

Influence of high-order optical parameters of tissue on spatially resolved reflectance in the region close to the source

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Influences of the scattering phase functions on spatially resolved diffuse reflectance from a homogenous semi-infinite medium close to source are studied with Monte Carlo simulation. It is shown that the influences of optical parameters higher than the second order on the diffuse reflectance are quite weak in the region from 0.3 to several transport mean free pathes when Henyey-Greenstein phase function or a combined phase function of two parameters are used. But this influence may be substantial if the double Henyey-Greenstein function is used to describe the scattering property of tissue.

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Steady-state spatially resolved diffuse reflectance has been studied experimentally and theoretically for many years^[1-4]. In particular, it has been shown that measurement of the spatially resolved reflectance allows for determination of the optical properties of biological tissue *in vivo*^[2,4,5]. In this technique a narrow light beam is directly projected onto a tissue, and the diffusely reflected light is collected by a rank of fiber-optical detectors in contact with the tissue surface at several distances ρ from the point of incidence. This propagation of light in tissue can be described by the transport theory, where the optical properties of the tissue are described by three quantities: the absorption coefficient μ_a , the scattering coefficient μ_s , and the phase function $p(\theta)$. It has been shown that the diffuse reflectance $R(\rho)$ is only dependent on μ_a and μ'_s if the source-detector distance $\rho \gg l_t$, where $\mu'_s = \mu_s(1-g)$ is called the reduced scattering coefficient, $g = g_1$ is the first-order Legendre moment of the phase function $p(\theta)$, $l_t \equiv 1/(\mu_a + \mu'_s) \approx 1/\mu'_s$ is called the transport mean free path^[6,7]. For typical values of biological tissue, $\mu_a = 0.01 \text{ mm}^{-1}$, $\mu'_s = 1 \text{ mm}^{-1}$, $l_t \approx 1 \text{ mm}$, ρ is usually larger than several l_t . However the research on diffuse reflectance close to source is necessary for many practical applications^[8], and has been paid great attention to recently^[5,7,9-12]. In this region close to source, the often used solution of the diffusion equation cannot be applied for estimating optical properties from the reflectance data^[5,11]. The diffuse reflectance by Monte Carlo simulation $R_{MC}(\rho)$ is close to $R_{DA}(\rho)$ obtained from the diffusion approximation (DA) if the Henyey-Greenstein phase function is applied in the simulations, but the deviation from $R_{DA}(\rho)$ may be substantial if a combined phase function is used^[1,12,13]. Bevilacqua *et al.*^[12] introduced a second-order parameter $\gamma = (1-g_2)/(1-g_1)$ and showed that $R(\rho)$ can be approximately described by μ_a , μ'_s , and γ . Kienle *et al.*^[11] studied the influence of the phase function on the reconstruction of optical parameters, and showed that errors in the derived reduced scattering and absorption coefficients are as great as 100% if a standard solution of

the diffusion equation is used in the analysis, and points out that an additional parameter γ should be considered if Monte Carlo simulation is used as the inversion algorithm.

In this paper, influences of phase functions on the diffuse reflectance in the region close to source are studied with Monte Carlo simulations. For the convenience of comparison, we keep the parameters $\mu_a = 0.01 \text{ mm}^{-1}$, $\mu'_s = 1 \text{ mm}^{-1}$, $l_t \approx 1 \text{ mm}$, and the refractive index $n = 1.4$. In the following Monte Carlo simulations, Henyey-Greenstein phase function $p_{HG}(\theta)$ and three combined phase functions $p_{Fried-Jacq}(\theta)$, $p_{Tissue}(\theta)$, and $p_{Zee}(\theta)$ are used^[11,12,14]

$$p_{HG}(\theta, g_{HG}) = \frac{1}{2} \frac{1 - g_{HG}^2}{(1 + g_{HG}^2 - 2g_{HG} \cos \theta)^{\frac{3}{2}}}, \quad (1)$$

$$p_{Fried-Jacq}(\theta, g_{HG}, \alpha) = \alpha p_{HG}(\theta, g_{HG}) + (1 - \alpha)/2, \quad (2)$$

$$p_{Tissue}(\theta, g_{HG}, \alpha) = \alpha p_{HG}(\theta, g_{HG}) + (1 - \alpha) \frac{3}{8} (1 + \cos^2 \theta), \quad (3)$$

