Influence of the scattering phase functions on the spatially resolved reflectance spectroscopy close to the source

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The influence of the different phase functions on the spatially resolved reflectance measurements is studied with Monte carlo simulations. We show that the spatially resolved reflectance from a homogenous semi-infinite medium is mostly dependent on the second-order factor of tissue except for the absorption coefficient, the reduced scattering coefficient and the refractive index at short source-detector separations. However, the effect of the high-order-factors is very weaker. Then we analyze the given conclusion and find that the parameter varies with the same current following the first-order moment for the phase functions containing two parameters.

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Steady-stated 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*[4−5]. In this technique a narrow of light is directly projected onto a tissue, and diffusely reflected light is collected by a 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 the three quantities: the absorption coefficient μ_a, the scattering coefficient μ_s, and the phase function $p(\theta)$. The diffusion equation is an approximation of the transport equation and does not account for the specific form of the scattering function. It has been shown that $R_{\rm Diff}(\rho)$ is close to $R(\rho)$ obtained from the transport equation or equivalently with Monte Carlo simulations, $R_{\rm MC}(\rho)$, if the generally used Henyey-Greenstein phase function is applied in the simulations[1]. However, for other phase functions and a short source-detector separation the differences between $R_{\rm Diff}(\rho)$ and $R_{\rm MC}(\rho)$ may be substantial[1,7,8]. In 1999, Bevilacqua *et al.* introduced a second-order factor $\gamma = (1-g_1)/(1-g_2)$ and showed that $R(\rho)$ can be approximately described by μ_a, μ_s', and γ[8], where g_1, g_2 are first- and second −order moments, μ_s' is the reduced scattering coefficient. Recently Kienle *et al.* have studied the influence of the phase function on determination of the optical properties of biological tissue by spatially resolved reflectance[9]. In this work, we applied Monte Carlo simulations to calculate the diffuse reflectance by using different phase functions that contain a single parameter, two parameters or three parameters. The result shows that, the spatially resolved reflectance from a homogenous semi-infinite medium is mostly dependent on γ of tissue except for μ_a, μ_s', and the refractive index n, not dependent on the g_1 and the weighting factorαat short source-detector. Then we find that the parameter γ varies with the same current following the g_1 for the phase functions containing two parameters. The Monte Carlo method is well-known to give accurate solutions for the light propagation in turbid media if interference effects are negligible. The essential theory is the same as the Monte Carlo program compiled by Wang *et al.*[10]. In the simulation, we use 100,000 photons for each simulation, boundary conditions are taken into account by using Fresnel and Snell laws for the each photon reaching the surface, and then take advantage of the semi-infinite geometry and the cylindrical symmetry.

In the work, we adopt six different phase functions ($p_{\rm HG}(\theta)$, $p_{\rm Fried-Jacq}(\theta)$, $p_{\rm Tissue}(\theta)$, $p_{\rm MHG}(\theta)$, $p_{\rm HG-HG}(\theta)$, and $p_{\rm Rayl}(\theta)$) to calculate the reflectance curves. These

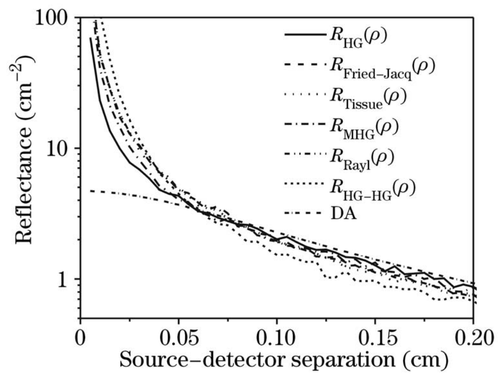

Fig. 1. Spatially resolved reflectance calculated by the different phase functions with Monte Carlo method. The other optical properties are $\mu_a = 0.1\,{\rm cm}^{-1}, \mu_s' = 10.0\,{\rm cm}^{-1}$, and $n = 1.4$.

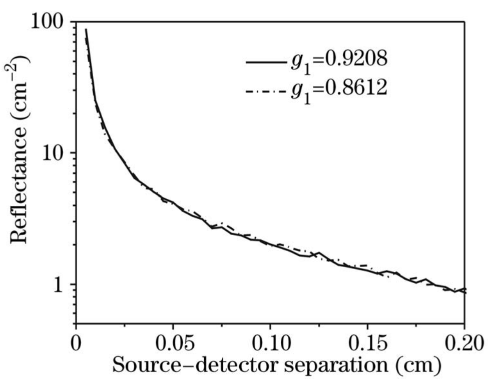

Fig. 2. Effect of g_1 on the reflectance. The two parameters are fixed:$\alpha = 0.99$, $\gamma = 1.8$.

