35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Study on Method to Simulate Light Propagation on Tissue with Characteristics of Radial-beam LED based on Monte-carlo Method*

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Abstract—**In biomedical, Monte-carlo simulation is commonly used for simulation of light diffusion in tissue. But, most of previous studies did not consider a radial beam LED as light source. Therefore, we considered characteristics of a radial beam LED and applied them on MC simulation as light source. In this paper, we consider 3 characteristics of radial beam LED. The first is an initial launch area of photons. The second is an incident angle of a photon at an initial photon launching area. The third is the refraction effect according to contact area between LED and a turbid medium.**

For the verification of the MC simulation, we compared simulation and experimental results. The average of the correlation coefficient between simulation and experimental results is 0.9954. Through this study, we show an effective method to simulate light diffusion on tissue with characteristics for radial beam LED based on MC simulation.

I. INTRODUCTION

At 600-1300nm wavelength (called “Optical window”), light is absorbed a little and penetrates well with dominant scattering on blood and water. Consequently, light diffusion on tissue is different depending on optical properties of each tissue. Using the difference of diffuse light propagation on a tissue, we can estimate tissue thickness on a multi-layered tissue such as skin layers [1].

To estimate the diffuse light on tissue, it is necessary to know the optical properties of light source, tissue, and find the distribution of light on tissue. There are several methods to show the distribution of light on tissue that are commonly performed: Radiative Transport Equation (RTE), Kubelka-Munk model, Multi-flux model, Adding-Double method, Diffusion Approximation (DA) and Monte-carlo (MC) simulation. Among these kinds of methods, DA and MC are widely used to simulate light diffusion. However, DA is not valid on a narrow region around a light source. However, MC simulation does not rely on the narrowness of simulation area. For this reason, it is being widely used in biomedical optics.

MC simulation is a statistical model introduced in order to find physical phenomena including biological tissues. It consists of several steps by the spread of a biological tissue using optical computer simulations [2]: Launching, Moving and Termination of Light Photons. But, in previous papers about light diffusion based on MC method, only a laser beam had been used as light sources on tissue. Also, there had been many researches about MC simulation for application in biomedical optics field using a laser beam as light source [3], [4], but not for a radial beam LED source.

A. *Objective*

Most of previous MC simulation has been performed commonly with a laser beam source. There are rarely simulation methods considering characteristics of a radial LED. Moreover, existing MC simulation without considerations of a radial beam LED source is used to validate an application of optical methods using it [5]. Therefore, in this paper, the objective is to propose a novel method to make MC simulation considering characteristics of a radial beam LED source, as well as verification to the proposed MC simulation with an experiment using radial beam LED as light source. The characteristics considered of a radial beam are as below:

- *It is not possible to assume LED as a point light source. (Initial launch area)*
- *A radial beam LED has very wide radiation angles of light at an initial launching area. (Radiation angle)*
- *Due to the round-shape of the head, it does not entirely contact with tissue. (Refraction according to contacted area)*

II. METHOD

MC simulation in this paper is based on the method proposed by S. A. Prahl, *et al.* [6]. The flowchart of their MC method for light propagation can be seen in Fig. 1. The details of MC method of light propagation in tissue has been described elsewhere [6], [7], [8], thus, we will explain only about photon initializing for application with radial beam LED characteristics, because only the launch of photons is different with general ones.

A. *Initial launch area*

A LED is not a point source, but a very small array of them. Therefore, a LED source has to be assumed as a set of point sources. To apply it on the simulation, we get and select launch points, x_0 and y_0 with a uniform probability distribution with radius of the LED, r. Its probability density function is as follow:

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*This work was supported in part by the Global COE (Center of Excellence) Program “Global Robot Academia,” the "High-Tech Research Center" Project for Private Universities, with matching fund subsidy from MEXT (the Ministry of Education, Culture, Sports, Science and Technology of Japan), and Grant-in-Aid for Young Scientists (B) (25750190).

