Experimental Study of Effect of Medium Boundary on Light Distribution in Tissue Phantoms *

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An experimental method for investigating the effect of medium boundary on distributions of light in the biological tissue phantom intralipid is presented. Measurements of distributions of light in intralipid-10% suspensions at 633 nm are described, in which a narrow collimated beam is incident on the surface of the phantoms and into the different depths inside of the phantoms. The experimental results show that the effect of the boundary of the medium on the curves geometry of light distributions is trivial, but the effect on intensity of scattering light is obvious, the maximal relative change of the energy fluence reaches 53.8 % and the position of the peak of the energy fluence curve has a shift of 1.1 mm in the reverse direction of incident light for the phantom with albedo $a = 0.998$, and the effect of the boundary is decreased with the increase of the absorption coefficients of tissue phantoms. The experimental results were analysed by the diffusion theory. These studies will be helpful for further understandings of the relation between the boundary of biological tissue and the distribution of light in tissue.

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When a light beam is incident on a biological tissue, the distributions of scattering light in the tissue are mostly determined by the optical properties of tissues. In addition, the geometry of the incident beam and the boundary of the tissue have effects on light distributions. The partial current boundary condition (PCBC) and extrapolated boundary condition (BEC), which are used to solve the diffusion equation, include the reflection effect of the radiation at the boundary of the medium.[1] The simulations of photon propagation in biological tissue by the Monte Carlo method record the reflection and the transmission of the photons at tissue boundary.[2−4] To date, there have been few reports on the experimental studies about the effect of the boundary of tissue on the light distributions in tissue.[5] Some experimental works presented the fluence distribution in tissues.[6,7] However, there have been no detailed studies of the effect of boundary on fluence distributions. In photodynamic therapy (PDT), the light from a suitable light source is delivered to the tumour target in *vivo* tissue by using a biopsy needle and optical fiber,[8] and if the incident point of the beam is close to the boundary of the tissue-ambient medium, the light distributions in tissue are related to the tissue boundary.

In this Letter, an experimental method for studying the effect of the medium boundary on the fluence distribution is presented and the fluence distributions in the tissue phantom intralipid are measured. In the experiments, a collimated narrow beam is incident on the surface and into the different depths inside the semi-infinite tissue phantom. Some valuable conclusions are drawn from the experimental results.

In our experiment, fat emulsion intralipid-10% was used as a simulation tissue. The investigations have shown that intralipid is almost purely scattering, and the asymmetry factor g of intralipid-10% suspensions is between 6.8 and 7.1.[9,10] Two kinds of the phantom solutions were prepared for the measurements , the first one was the pure intralipid-10% dilute solution with concentration of 5.18%, the scattering coefficient $\mu_{s_1} = 2\,\mathrm{mm}^{-1}$ and absorption coefficient $\mu_{a1} = 0.003\,\mathrm{mm}^{-1}$;[5] the other was the aqueous mixture of 5.18% intralipid solution and the black ink which is a pure absorber with absorption coefficient $\mu_{a-\mathrm{ink}} = 39.6\,\mathrm{mm}^{-1}$, which was determined by us with the transmission method. In the experiment, the optical parameters of the intralipid/ink phantom were $\mu_{s_2} = 2\,\mathrm{mm}^{-1}$ and $\mu_{a2} = 0.02\,\mathrm{mm}^{-1}$, respectively.[5,11]

The experimental setup is shown in Fig. 1, a cylindrical plastic tank (height 17.5 cm, diameter 20 cm) was filled with 5 L diluted intralipid-10% suspension. In order to obtain the different depths of the incident points inside the phantom medium, a thin metallic pipe with diameter of 3.5 mm was used to transmit the probe beam into the phantom medium, the outside

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surface of the pipe was wrapped with a white medical plaster to prevent mirror reflection of the outer surface. One end of the pipe was sealed with a thin glass plate (the thickness was 1 mm) and was inserted into the solution. In Fig. 1, d denotes the depth of the beam incident point in the phantom medium. A He–Ne laser beam (14 mW, 632.8 nm) was collimated with a lens and then was chopped (2 kHz, chopper Mode SR450) before entering into the centre of the pipe (the diameter of the beam is 1.6 mm), then the beam was normally incident on the intralipid phantom. The relative fluence $\Phi_r(\rho, z)$ was detected by using a fibre (diameter 300 μm; NA=0.3; multimode) with a sphere of highly scattering material (sphere diameter 2 mm) attached to the end of the fibre. The photoelectrical signal of the photodiode was fed into a pre-amplifier and a lock-in amplifier (Model SR830). A translation stage was used to move the probe end of the optical fibre in the z and ρ directions in which the accuracy was better than 0.01 mm.

