Monte Carlo modelling of OCT with finite-size-spot photon beam

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Infinitely narrow photon beams have been used in the former Monte Carlo modelling about the signal of optical coherence tomography (OCT). However, the focused spot size is finite and determined by the center wavelength of the optical source. In the present paper, finite-size photon beams are launched into a multi-layer numerical phantom, and the signals of OCT are obtained based on Monte Carlo technique and Mie theory. By use of the model we confirm the shower curtain effect as researchers have found before.

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Optical coherence tomography (OCT)[1] is a very effective imaging technology that produces high-resolution cross-sectional images of the internal microstructure of scattering media like the retina and other biological tissues. OCT uses short coherence light source and Michelson interferometer to enhance axial resolution and to discriminate against scattered light. Depth scanning is achieved by the longitudinal translation of a reference mirror, and lateral scanning is obtained by the lateral translation of a focused probe beam by use of scanning mirrors, so that cross sectional images are usually generated. To optimize the OCT technique in biological imaging, much researches have been done in the area of theoretical modelling of OCT imaging of scattering media: single backscattering[2], linear system theory[3], the extended Huygens-Fresnel analytical model[4], and so on. On the other hand, numerical modelling, especially Monte Carlo modelling, is extensively discussed[5−7]. In these studies, researchers assumed that an infinitely thin beam be launched into the scattering media. However, in real OCT setup, the size of the optical source spot is finite. Some researchers considerd that a Gaussian beam is launched into the scattering media by use of two sets of straight lines which construct a hyperboloid with one sheet[8]. In the present paper, we will give a new model of finite size spot of the optical source based on Monte Carlo techniques and Mie theory. We consider a phantom which is illuminated by finite size spot of optical source, and then we will find that the lateral resolution can be much better than the spot size of the optical source.

Our model is based on Monte Carlo technique; however, we use Mie theory[9] to calculate the phase function $p(\theta,\varphi)$ instead of the Henyey-Greenstein phase function:

$$\begin{aligned} p(\theta,\varphi) \propto \cos^2\varphi[|S_2(\theta)E_{\mathrm{p}}|^2 + |S_1(\theta)E_{\mathrm{s}}|^2] \\ + \sin^2\varphi[|S_2(\theta)E_{\mathrm{s}}|^2 + |S_1(\theta)E_{\mathrm{p}}|^2] \\ - \sin 2\varphi[|S_2(\theta)|^2 - |S_1(\theta)|^2]\mathrm{Re}(E_{\mathrm{p}}E_{\mathrm{s}}^*), \end{aligned} \quad (1)$$

where θ, φ are scattering angle and azimuthal angle respectively, S_1, S_2 are the items of the scattering matrix, and E_{p}, E_{s} are the field components parallel and perpendicular to the scattering plane respectively. We use Monte Carlo technique to track each photon and use Mie theory to find the electronic field components. And then we select the photons as[6]

$$f(L_n) = \{ \begin{array}{l} 1 \text{ if } L \in [L_0 - L_{\mathrm{c}}/2, L_0 + L_{\mathrm{c}}/2], \\ 0 \text{ others} \end{array} \quad (2)$$

where L_n is the overall optical pathlength of nth photon, L_0 is the special optical length of photons directly backscattered from the layer desired to image, and L_{c} is the coherence length. To simulate OCT imaging through the phantom, a full-reflect mirror with sharp edge is embedded in the phantom. Finally, we record the backscattering field at the surface of the phantom.

In our model, we launch two beams straightly on the surface of the phantom. Their centers are located at different points and each beam has a Gaussian distribution in the lateral plane (x-y plane, $z = 0$).

By use of our model of OCT with finite-size-spot beam, we consider a phantom who consists of two layers and in each layer, polystyrene spheres are uniformly distributed in the solvent (gumwater or water). The parameters of each layer are collected in Table 1.

By use of our model, we consider the fields backscattered from the interface of the two layers. The mirror is embedded at the interface of the two layers and stretches from −40 μm to 40 μm in x-coordinate and from −20 μm to 20 μm in y-coordinate. Then the special optical pathlength L_0 is product of the two times of the width of the first layer and the refractive index of the first layer. The coherence length $L_{\mathrm{c}} = 40\mu$m.