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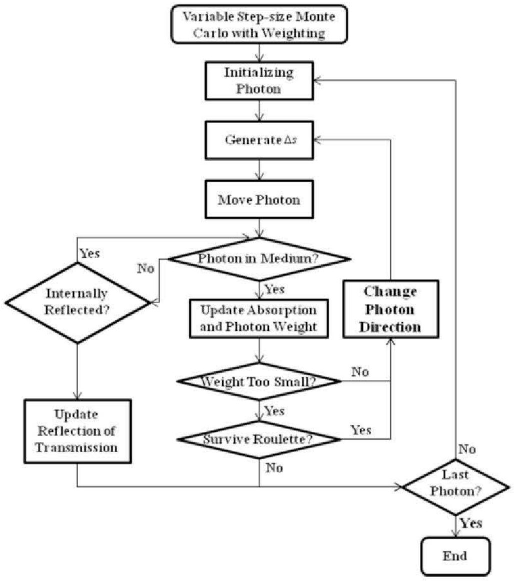


Figure 1. Flowchart of Monte-carlo simulation by S. A. Prahl. *et al.*

$$f_n(x_0, y_0) = \begin{cases} \frac{1}{\pi r^2} & for\, r \geq \sqrt{{x_0}^2 + {y_0}^2} \\ 0 & for\, r \leq \sqrt{{x_0}^2 + {y_0}^2} \end{cases} \quad (1)$$

In this equation, x_0 and y_0 are the launch position of n-photon. We set the center of LED as (0, 0, 0) and the coordinates axis as shown in Fig. 2. The schematic of candidate area of a LED source as the gray area is also shown in the same figure. That is, photons are selected uniformly in the area of LED of Fig. 2.

B. *Incident angle*

The radiation angle of a radial beam LED source is very wide. To get a meaningful simulation with an LED source, the radiation angle of launch point has to be considered. This parameter is obtained from the LED specification. The radiation angle of the LED used in our experiment is as Fig. 3(a). It can be approximated assuming a Gaussian probability distribution as Fig. 3(b).

Using the Gaussian probability distribution, a random number generator is configured with the mean and the standard deviation of the radiation angle. Because the intensity of light is the number of photons per time on quantum mechanics, the intensity on radiation angle is assumed as the probability of the radiated photon.

The Gaussian random number generator generates angles for the incident angle of n-photons with a given stochastic frequency. The angles from the number generator are used as the elevation angle, θ at the spherical coordinates $(1, \theta, \phi)$. In case of the azimuth angle ϕ, because it is not related with the incident angle, we generate the azimuth angle by a uniform random generator. The probability density functions for generation of the elevation (2) and the azimuth angle (3) are respectively:

$$f_\theta(\theta) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{\theta-\mu}{\sigma})} \quad for -90 < \theta < 90 \quad (2)$$

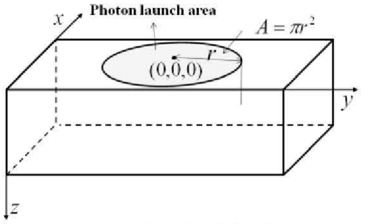
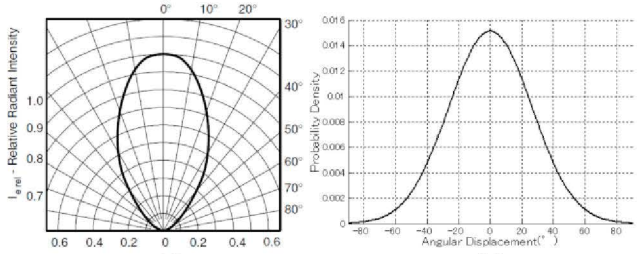


Figure 2. Schematic of an initial launch area



(a) (b)

Figure 3. Radiant intensities of LED on the radiation angle, (a) relative radiant intensity on angular displacement (TSAL 7600, Vishay®, PA), (b) approximated Gaussian distribution (mean = 0, std = 26.3644)

$$f_\phi(\phi) = \frac{1}{\pi r^2} \quad for -180 \leq \phi \leq 180 \quad (3)$$

When θ_x and θ_y are projected angles in xz-and yz-plane respectively at the Cartesian coordinates, $\cos\theta_x$ and $\cos\theta_y$ are calculated as follow:

$$\begin{aligned} \cos\theta_x &= \frac{x}{\sqrt{x^2+z^2}} = \frac{\sin\theta\cos\phi}{\sqrt{\sin^2\theta\cos^2\phi + \cos^2\theta}} \\ \cos\theta_y &= \frac{y}{\sqrt{y^2+z^2}} = \frac{\sin\theta\sin\phi}{\sqrt{\sin^2\theta\sin^2\phi + \cos^2\theta}} \end{aligned} \quad (4)$$

Eventually, it calculates a new position, (x_1, y_1, z_1) using the incident direction (μ_x, μ_y, μ_z).

$$\begin{aligned} x_1 &= x_0 + \mu_x \Delta s_x, & \mu_x &= \sqrt{1-\cos\theta_x{}^2} \\ y_1 &= y_0 + \mu_y \Delta s_y, & \mu_y &= \sqrt{1-\cos\theta_y{}^2} \\ z_1 &= z_0 + \mu_z \Delta s_z, & \mu_z &= \cos\theta \end{aligned} \quad (5)$$