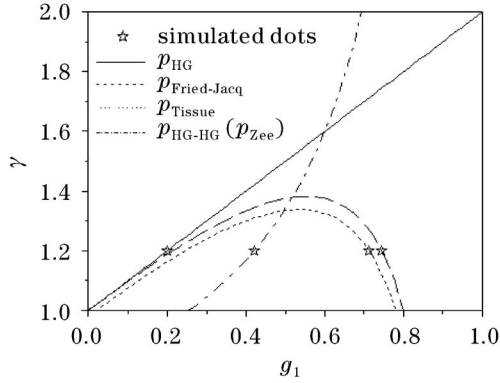
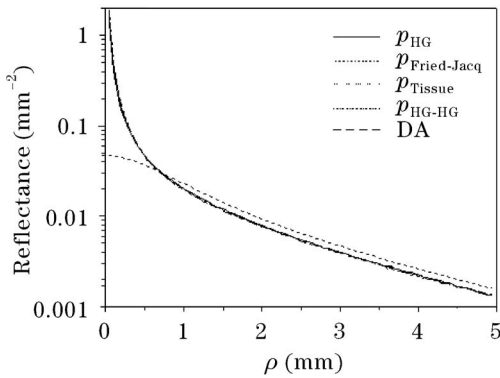
$$p_{Zee}(\theta, g_{HG1}, g_{HG2}, \alpha) = \alpha p_{HG}(\theta, g_{HG1}) + (1 - \alpha) p_{HG}(\theta, g_{HG2}), \quad (4)$$

the weighting factor α ($\alpha \in [0, 1]$) guarantees the normalization of the combined phase functions and the distribution proportion between two types of scattering events.

Several lower order Legendre moments of these phase functions are listed in Table 1, where $\{g_1, g_2, g_3, \dots, g_N\}$ are the parameterized expressions of phase functions. These phase functions are divided into three classes according to the numbers of the containing parameters, the difference can be characterized by the curves in which γ changes with g_1 , as shown in Fig. 1. Now we consider four media which have the same first-order optical parameters ($\mu_a = 0.01 \text{ mm}^{-1}$, $\mu'_s = 1 \text{ mm}^{-1}$) and second-order para-

Table 1. Expressions of Parameterized Phase Functions and Second-Order Parameter γ

	$g_1 = g$	g_2	g_3	$\gamma = (1 - g_2)/(1 - g_1)$
p_{HG}	g_{HG}	g_{HG}^2	$g_{\text{HG}}^3 = g_1^3$	$1 + g_1$
$p_{\text{Fried-Jacq}}$	αg_{HG}	$\alpha g_{\text{HG}}^2 = g_1^2/\alpha$	$\alpha g_{\text{HG}}^3 = g_1^3/\alpha^2$	$(1 - g_1^2/\alpha)/(1 - g_1)$
p_{Tissue}	αg_{HG}	$\alpha g_{\text{HG}}^2 + 0.1(1 - \alpha)$	$\alpha g_{\text{HG}}^3 = g_1^3/\alpha^2$	$(0.9 + 0.1\alpha - g_1^2/\alpha)/(1 - g_1)$
p_{Zee}	$\alpha g_{\text{HG}1} + (1 - \alpha)g_{\text{HG}2}$	$\alpha g_{\text{HG}1}^2 + (1 - \alpha)g_{\text{HG}2}^2$	$\alpha g_{\text{HG}1}^3 + (1 - \alpha)g_{\text{HG}2}^3$	$(1 - \alpha g_{\text{HG}1}^2 - (1 - \alpha)\alpha g_{\text{HG}2}^2)/(1 - g_1)$

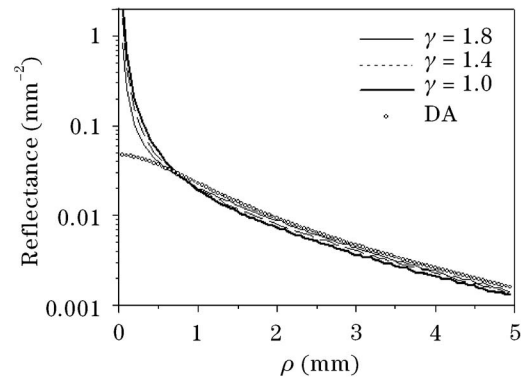
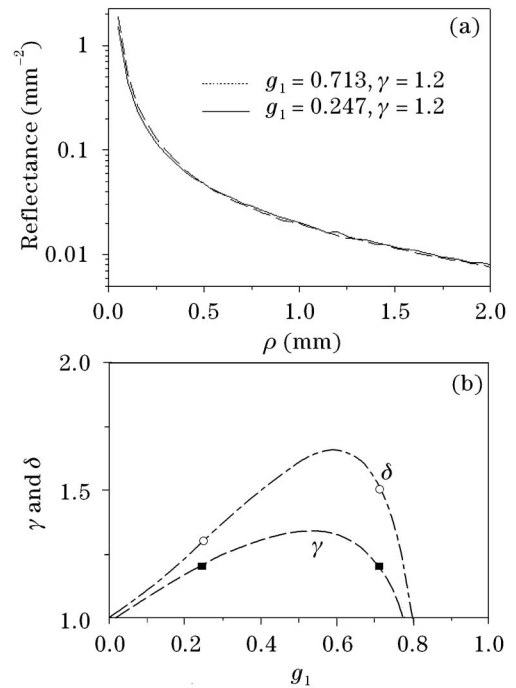
Fig. 1. Relationships between γ and g_1 for the three classes of the phase functions.Fig. 2. Spatially resolved diffuse reflectance from semi-infinite homogeneous media with several phase functions. g_1 and γ are shown in Fig. 1 with asterisks, the other optical parameters are $\mu'_s = 1.0 \text{ mm}^{-1}$, $\mu_a = 0.01 \text{ mm}^{-1}$. $l_t \approx 1 \text{ mm}$.