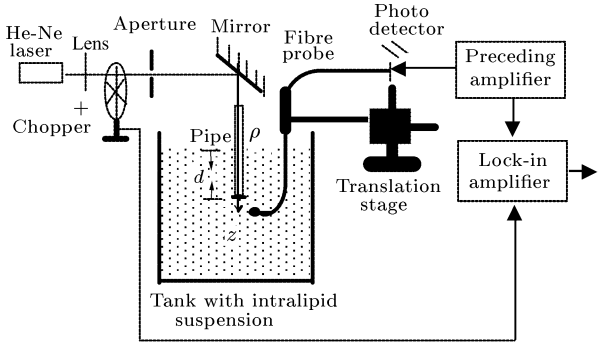


Fig. 1. Experimental setup for researching the effect of the tissue phantom boundary on light distribution in the intralipid phantom.

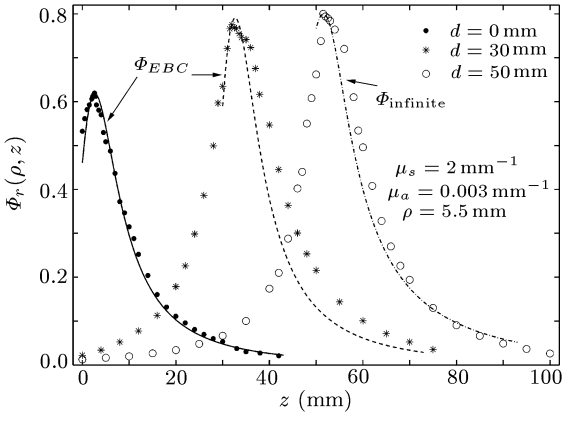


Fig. 2. Relative fluence as a function of distance z.

The experimental results are shown in Figs. 2–5. The analyses of the experimental results are given as follows. (1) For the intralipid phantom with the parameters $\mu_{s_1} = 2\,\text{mm}^{-1}$, $\mu_{a1} = 0.003\,\text{mm}^{-1}$ and the different depths d, Figs. 2 and 4 show that the shapes of the curves of the fluence $\Phi_r(\rho, z)$ are similar, but the fluence $\Phi_r(\rho, z)$ increases evidently with the increase of the depth d, and the distributions of $\Phi_r(\rho, z)$ with z trend towards the symmetrical distributions about the peaks of fluence. Figure 3 shows that the maximal fluence $\Phi_{r\,max}(\rho, z)$ in the z direction increases with the depth d, $\Phi_{r\,max}(\rho, z)$ appears saturation when the depth d reaches to a certain value and the relative change of $\Phi_{r\,max}(\rho, z)$ is about 53.8%. The experimental data also show that the distances between the beam incident points and the position of the peaks of the fluence $z_{\max}$ slightly reduce as the increase of the depth d. Figure 2 shows that d increases from 0 mm to 50 mm, $z_{\max}$ decreases from 2.6 mm to 1.5 mm

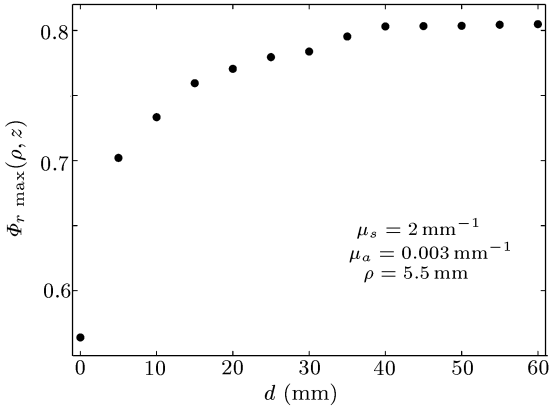


Fig. 3. Changes of maxima of $\Phi_r(\rho, z)$ versus z with the depth d of beam incident points in phantom.