Here, the first step size $(\Delta s_x, \Delta s_y, \Delta s_z)$ is calculated with the absorption coefficient, μ_a and reduced scattering coefficient $\mu_s{}'$, based on similarity relation theory as follows:

$$\Delta s_x = \frac{\cos\phi}{\mu_a + \mu_s{}'} \quad \Delta s_y = \frac{\sin\phi}{\mu_a + \mu_s{}'} \quad \Delta s_z = \frac{1}{\mu_a + \mu_s{}'} \quad (6)$$

C. *Refraction according to contact area*

When light photons are radiated in a turbid medium by a radial beam LED, there is a non-contact area between LED and turbid medium caused by the round-shape head of the LED. This is the reason for a difference of refractive effects according the photon launch position of the source. The contact area and non-contact area are shown in Fig. 4(a). This is distinctive characteristics of a radial beam LED source compared to a laser beam source.

To simplify the calculation, it is approximated as per Fig. 4(b). When the photons are radiated from the non-contacted area, they pass to the turbid medium (tissue) from the ambient medium (air). This means that refractive effects between the turbid and the ambient medium have to be considered in case of the non-contact area. A schematic of the refraction effects depending on the contact state is shown in Fig. 5. In case 1 in Fig. 5, because LED source contacts with the turbid medium, the effects of refraction are not considered. On the contrary, the case 2 suffers the effects of refraction between the ambient medium and the turbid medium. In this case, the incident direction (μ_x, μ_y, μ_z) by refraction angle α can be expressed as:

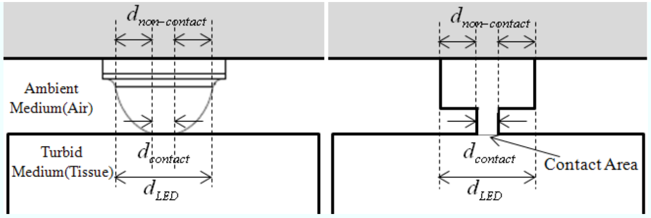
$$\begin{aligned} \mu_x &= \sin\alpha_x = \frac{n_0}{n}\sin\theta_x \\ \mu_y &= \sin\alpha_y = \frac{n_0}{n}\sin\theta_y \qquad (7) \\ \mu_z &= \cos\alpha = \frac{n_0}{n}\cos\theta \end{aligned}$$

Also, in case of the non-contact case, the photon energy is attenuated due to specular reflectance. To quantify it, we use Fresnel’s equation for the effects of the specular reflection. Using the specular reflectance R_{sp} by the Fresnel’s equation, attenuation is calculated as (7). Consequently, the weight is 1 in case 1, because there is no refraction. In the case 2, the weight is attenuated as below:

$$\begin{aligned} &\textit{case 1}: \qquad w = 1 \\ &\textit{case 2}: \qquad w = 1 - R_{sp} \qquad (8) \\ &\text{Where,} \quad R_{sp} = \frac{(n_0 - n_1)^2}{(n_0 + n_1)^2} \qquad n_0, n_1: \textit{Refractive indices (Air and Tissue)} \end{aligned}$$

III. EXPERIMENTS

To verify the MC simulation considering the characteristics of a radial beam LED, we measured light intensity on phantom and compared it with simulation result.



(a) (b)

Figure 4. Contacted area between LED and tissue, (a) appearance of LED contacted on tissue, (b) simple model for LED contacted on tissue

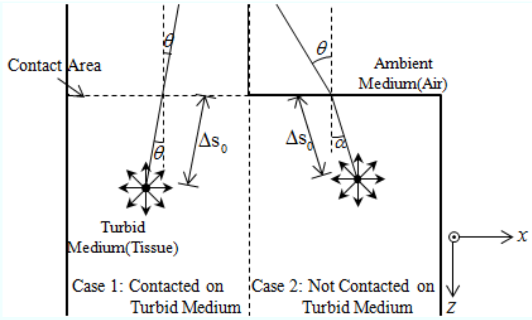


Figure 5. Cases of refraction effects according contact statues

A. *Preparation for experiment*

LED & Photodiode: To measure light intensity, we used the radial beam LED (TSAL 7600, Vishay®, PA) and the photodiode (TPS703, Toshiba, Japan). Their specifications can be seen in Table 1 and Table 2 respectively.

