absorption parameter of each phantom using Eq. (2) above.

3b. Measurements

Reflected light intensity from different phantoms (as described in section *2b.* above) was measured using the experimental set-up described in section *2c.* Representative results of the reflected light intensity profile from three different phantoms are presented in Fig. (**4**).

Fig. (**4a**) presents the reflected light intensity measured (in logarithmic scale) from the different homogeneous phantoms. The experimental results fit well the simulations



(**a**) (**b**)

Fig. (3). Simulated reflected light intensity profiles at the surface z=0 (**a**) in logarithmic scale. (**b**) The $\ln(\rho^2\Gamma(\rho))$ decay graphs. The absorption parameters are per lattice step. The resulted absorption parameters, calculated using Eq. 2, were: 0.015, 0.052, 0.115 and 0.26.

character; the larger is μ_α the sharper is the graph slope. The phantoms absorption coefficients were 0.0064, 0.0096 and 0.0192 mm^{-1} and the graphs slopes present the increasing values of: 0.42, 0.47 and 0.56, respectively.

Yet, Fig. (**4b**) presents a non expected result for $\ln(\rho^2\Gamma(\rho))$: instead of the linear decay, predicted by Eq. 2 and also observed by our simulations, these graphs present a non linear increase. These results suggest that the diffusion approximation for light path within a tissue, as described by Eqs. 1 and 2, might not be adequate for our phantom experiments as long as the IL concentration is 0.8 % and ρ<5 mm.

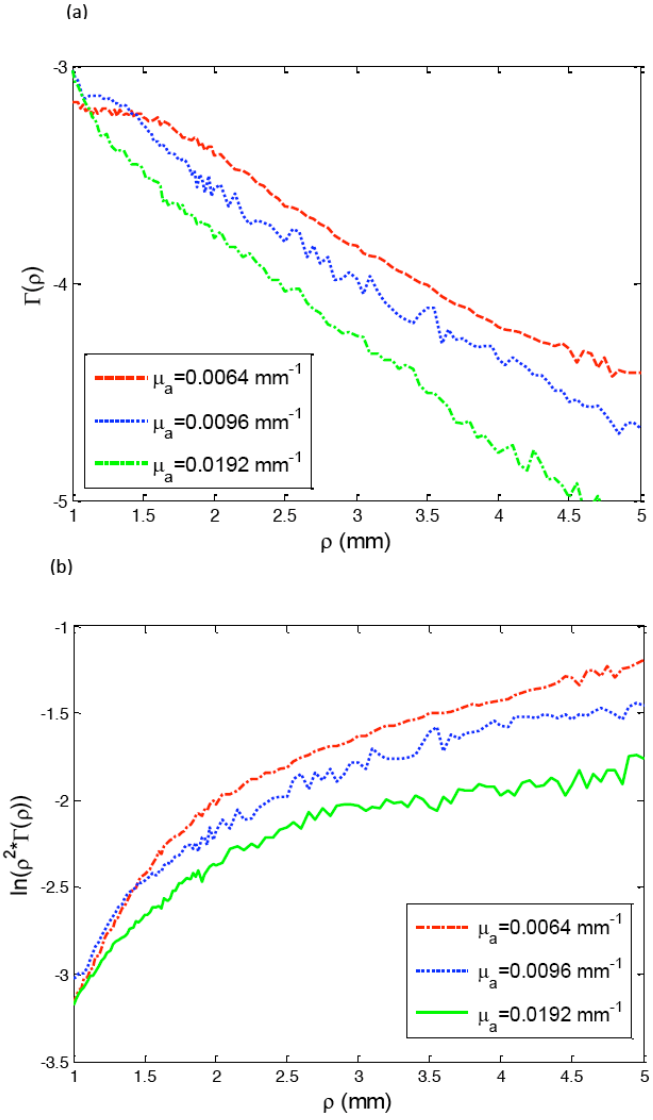


Fig. (4). Reflected light intensity from homogeneous phantoms as a function of the distance ρ. (**a**) The decrease of ln(Γ(ρ)), presenting the decaying character of the different μ reflectance. (**b**) The increasing $\ln(\rho^2\Gamma(\rho))$ profile.

4. DISCUSSION AND SUMMARY

The dependence of reflected light intensity profile on the tissue optical properties was intensively discussed [20, 35, 36]. The above described photon migration model presents a very simple tool for the tissue optical properties deduction, using reflected intensity analyses. The extraction of the phantom optical properties can be used as a proof for the validity of the photon migration model for light path within an irradiated tissue.

In the present study, computer simulations and a non invasive optical technique for reflected light intensity profile measurements from phantoms were presented. The reflectance was analyzed using the photon migration model for light path within the tissue. The simulation results agreed with the theory (Eq. 1). Yet, the experimental results present a partial fitting to the model equations: while Fig. (**4a**) presents a behavior similar to the decay predicted by Eq. (1), Fig. (**4b**) does not agree with the reflectance behavior presented by Eq. 2.

A possible reason could have been the anisotropic correction for the photon migration model [23] that was not considered in this presented research. Yet, the anisotropic version for light path within a tissue suggests that this correction is significant in short distances only (ρ<2 lattice units, while one lattice unit was suggested to be 0.1 mm [20]) while our results present a non-expected behavior in large distances (>2 mm) on the phantom surface as well.

Another possible reason might be the low scattering properties of the phantom (% IL = 0.8) that causes low reflected light intensity. Thus, by the multiplication of Γ(ρ) with ρ^2 one gets the increasing graphs, corresponding with the increasing ρ^2. Higher values of IL concentration should present higher reflected light intensity and the multiplication with ρ^2 will not change the decaying character of Γ(ρ), as presented by Fig. (**4a**). In order to test this suggestion, additional experiments are required.

However, the partial dependence of the experimental reflected light intensity graphs' slopes with the absorption values of the phantom (as presented in Fig. (**4a**)) indicates that reflected light intensity measurements can be used as a diagnostic tool for different tissues and their physiological condition. Fig. (**4b**) suggests that further investigation is required in order to extract a phantom absorption parameter from reflectance light intensity measurements.

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