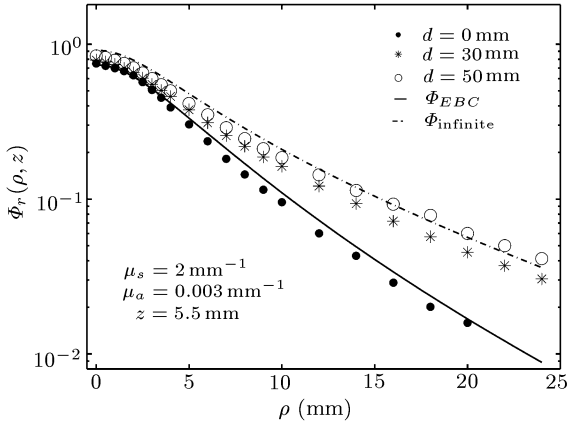


Fig. 4. Relative fluence as a function of distance ρ.

From the diffusion theory, an incident collimated tiny beam that is incident on a semi-infinite turbid medium can be simulated as a couple of image sources, which was shown with the dashed line in the left part in Fig. 6. With the extrapolated boundary condition,

the fluence $\Phi_{EBC}(\rho, z)$ is given by[12]

$$\Phi_{EBC}(\rho,z)=\frac{1}{4\pi D}\Big(\frac{\exp\{-\mu_{\rm eff}[(z-z_0)^2+\rho^2]^{1/2}\}}{[(z-z_0)^2+\rho^2]^{1/2}} - \frac{\exp\{-\mu_{\rm eff}[(z+z_0+2z_b)^2+\rho^2]^{1/2}\}}{[(z+z_0+2z_b)^2+\rho^2]^{1/2}}\Big), \quad (1)$$

where $D=[3(\mu_a+\mu_s')]^{-1}$ is the diffusion constant, $\mu_s'=(1-g)\mu_s$ is the reduced scattering coefficient, $\mu_{\rm eff}=\sqrt{3\mu_a(\mu_a+\mu_s')}$ is the effective attenuation coefficient, $z_0=[(1-g)\mu_s]^{-1}$, $z_b=2D(1+R_{\rm eff})/(1-R_{\rm eff})$ and the inner reflective coefficient $R_{\rm eff}$ is equal to 0.493 for the refractive index $n=1.4$.[1]

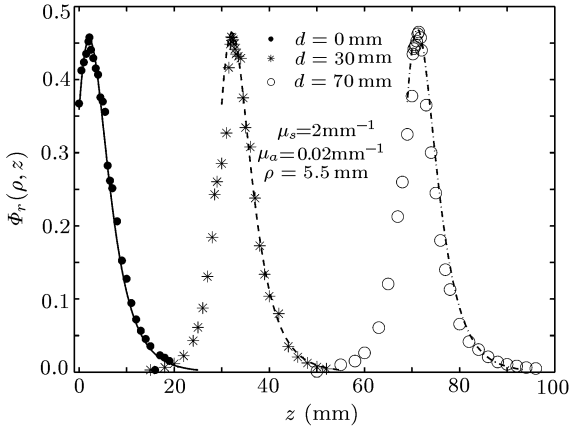


Fig. 5. Relative fluence as a function of distance z for intralipid phantom with larger absorption coefficient. The solid, dashed and dot-dashed lines represent $\Phi_{EBC}(\rho, z)$.

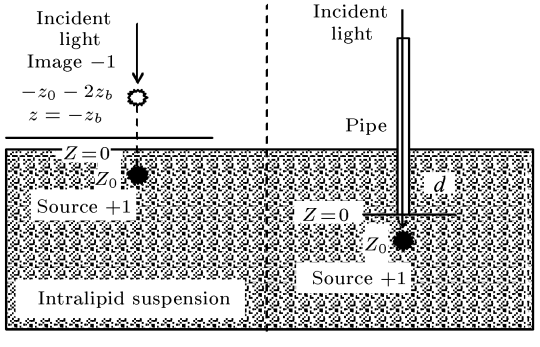


Fig. 6. Configurations of image sources of narrow collimation beam incident on the surface and inside of intralipid suspension.

The results calculated by Eq. (1) are shown in Figs. 2, 4, and 5 in comparison with the experimental results. With the increase of the depth d of the beam incident points in the phantom, the fluence distributions in the phantom trend to the radiation distribution from an isotropic point source in an infinite homogeneous medium as shown in Figs. 2 and 4, which can be described by the following equation:

$$\Phi_{\rm Infinite}(\rho,z)=\frac{1}{4\pi D}\Big(\frac{\exp\{-\mu_{\rm eff}[(z-z_0)^2+\rho^2]^{1/2}\}}{[(z-z_0)^2+\rho^2]^{1/2}}\Big). \quad (2)$$