Table 1. LED specification

Type	Head type	Dimensions	Dominant Wavelength
GaAlAs/GaAs	Round plastic	Ø 5mm	940nm

Table 2. Photodiode specification

Type	Dominant Wavelength	Viewing Angle (half-value)
Silicon PIN	960nm	±65 °

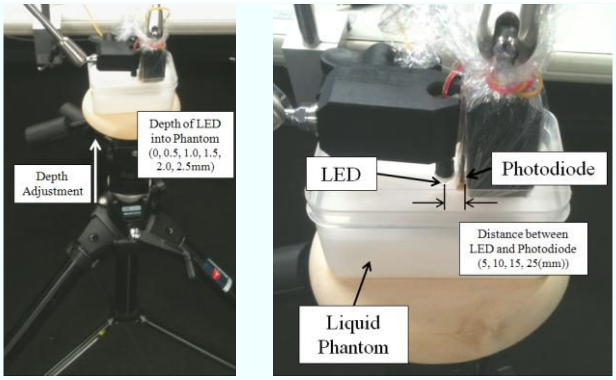
Liquid Phantom: To make a liquid phantom having an optical property similar to subcutaneous fat. We used Intralipid 10% (Lipision, JW Pharm., Korea) as a scattering material and india ink (Rotring, Germany) as an absorption material. For the experiment, the liquid phantom is has the following optical properties at 940nm as seen in Table 3. The preparation of the liquid phantoms is based on the recipe given in [8], [9].

Table 3. An optical property of liquid phantom at 940nm for simulation

Refractive Index n	Absorption Coefficient μ_a (cm^{-1})	Reduced Scattering Coefficient μ_s' (cm^{-1})
1.4	0.1	10

B. *Experiments*

To verify the proposed MC simulation, we performed an experiment with liquid phantom. The intensity of light diffused (emitted from a radial LED) in the phantom is measured by the photodiode. To adjust the depth that the LED is inserted into the phantom, we hold the phantom on tripod as seen in Fig. 6. With this setup, we can examine the refraction effect according the contact area. The depth of the LED into the phantom is from 0 to 2.5 mm at 0.5mm interval. The distance between LED and photodiode is set to 0 to 25 mm at 5 mm interval.



(a) (b)

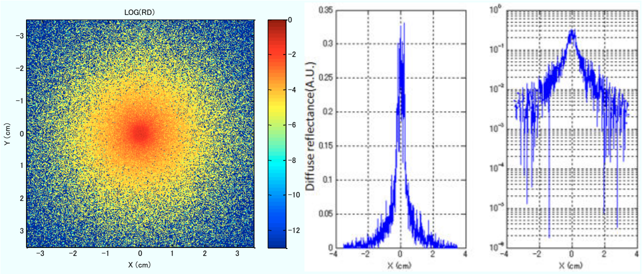
Figure 6. Experimental setup, (a) depth of LED into phantom, (b) distance between LED and Photodiode

IV. RESULT AND ANALYSIS

For simulation, the number of photons is set to 1,310,720 and the optical properties are the same as in Table 3. Simulation data can be seen in Fig. 7. Here, simulation data is in a log scale, because measured data from photodiode are also log scale value, due to the photodiode characteristics.

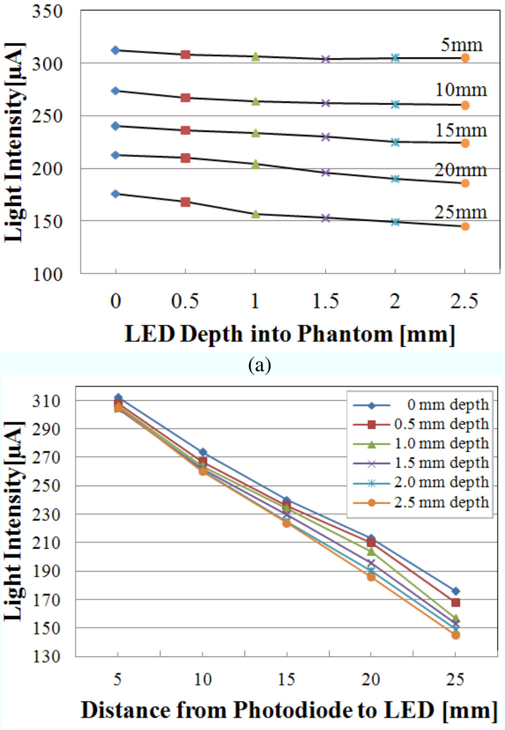
The measured data are as Fig. 8. To compare both data, the measured data are divided by the intensity value at 5 mm. It is use a difference of value without uniqueness of LED and photodiode. To make them to the same scale, we normalized both data at distances of 10 to 25 mm. And then, both results are calculated the second regression.