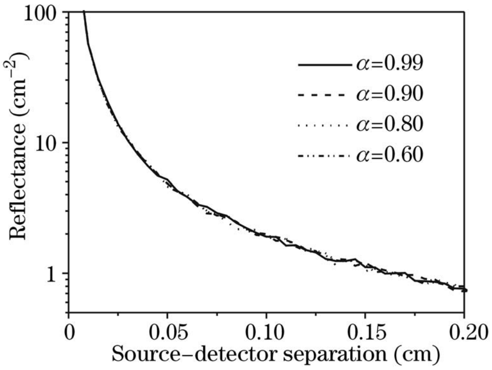

Fig. 3. Effect of α on the reflectance for a constant second-order factor $\gamma = 1.1$.

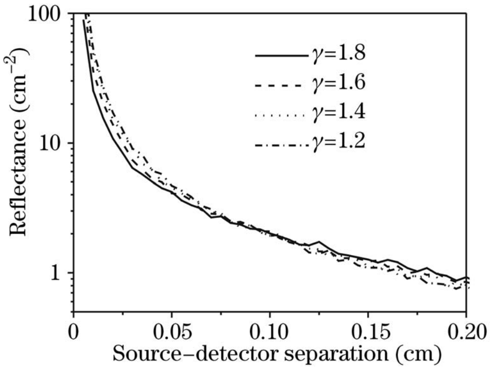

Fig. 4. The effect of γ on the reflectance with the phase function $p_{\text{Tissue}}(\theta)$ for a constant weighting factor $\alpha = 0.99$.

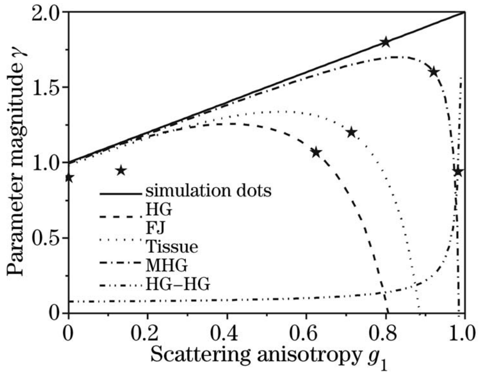

Fig. 5. Relationships between γ and g_1 when $\alpha = 0.65, 0.8, 0.98, 0.995$ respectively for $p_{\text{Fried-Jacq}}(\theta)$, $p_{\text{Tissue}}(\theta)$, $p_{\text{MHG}}(\theta)$, $p_{\text{HG-HG}}(\theta)$ and then when $g_{\text{HG1}} = 0.992$, $g_{\text{HG2}} = -0.93$ for $p_{\text{HG-HG}}(\theta)$.

phase functions are divided into three species according to the curves that γ varies with g_1. Liu *et al.* have summarized the expressions of these phase functions and their γ respectively in detail[11].

The spatially resolved reflectance for these six phase functions and typical optical parameters of biological tissue, $\mu_a = 0.1$ cm^{-1}, $\mu_s' = 10.0$ cm^{-1}, and $n = 1.4$, are calculated by Monte Carlo method. In Fig.1 six $R(\rho)$ curves are depicted. Similarly to those reported in Refs.[8] and [9], these reflectance curves have considerable difference, and all $R(\rho)$ curves have similar the values of reflectance at $\rho \approx 0.07$cm. To study how these phase functions influence these differences in the reflectance curves, we analyze the effect of g_1, the weighting factor α, and γ.

Firstly, we examine the effect of g_1 on the reflectance. For this, α and γ are held constant, and g_1 is varied, other typical optical parameters of biological tissue are $\mu_a = 0.1$ cm, $\mu_s' = 10.0$ cm and $n = 1.4$. In Fig. 2 the reflectance is computed with$p_{\text{Tissue}}(\theta)$and $\alpha = 0.99$, $\gamma = 1.8$. Figure 2 show clearly that the influence of$g_1$is weaker for compounding phase functions mostly containing two parameters whenα and $\gamma$are held constant. In view of this, we show that the effect of the high-order factors, such as the third-order factor δ, is weaker on the reflectance at a short distance. Note that we mostly discuss these phase functions containing one and two parameters, not talk the phase functions containing more parameters over.

