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A modified condensed Monte Carlo simulation of reflectance with focus light beam from scattering medium

Lin Lin [a], Mei Zhang [b,*], Shaoxin Li [a]

[a] School of Information Engineering, Guangdong Medical University, Dongguan 523808, China
[b] College of Electronic Engineering, Dongguan University of Technology, Dongguan 523808, China

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ABSTRACT

Condensed Monte Carlo (MC) methods were modified to predict the spatially-resolved reflectance from turbid medium with arbitrary scattering and absorption coefficients. The calculation was accelerated by direct scaling the radial reflectance of baseline simulation, which is more efficient than the photon-by-photon scaling method. We have demonstrated that the methods are valid for focus incident light as well as homogeneous single-layer turbid media. This approach was validated against a standard MC model with very low cost of time to the level of tens of microseconds.

1. Introduction

Prediction of propagation of light beam in a turbid medium is a challenge tusk which cannot be solved by conventional and deterministic mathematical methods [1–3]. To solve the problems of light migration in turbid media, stochastic methods are preferred for their accuracy and universality such as Monte Carlo (MC) method which is widely applied in biomedical or tissue optics [4–6]. The results of MC simulation can be used as the gold standard for evaluation of other numerical or analytical models [7–9]. It has become a popular tool for simulating light transport in tissues, such as skin, because it can give reliable results for arbitrary structure and optical properties. Inverse Monte Carlo methods have also been successfully applied to reconstructing optical properties of samples [10–12]. However, high time cost is the main obstacle to application in real-time measurement and reconstruction of optical parameters. Some methods for accelerating MC calculations have been developed, such as scaling methods (sMC) [13,14], importance sampling methods [15], perturbation methods [4], and parallel computation [16,17]. The scaling methods utilize the results of a single standard MC simulation, in which the information of backscattered photons are recorded as baseline data. Then the temporal and spatial diffuse reflectance or transmittance for a wide range of optical properties can be calculated by utilizing the information of baseline data. Generally, the scaling Monte Carlo is accurate and suitable for medium of layered tissue and optical system with arbitrary parameters. However, it is still time consuming for scaling method when applied to photon-by-photon calculation.

In this paper, we modify the scale Monte Carlo methods for non-contact setups with various lenses for illumination and detection. It means that the light beam is more likely to have a Gaussian distribution on arbitrary transversal surfaces. The alternation of light shape and location of focal plane will affect the property of reflectance directly. The scale Monte Carlo (MC) methods were modified to predict the spatially-resolved reflectance from turbid medium with arbitrary scattering and absorption coefficients. This approach was proved a faster way to predict reflectance for real time calculation.

2. Theory

2.1. Monte Carlo base line simulation

The program of Monte Carlo baseline simulation was modified from MCML code developed by Wang et al. [18]. The photon is assumed to be launched from Gaussian light beam with initial status determined by hyperboloid method [19]. The optical axis and the surface of sample are perpendicular to each other. The focus depth d varies from 0 to f, where f is focus length of incident light. Reflectance of light at the interface between medium and air will obey the Fresnel law. The model of the sample is half infinite and homogeneous with scattering coefficient μ_{s0} and zero absorption for white simulation [20].

* Corresponding author. Tel.: +86 0769 22861102.
E-mail address: zhangmei@dgut.edu.cn (M. Zhang).

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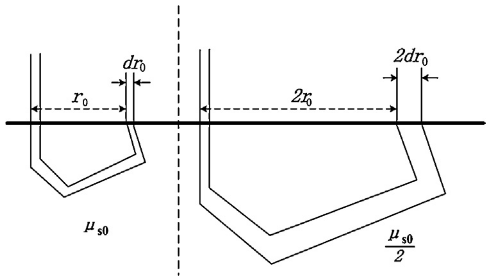

Fig. 1. Principle of the scaling method as applied in a homogeneous medium.

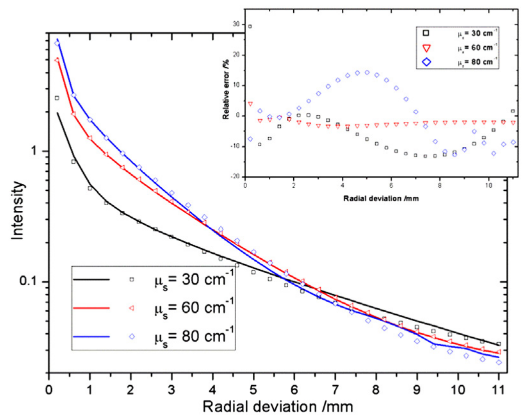

Fig. 2. Reflectance as a function of the radial deviation.