After pre-processing each data, we calculated the correlation coefficient between depth of LED in the phantom and simulation data as Fig. 9. The mean of the correlation coefficient between obtained is 0.9954.



(a) (b) (c)

Figure 7. Results of the Monte-carlo simulation with a radial beam LED (depth on phantom: 0.20 mm), (a) diffusion reflection (xy-plane), (b) cross-section of x-axis, (c) cross-section of x-axis (log scale)



(a)

(b)

Figure 8. Measured data, (a) light intensity according LED depth on phantom, (b) light intensity according distance between LED and photodiode

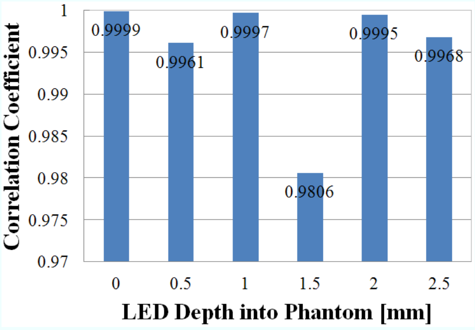


Figure 9. Correlation coefficients between simulation and measured data

V. CONCLUSION

In this paper, we suggest a novel method to simulate diffuse light from a radial beam LED source based on MC simulation. For this simulation, 3 characteristics of a radial beam LED are considered and applied in MC simulation.

In addition, we verified the validity of the simulation compared with experimental data, MC simulation considering a radial beam LED source is confirmed by the experimental results. Therefore it is suitable to estimate diffuse photon propagation.

REFERENCES

[1] L.Wang, S.L. Jacques, and L. Zheng, “Mcml - Monte-carlo modeling of light transport in multi-layered tissues,” *Computer Methods and Programs in Biomedicine*, pp. 131–146, 1995.

[2] S.J. Wallner, N. Luschnigg, W.J. Schnedl, T. Lahousen, K. Crailsheim, R. Moller, E. Tafeit, and R. Horejsi, “Body fat distribution of overweight females with a history of weight cycling,” *International J. Obesity,* vol. 28, pp.1143, 2004.

[3] C.R. Simpsonyz, M. Kohlyx, M. Essenpreisk, and M. Copey, “Near-infrared optical properties of ex vivo human skin and subcutaneous tissues measured using the Monte-carlo inversion technique,” *Phys. Med. Biol.*,vol. 43, pp. 2465–2478, 1998.

[4] Tiziano Binzoni, Terence S. Leung, and Dimitri Van De Ville, “The photo-electric current in laser-Doppler flowmetry by Monte-carlo simulations,” *Phys. Med. Biol.*, vol. 54, 2009.

[5] I.D. Hwang, K.S. Shin, D.S. Ho, and B.M. Kim, “Evaluation of Chip LED Sensor Module for Fat Thickness Measurement using Tissue Phantoms,” *Proceedings of the 28th IEEE EMBS*, pp.5993-5996, 2006.

[6] Prahl, S.A., M. Keijzer, S.L. Jacques, and A.J. Welch, “A Monte- carlo Model of Light Propagation in Tissue,” *Dosimetry of Laser Radiation in Medicine and Biology*, SPIE Institute Series, IS 5, pp. 102-111, 1989.

[7] B.C. Wilson and G. Adam, “A Monte-carlo model for the absorption and flux distribution of light in tissues,” *Med. Phys.*, vol. 10, pp. 824-830, 1983.

[8] Stephen T. Flock, Steven L. Jacques, Brian C. Wilson, Willem M. Star, and Martin J.C. van Gemert, “Optical Properties of Intralipid: A Phantom Medium for Light Propagation Studies,” *Lasers in Surgery and Medicine*, 12516519, 1992.

[9] H.G. van Staveren, C.J.M. Moes, J. van Marle, S.A. Prahl, and M.J.C. van Gemert, “Light scattering in Intralipid-10% in the wavelength range of 400-1100 nanometers,” *Applied Optics*, vol. 30, pp. 4507-4514, 1991.

[10] S.H. Song, Y. Kobayashi, and M.G. Fujie, “Monte-carlo Simulation of Light Propagation considering Characteristic of Near-infrared LED and Evaluation on Tissue Phantom,” *1^{st} CIRP Conference on Biomanufacturing*, Volume 5, pp. 25−30, 2013.

[11] S.H. Song, Y. Kobayashi, and M.G. Fujie, “Detection of Dermis and Fascia on Skin Layers for Liposuction Surgery Robot using Texture and Geometric Information,” *12th International Conference on Control, Automation and Systems*, pp. 1546-1551, 2012.