In Eq. (2), the coordinate origin is shifted a distance of $-z_0$ from the isotropic point source in the $-z$ direction, which is shown with the dashed line in the right part of Fig. 6. Equation (2) is equivalent to the first term $\Phi_+(\rho, z)$ of Eq. (1). The reason for these distributions is that when the depth d increases gradually, the photons arrived the boundary of the phantom decrease gradually and the backscattering of the photons in the phantoms increases gradually. From Eq. (1), the distributions of the fluence $\Phi_+(\rho, z)$ of the positive point source and the fluence $\Phi_-(\rho, z)$ of the negative point source and $\Phi_{EBC}(\rho, z)$ versus z are shown in Fig. 7, respectively, which indicates $\Phi_+(\rho, z) > \Phi_{EBC}(\rho, z)$ and the distance between the position z_0 of the peak of $\Phi_+(\rho, z)$ and the incident point of the beam is less than that of $\Phi_{EBC}(\rho, z)$. These theoretical analyses can be used to explain the experimental results. The fluence in Fig. 2 appears the slight asymmetrical distribution about the peak of the fluence, even if the depth d is larger, which indicates the propagation of the photons in the phantom still presents the forward-scattering characteristics. Figure 3 shows that the thickness of the phantoms in which the photons undergo backscattering is approximately equal to 26 optical mean transport free paths for $d \geq 40$ mm, and the maximal values of the fluence almost saturate with the increase of the depth d, thus it can be approximately considered as the photons propagating in an infinite medium, and the effect of the boundary of medium on the fluence can be ignored.

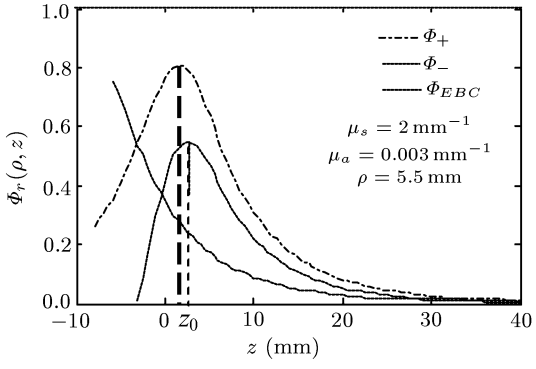


Fig. 7. Fluence $\Phi_+(\rho, z)$ of positive point source, influence $\Phi_-(\rho, z)$ of negative point source, and $\Phi_{EBC}(\rho, z)$ versus distance z.

For the intralipid-10% suspension with larger absorption coefficient $\mu_{a2}=0.02\,{\rm mm}^{-1}$, the fluence $\Phi_r(\rho, z)$ as a function of z are shown in Fig. 5. It can be seen that the variations of the distributions of the fluence with the depth d are small, the relative changes

of $\Phi_{r\,max}(\rho, z)$ are less than 14.8 %, the fluence distributions have good symmetry about the peaks of fluence due to the most of the photons are absorbed at the area near the positive point source and few of the photons can arrive the boundary of the phantom with larger absorption coefficient, therefore the effect of the boundary of phantom on the fluence in the phantom is smaller. According to the analyses given above, the probe beam, whose incident point is within the medium, can be approximately replaced by a positive point source. The calculated results by Eq. (1) show that as the absorption coefficient μ_a increases, $\Phi_+(\rho, z)/\Phi_{EBC}(\rho, z)$ with albedo $a = \mu_s/(\mu_a + \mu_s)$ rapidly decreases and trends toward 1, for example, $\Phi_+(\rho, z)/\Phi_{EBC}(\rho, z) = 1.23$ for $\mu_a = 0.02\,\mathrm{mm}^{-1}$, $\mu_s = 2\,\mathrm{mm}^{-1}$, $z = z_0$ and $\rho = 5.5\,\mathrm{mm}$.

In summary, based on the experimental results and analyses, we have the following conclusions. (1) For the intralipid phantom with a smaller absorption coefficient and higher albedo, with the increase of the depth of the incident point of the beam in the phantom, the fluence in the phantom has a distinct increase, and trends toward the fluence distribution of the point source in the infinite medium; when the thickness of the phantoms in which the photons undergo backscattering is larger than 26 optical mean transport free paths, it can be approximately considered as the propagation of photons is in an infinite medium, and the effect of the medium boundary on the fluence distributions can be ignored. (2) For the phantom mediums with a larger absorption coefficient, the effect of the boundary on the fluence distributions decreases evidently, and the fluence distributions approximate to the distributions of the radiation from an isotropic source in infinite medium for the different depths of the incident points of the beam in the medium.

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