Each step size that a photon will take in the medium is calculated based on the probability density function of free path to yield $s_i = -\ln(1-\xi)/\mu_{t0}$ where $\mu_{t0} = \mu_{s0}$ is attenuation coefficient with absence of absorption and ξ is random number from 0 to 1. The tracing process should be terminated when the optical path length reaches 10 cm corresponding to time delay of 250 ps. The Henyey–Greenstein (HG) phase function is used Monte Carlo simulations of light transport in tissue. The status of each photon that exits from sample surface, such as the weight W_i, the number of collisions N_i, the radial deviation from optical axis on surface of sample r and total path length l, will be recorded as baseline data.

2.2. Calculation of reflectance from baseline data

The baseline data is stored as a $N \times 7$ matrix where N denotes the number of photons reflected from the medium. There are five long double data which record the status of a photon including weight, number of scattering events, path length, incident and exit coordinates (x and y). The reflectance is derived from base data as a function of radial deviation or time delay. The intensity of reflected light at distance r_0 is presented by

$$I_0(r_0) = \frac{N(r_0)w_0}{2\pi r_0 \Delta r_0} \tag{1}$$

where w_0 is weight of photon. With absence of absorption all photons exiting from the medium have the same weight. The denominator in the equation denotes square of the ring at radius r_0 with width Δr_0. The intensity will be fit by polynomial function to reduce error generated by Monte Carlo simulation as shown below.

$$y = a_0 + a_1 e^{-x/a_2} + a_3 e^{-x/a_4} + a_5 e^{-x/a_6} \tag{2}$$

2.3. Fast calculation by scaling method

As shown in Fig. 1, the radial deviation is inversely proportional to scattering coefficient as well as the correspond square of ring.

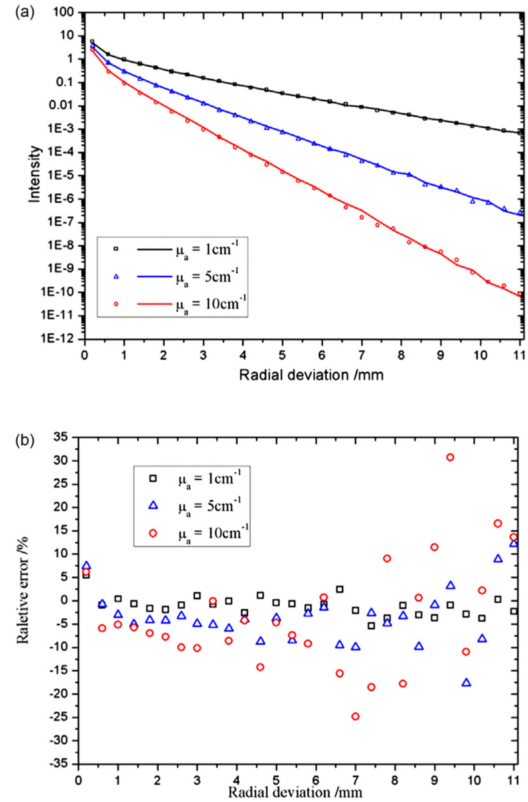

Fig. 3. Reflectance as a function of the radial deviation.

Assume the scattering coefficient is denoted by μ_s and μ_a is also zero. Then the radial deviation from original point of a photon in a homogeneous medium is μ_{s0}/μ_s times as long as that in baseline medium. The surface of medium is divided into rings with width Δr_0 for baseline medium and $\Delta r = \Delta r_0 \times \mu_{s0}/\mu_s$ for medium with different scattering coefficient. So according to Eq. (2), the intensity $I(r)$ is calculated by

$$I(r) = \frac{\mu_s^2}{\mu_{s0}^2} I_0\left(r \cdot \frac{\mu_s}{\mu_{s0}}\right) \tag{3}$$

It means that the radial reflectance can be obtained by directly scaling from the reflectance distribution of baseline medium as shown in Fig. 1. It is assumed that the new μ_s is half of μ_{s0}. The path of the photon in the new medium will be doubled as well as the radial deviation of the exit point. For the absorption of medium has nothing to do with the trajectory of the photons, the change of reflectance will be determined according to Lambert–Beer law with consideration of absorption coefficient. The degreasing of weight of a photon depends on the total path length which has been stored in the base data.

3. Results

A total of 2×10^7 photons were launched on the sample to obtain baseline data stored in a TXT file. A single Monte Carlo simulation took about 1 h in a Dell workstation with a 2.6 GHz Xeon E5-1603 CPU and 4GByte RAM. About 1×10^7 photons will be detected in this manner and a total memory of 3 GB was needed for the storage of the trajectory data. It took about 3000 s to do a standard Monte Carlo simulation but 30 ms was enough for fast scaling method. The photon-by-photon scaling calculation will take about 600 s which is 2×10^4 times as the fast way.