meter γ ($\gamma = 1.2$), as denoted by asterisks in Fig. 1. But these media are different because different g_1 will result in different higher-order parameters (as shown in Table 1). The reflectance curves from above media with Monte Carlo simulations are shown in Fig. 2, the curve DA is the solution of steady-state diffusion equation for a homogenous infinite medium when the extrapolated-boundary condition is used^[1]. Figure 2 shows that the influence of the phase functions on the reflectance is weaker at the distance $\rho > 0.4l_t$, and a small deviation from $R_{\text{DA}}(\rho)$ in the region close to source from $1.0l_t$ to several l_t .

In order to confirm that $R(\rho)$ is dependent on γ in the region close to source from $0.3l_t$ to several l_t , we simulated the diffuse reflectance with different γ , $\gamma = 1.8, 1.4, 1.0$, respectively. The results of Monte Carlo simulations with $p_{\text{Tissue}}(\theta)$ are shown in Fig. 3, where three curves have the same values at $\rho \approx 1.0l_t$, larger difference for $\rho < 1.0l_t$, and smaller difference for $\rho > 1.0l_t$. It is apparent that there are small devi-

ations from $R_{\text{DA}}(\rho)$ in the region of $\rho > 1.0l_t$, and the deviation decreases with increasing γ . The same results with $p_{\text{HG}}(\theta)$ and $p_{\text{Fried-Jacq}}(\theta)$ can be obtained, and the effects of different phase functions become important only in the region of $\rho < 0.3l_t$.

In order to confirm that $R(\rho)$ is only dependent on γ but not parameters of higher order than γ in the region

Fig. 3. Spatially resolved diffuse reflectance is confirmed to be dependent on γ in the region of several transport mean free paths when Henyey-Greenstein phase function or a combined phase function of two parameters is used.Fig. 4. (a) Influences of parameters higher than the second order on the diffuse reflectance are confirmed to be quite weak in the region of several transport mean free paths. (b) High-order parameters γ and δ as functions of g_1 .

close to the source from $0.3l_t$ to several l_t , we simulated the diffuse reflectance with the identical γ but different g_1 . The results of Monte Carlo simulations are shown in Fig. 4(a), the reflectance computed with $p_{\text{Tissue}}(\theta)$ characterized by identical $\gamma = 1.2$, $\alpha = 0.8$, but different g_1 ($g_1 = 0.247, 0.713$), and therefore the Legendre moments of $p_{\text{Tissue}}(\theta)$ of higher order than g_1 are also different. A third-order parameter δ is defined by $\delta \equiv (1 - g_3)/(1 - g_1)^{[15]}$, and the simulated values of curves γ and δ in Fig. 4(a) are shown in Fig. 4(b). We found that, though with different δ , the curves in Fig. 4(a) are almost the same. The results of Monte Carlo simulations with other phase functions with two parameters led to the same conclusion, however the $R_{\text{MC}}(\rho)$ simulated with $p_{\text{Zee}}(\theta)$ has a substantial difference, as shown in Fig. 5.

Our studies showed that spatially resolved diffuse reflectance from a homogenous semi-infinite medium in the region close to the source from $0.3l_t$ to several l_t can be characterized by parameters μ_a , μ'_s , and γ when $p_{\text{HG}}(\theta)$ or a combined phase function of two parameters is used. But the influences of parameters of higher order than γ on the diffuse reflectance are substantial if $p_{\text{Zee}}(\theta)$ with three parameters are used to describe the scattering properties of tissue. The studies also showed that

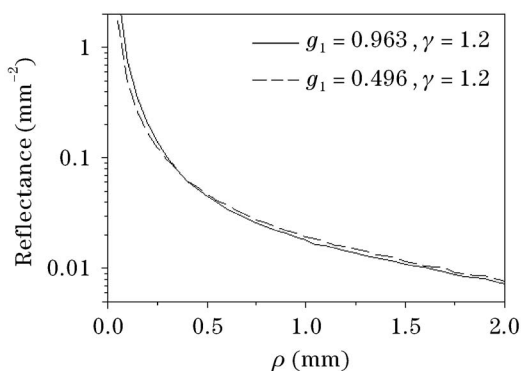


Fig. 5. Influences of parameters of higher than the second order on the diffuse reflectance are confirmed to be substantial if the double Henyey-Greenstein function is used to describe the scattering property of tissue.

the influences of second order parameter γ on $R_{\text{MC}}(\rho)$ curves are well-regulated. These results are important and useful to reconstruct the optical properties of tissue from experimental data of diffuse reflectance close to the source.

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