Secondly, we examine the effect of αon the reflectance. Figure 3 shows the reflectance computed with $p_{\text{Tissue}}(\theta)$ characterized by identical $\gamma = 1.1$ but with different α ($\alpha = 0.99, 0.9, 0.8, 0.6$), and other typical optical parameters of biological tissue being $\mu_a = 0.1$ cm, $\mu_s' = 10.0$ cm, and $n = 1.4$. We find that the effect of the αon the reflectance is not important. That is to say, the values of the reflectance do not almost change when we change the values of α, making the values of γ held constant.

Thirdly, we study the effect of the second-order factor γ on the reflectance. In Fig.4, the reflectance is calculated with $p_{\text{Tissue}}(\theta)$ by identical $\alpha = 0.99$ but different γ ($\gamma = 1.8, 1.6, 1.4, 1.2$), and other parameters are $\mu_a = 0.1\,\text{cm}^{-1}$, $\mu_s' = 10.0\,\text{cm}^{-1}$, and $n = 1.4$ for all reflectance curves. Figure 4 indicates clearly that the influence of γ on the reflectance is important close to the source.

Then, we analyze the relation of γ and g_1 to find between the similarities of the phase functions. Figure 5 is the relation of γ and g_1 with these six phase functions given in Fig. 1. Figure 5 bring forward that the parameter γ varies with the similar current following g_1 for $p_{\text{Fried-Jacq}}(\theta)$, $p_{\text{Tissue}}(\theta)$, and $p_{\text{MHG}}(\theta)$, and the phase function $p_{\text{HG}}(\theta)$ is a particular case of the phase functions $p_{\text{Fried-Jacq}}(\theta)$, $p_{\text{Tissue}}(\theta)$, and $p_{\text{MHG}}(\theta)$. So we can use $p_{\text{Tissue}}(\theta)$ to substitute these phase functions $p_{\text{HG}}(\theta)$, $p_{\text{Fried-Jacq}}(\theta)$, and $p_{\text{MHG}}(\theta)$ close to the source when γ is held constant.

In summary, we have studied the effect of the different parameters (g_1, α, γ) or phase functions ($p_{\text{HG}}(\theta)$, $p_{\text{Fried-Jacq}}(\theta)$, $p_{\text{Tissue}}(\theta)$, $p_{\text{MHG}}(\theta)$) on the spatially resolved reflectance with Monte Carlo method. We found that the spatially resolved reflectance from a homogenous semi-infinite medium is mostly dependent on the second-order factor γ of tissue, except for the absorption coefficient μ_a, the reduced scattering coefficient μ_s' and the refractive index$n$at short source-detector separations. However, the effects of the high-order-factors (i.e., the third-order factor δ) or the weighting factor$\alpha$are very weaker. And then we can use $p_{\text{Tissue}}(\theta)$ to substitute these phase functions $p_{\text{HG}}(\theta)$, $p_{\text{Fried-Jacq}}(\theta)$, and $p_{\text{MHG}}(\theta)$ close to the source when γ is held constant. These results are important and useful to measure the parameter γ of tissue, built up the diffuse theory containing the higher-order parameter of the phase function, and exactly measuring other optical parameters.

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References

1. A. Kienle and M. S. Patterson, J. Opt. Soc. Am. A **14,** 246 (1997).
2. T. J. Farrell, M. S. Patterson, and B. C. Wilson, Med. Phys.**19,** 879 (1992).
3. A. Kienle, L. Lilge, M. S. Patterson, R. Steiner, and B. C. Wilson, Appl. Opt. **35,** 2304 (1996).
4. R. Bays, G. Wagnières, D. Robert, D. Braichotte, J.-F. Savary, P. Monnier, and H. van den Bergh, Appl. Opt. **35,** 1756 (1996).
5. F. Bevilacqua, D. Piguet, P. Marquet, J. D. Gross, B. J. Tromberg, and C. Depeursinge, Appl. Opt. **38,** 4939 (1999).
6. A. Kienle, *Lichtausbreitung in Biologischem Gewebe* (University of Ulm, Germany, 1995).
7. J. R. Mourant, J. Boyer, A. H. Hielscher, and I. J. Bigio, Opt. Lett. **21,** 546(1996).
8. F. Bevilacqua and C. Depeursinge, J. Opt. Soc. Am. A **16,** 2935 (1999).
9. A. Kienle, F. K. Forster, and R. Hibst, Opt. Lett. **26,** 1571 (2001).
10. L. Wang, S. L. Jacques, and L. Zheng, Computer Methods and Programs in Biomedicine **47,** 131 (1995).
11. Y. Liu, X. Zhang, and Y. Hu, Acta Opt. Sin. (in Chinese) **24,** 877 (2004).