Time Resolved Photon Fluencies for Different Input Angle Sources

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Time Resolved Photon Fluencies for Different Input Angle Sources

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Abstract. The variation of photon fluence distributions [photon/cm².s] for different input angle laser sources was shown by researchers experimentally ^[1]. According to this philosophy, different input angle source and detector photon entrance from tissue surface into imaging media have different photon fluence distributions for a specific tissue type. In this study, different input angle simulations were used for pulsed laser photons which uses time resolved (TR) Monte Carlo (MC) photon-tissue interaction simulation program to prove the philosophy in TR run mode. TR run mode MC simulation program `trmc.c` ^[2] was modified and used to generate TR photon counts inside the homogenous simulation environment. It has homogeneous tissue optical properties, absorption $\mu_a = 0.1 \text{ cm}^{-1}$, scattering $\mu_s = 100 \text{ cm}^{-1}$, and anisotropy $g = 0.90$ coefficients. Multi-input angle philosophy was first demonstrated by the researchers ^[1]. It was defined and experimentally proven. Photon fluencies which are forward model weight matrix coefficients differences were successfully shown for TR laser as a general procedure. In this study, differences were drawn for seven different input angle sources with pulsed laser photons. The proof-of-concept philosophy was shown successfully. The purpose of the use of pulsed laser is to show the righteousness of the philosophy in TR run mode, since the TR diffuse optical tomography (TRDOT) device would be made as a biomedical optic imaging (BOI) device. Cylindrical radial coordinate system which was defined in `trmc.c` ^[2] in earlier was used, the code was modified, and photon fluencies were generated based on the different input angle laser photons. Cylindrical coordinate system has 1 cm and 36-element radial r , and depth z grids. 100.000 photons were sent from pencil beam tissue surface point. Photons would be thought as group of ultra-narrow band pulsed laser photons. The main purpose of showing photon fluencies for different laser source input angles were succeeded and image reconstruction procedure was also applied. Ten time series were used which are [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] picoseconds (ps). Different input angle photon fluence distribution figures were drawn. These are 0°, 15°, 30°, 45°, 60°, 75°, 90°. Photon fluence differences were also drawn and observed for different input angle laser sources. Forward model problem different input angle laser source and detector transfer functions were also drawn. Finally inclusion was embedded inside the homogenous simulation environment and images were reconstructed for both scenarios and localization error (LE), and concentration error (CE) was calculated for both scenarios and compared with each other.

Keywords: Pulsed Laser Photon Fluencies; Different Input Angle Laser Sources.

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1. INTRODUCTION

Researchers successfully showed multi-input angle laser source and detector photons approach experimentally. They generated simulative photon fluence distributions [photon/cm².s] for diffuse optic imaging (DOI) purpose^[1]. They emitted multi-input angle laser source photons and collected back-reflected detector photons from the tissue surface in the continuous wave (CW) run mode. In this study, a modified time resolved (TR) Monte Carlo (MC) photon-tissue interaction simulation program code `trmc.c`^[2] was used to show the advantage of multi-input angle approach. TR run mode was used to reconstruct the inclusion image for time resolved diffuse optical tomography (TRDOT) model^[3]. The concept gets benefit from emerging electronics technology by using single photon avalanche diode (SPAD) detectors^[4]. Detailed information for solid-state instrumentation were mentioned^[5]. Researchers used SPAD technology for TRDOT devices^[6, 7]. In this study, the TR run mode was used to show the differences of different input angle laser source photon fluencies. TR run mode is the emerging field for diffuse optic tomography (DOT) researchers. TRDOT modality has some advantages over CW run mode since it is possible to distinguish the penetrated photons versus depth in imaging tissue through TR analysis. Thus, researchers have shifted their focus towards TR run mode especially with the help of emerging electronic technology. Vertical cavity surface emitting laser (VCSEL) as source units and SPAD as photo-detector units are being used with the growing demand. TR run mode has become popular by compiling the existing philosophy^[1] with the emerging electronic VCSEL and SPAD technologies in TR run mode. For this purpose, TR run mode Monte Carlo (MC) photon-tissue interaction simulation program code `trmc.c`^[2] was modified and used with different time steps. Different azimuthal (ψ) and deflecting (θ) angles were tested, and finally seven different θ angles 0°, 15°, 30°, 45°, 60°, 75°, 90° were selected to show the photon fluence differences depend on the θ input angle. TR photon fluencies for different input θ angles will be applied while making TRDOT instrument with emerging electronic integrated circuits (IC) in near future. VCSEL laser source and SPAD

photodetector modules were already used successfully [5]. TR mode photon tissue interaction simulation study was also demonstrated in [9]. Based on the work in [9], similar procedure was applied in this study.