The two incident beams (whose center wavelength is 1.55 μm) with full-width at half-maximum (FWHM) of 20 μm and the location of their center on the surface of the phantom where $z = 0$ (for simplicity, we will omit z-coordinate when we describe the points in this plane) can be considered for three situations: 1) the centers [described by (x, y)] of two incident beams are located at (−20, 0), (20, 0), respectively; 2) the centers are located at (−10, 0), (10, 0); 3) the centers are located at (−5, 0), (5, 0). The backscattering intensity patterns of the three situations are shown in Fig. 1. Some researchers insist that the lateral resolution is the waist of the Gaussian beam[10], i.e., the lateral resolution is the almost 24 μm for the FWHM of the incident beams being 20 μm. However, from Fig. 1, we find that we can discriminate the two backscattering intensity peaks even if the distance between the centers of the two beams is 10 μm. This is so called shower curtain effect which indicates that the lateral resolution increases with increasing distance

Table 1. Parameters of the Two Layers Composing the Phantom

Layer	Width (μm)	Refractive Index of the Layer	Refractive Index of the Spheres	Radius of the Spheres (μm)	Scattering Coefficient (cm^{-1})
1	2000	1.329	1.565	0.3	18.71
2	1000	1.85	1.565	0.4	14.24

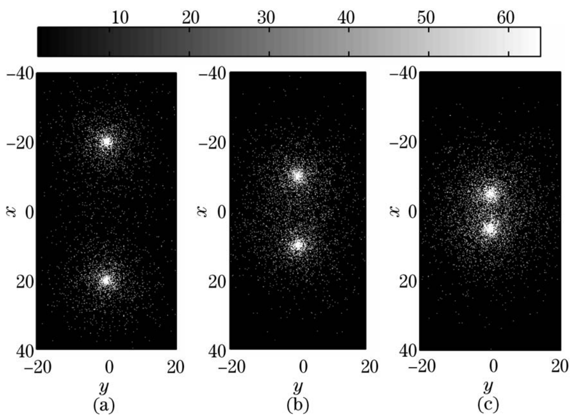

Fig. 1. The first case in which the width of the first layer is 2000 μm and three intensity patterns are shown for three different center locations of two incident beams: (a) (–20, 0) and (20, 0); (b) (–10, 0) and (10, 0); (c) (–5, 0) and (5, 0).

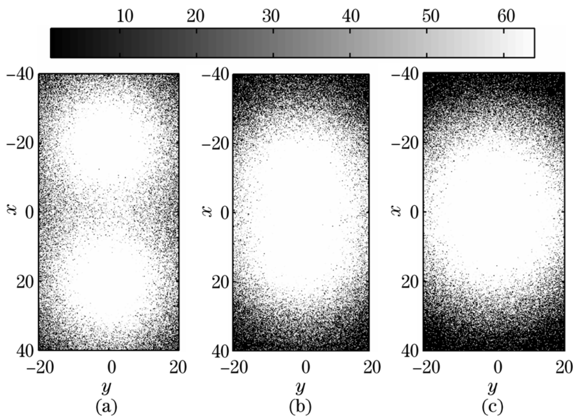

Fig. 2. The second case in which the width of the first layer is 1000 μm and three intensity patterns are shown for three different center locations of two incident beams: (a) (–20, 0) and (20, 0); (b) (–10, 0) and (10, 0); (c) (–5, 0) and (5, 0).

between the tissue (phantom in the present paper) surface and the desired interface[4,11]. To show this effect clearly, we use our model to calculate another case in which the width of the first layer is 1000 μm and other parameters are unchanged, as shown in Fig. 2. From Fig. 2, we can find that the lateral resolution is lower than that of the first case which is shown in Fig. 1 because of the shorter distance between the interface and the phantom surface (i.e., the width of the first layer).

From Figs. 1 and 2, we can find that our model confirms the shower contain effect, which proves the validity of our model.

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