2. MATERIALS AND METHODS

2.1. Forward Model Problem

Homogeneous tissue simulation model has optical properties absorption coefficient $\mu_a = 0.1 \text{ cm}^{-1}$, scattering coefficient $\mu_s = 100 \text{ cm}^{-1}$, and anisotropy coefficient $g = 0.90$. Photon fluence transfer functions build forward model in homogenous tissue model. Forward model photon fluence distributions can be obtained by using time domain diffusion equation of radiative transfer equation (RTE) or Monte Carlo (MC) photon transport simulation model.

Figure 1. Photon fluencies for a 0° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

In this work, photon fluencies were generated by the help of time domain MC simulation model which was demonstrated and explain in [2,9]. TR MC simulation program trmc.c ^[2] was successfully modified and used for ten time series which are [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] picoseconds (ps). Seven different pencil beam laser illumination MC simulation codes were run and photon fluence distribution were obtained. Figure 1 is showing, photon fluencies for 0° input angle pulsed laser source for [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps discrete times. Angles are referenced to normal of tissue surface.

Figure 2. Photon fluencies for an 15° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 2 is showing, photon fluencies for 15° input angle pulsed laser source photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. Figure 3 is showing, photon fluencies for 30° input angle pulsed laser source

photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. Figure 4 is showing, photon fluencies for 45° input angle pulsed laser source photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. Figure 5 is showing, photon fluencies for 60° input angle pulsed laser source photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. Figure 6 is showing, photon fluencies for 75° input angle pulsed laser source photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. Figure 7 is showing, photon fluencies for 90° input angle pulsed laser source photons at [4, 8, 12, 16, 22, 26, 30, 38, 46, 52] ps time steps. TR photon fluence differences for different input angle laser source photons were drawn. We used cylindrical radial coordinate system, which was defined in trmc.c code in earlier for MC simulations. The code was modified, and photon fluencies were generated based on the seven different laser source input angle photons. Cylindrical coordinate system has radial r and depth z grid coordinates. Radial r and depth z are 1 cm each. Grid system has 35x35 grid elements.

Figure 3. Photon fluencies for an 30° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 4. Photon fluencies for an 45° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 5. Photon fluencies for an 60° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 6. Photon fluencies for an 75° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 7. Photon fluencies for an 90° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 8. Photon fluence differences for 0° and 15° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 9. Photon fluence differences for 0° and 30° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 10. Photon fluence differences for 0° and 45° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 11. Photon fluence differences for 0° and 60° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 12. Photon fluence differences for 0° and 75° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 13. Photon fluence differences for 0° and 90° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Photon fluence differences for 0°-15°, 0°-30°, 0°-45°, 0°-60°, 0°-75°, 0°-90° input angles at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 ps were shown in Figure 8 – Figure 13. Forward model problem photon fluence distributions can also be generated by using time domain diffusion equation which was demonstrated in Equation 1 [8].

$$(\frac{\partial}{c\partial t} - D\nabla^2 + \mu_a)\Phi = S \quad \text{Equation 1.}$$

$$D = \frac{1}{3(\mu_a + \mu_s')}$$

S is the isotropic light source, D is the diffusion equation, c is the light speed inside the homogenous tissue simulation model.

2.2. Inverse Problem Solution

Based on the Equation 1, forward model photon fluence distributions Φ was generated from pencil beam source position to each voxel position and from each voxel position to each detector position inside the simulation tissue model. D is the diffusion coefficient in homogeneous simulation tissue model. Homogenous simulation model μ_a is the absorption coefficient for 800 nm laser wavelength. In our model, we used gaussian pencil beam laser source. Source and detectors were placed in rectangular form on back reflected tissue surface. Φ is the forward model problem weight functions which comes from Equation 1. In the numeric form of solution, Equation 2 was used. In the Equation 2, b is the total source-detector (SD) match measurements which also include different input angle measurements. ξ is the unknown absorption differences over homogenous simulation tissue model. To obtain the unknown ξ absorption differences over

Figure 14. Sources and detectors are on the back-reflected imaging surface.

homogenous tissue simulation model, basic pseudo inverse method was used which was shown in Equation 3. W is the forward model problem photon fluence transfer functions between source and detector positions which is the same as Φ .

$$b = W \cdot \xi \quad \text{Equation 2.}$$

$$\xi = \text{pinv}(W) \cdot b \quad \text{Equation 3.}$$

W transfer functions are demonstrated in Figure 15, and Figure 16. 0° input angle 1st source - 24th detector forward model transfer functions on 52 ps at xy top view are in Figure 15. 2nd source - 5th detector forward model transfer functions on xz depth view are in Figure 16.

Figure 15. 0° input angle 1st source – 24th detector forward model transfer functions on 52 ps at xy top view.

Figure 16. 2nd source – 5th detector forward model transfer functions on xz depth view.

3. RESULTS

Figure 17. All angles SD matches A. Real inclusion @xz B. Real inclusion @xy C. Reconstructed inclusion @xz D. Reconstructed inclusion @xy.

Figure 18. Only 90° angle SD matches A. Real inclusion @xz B. Real inclusion @xy C. Reconstructed inclusion @xz D. Reconstructed inclusion @xy.

In the inverse problem solution algorithm, two different scenarios were done for comparison. In the first scenario, all input angles pencil beam approach was used. Input angles were 0°, 15°, 30°, 45°, 60°, 75°, 90° for both source and detector positions. Figure 17 is representing all input angles scenario real and reconstructed inclusion images. Figure 18 is representing only 90° input angle scenario real and inclusion images. Both scenarios have image spikes and artifacts for localization comparison. But for localization error comparison all input angles scenario has more precise and high resolution than only 90° input angle scenario. Localization error (LE) calculation was done based on the Equation 4. r is the radial grid size dimension.

$$LE = \frac{\sqrt{(x_{inclusion} - x_{reconst.})^2 + (y_{inclusion} - y_{reconst.})^2 + (z_{inclusion} - z_{reconst.})^2}}{r} \quad \text{Equation 4.}$$

Based on the Equation 4, LE was calculated as %12 for all input angles scenario. On the contrary LE was calculated as %29.2 for only 90° input angle scenario. Contrast error (CE) was calculated based on the Equation 5.

$$CR_{error} = \frac{|\mu_{a,real} - \bar{\mu}_{a,ROI}|}{\mu_{a,real}} \quad \text{Equation 5.}$$

Based on the Equation 5, CE was calculated as %19.2 for all input angles scenario. On the contrary CE was calculated as %35 for only 90° input angle scenario. In CE formula, the average of region of interest (ROI) absorption coefficient $\bar{\mu}_{a,ROI}$ and embedded inclusion absorption coefficient $\mu_{a,real}$ values were used to calculate the error.

4. DISCUSSION

Multi-input angle pulsed laser source photons have different photon fluencies inside the tissue model. Photons would be thought as group of narrow-band pulsed laser photons, which was sent in ultra-short time interval. It was clearly shown that photons, which were initially penetrated from the laser source position with different input angles from pencil beam node, are generating different photon fluencies in homogenous tissue simulation model. In TR run mode, photon fluence difference is generating depth-dependent photon fluence correlation versus time. This relation is useful since it will distinguish depth dependent tissue molecule concentrations for DOT researchers. Different input angle laser source photon fluencies will be used while making TRDOT device in near future with emerging electronic IC technologies.

Competing Interest

The authors declare that they have no competing interests.

Financial competing interests:

- In the past five years the authors have not received reimbursements, fees, funding, or salary from any organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future. The authors work as Associate Prof. Dr.'s at universities that is not financing this manuscript (including the article-processing charge).

The authors have not held any stocks or shares in an organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future.

- The authors do not hold or they are not currently applying for any patents relating to the content of the manuscript. The authors have not received reimbursements, fees, funding, or salary from an organization that holds or has applied for patents relating to the content of the manuscript.
- They do not have any other financial competing interests.

Non-Financial competing interests:

- There are no non-financial competing interests (political, personal, religious, ideological, academic, intellectual, commercial or any other) to declare in relation to this manuscript.

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Figure Caption List

Figure 1. Photon fluencies for a 0° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

Figure 2. Photon fluencies for an 15° laser source input angle at 4, 8, 12, 16, 22, 26, 30, 38, 46, 52 picoseconds (ps).

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Figures

Figure 1

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