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Theoretical and experimental study of the intensity distribution in biological tissues*

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Based on the diffusion approximate theory (DA), a theoretical model about the distribution of the intensity of a narrow collimation beam illuminating on a semi-infinite biological tissue is developed. In order to verify the correctness of the model, a novel method of measuring the distributions of the intensity of light in Intralipid-10% suspension at 650 nm is presented and measurements of the distributions of the distance-dependent intensity of scattering light in different directions are made. The investigations show that the results from our diffusion model are in good agreement with the experimental results beyond and in the areas around the light source, and the distance-dependent intensity in the incident direction attenuates approximately in the exponential form. Furthermore, our theoretic results indicate the anisotropic characteristics of the intensity in different directions of scattering light inside the biological tissue.

Keywords: biological tissue, light distribution, radiation intensity
PACC: 4225B, 4225F, 8750E, 9530J

1. Introduction

The knowledge of the propagation and scattering of light in biological tissues is important for the investigation and application of biomedical optics.[1,2] In the study related to this subject, the radiation intensity is one of the basic physical quantities, which is expressed by $I(\boldsymbol{r}, \hat{s}, t)$ and dependent on the position vector $\boldsymbol{r}$, direction vector $\hat{s}$ and time t. Biological tissue is a complicated scattering medium; the detection and investigation of radiation intensity in biological tissues can lead to knowing how the light transports in biological tissues and what the anisotropic characteristics of scattering light are, and determining the relevant optical parameters, such as, the anisotropy factor g. In the bio-photonics study and application, fibre is used to transport the radiation light from light source and detect the radiation light.[3] The fibre with an isotropic sphere is used to radiate light energy fluence and detect the fluence rate in biological tissues, however, the device for measuring these quantities is relatively complicated.[4] The fibre without any isotropic sphere is mostly used for radiating light and detecting the radiant intensity in biological tissues. At present, there are many theoretical and experimental studies (including simulations) about the distribution of fluence rate in tissue and tissue phantom, but little theoretical study and numerical simulation of the intensity distribution are reported. Thus it is necessary to study the intensity distribution of light transporting in biological tissue theoretically and experimentally. The purpose of the present study is to present a theoretic method of investigating the intensity distribution of light in biological tissue and verify the correctness of the theory experimentally.

According to the diffusion approximate theory (DA) and the results from Ref.[5], the distribution of radiant intensity of a narrow collimation beam being incident on a semi-infinite biological tissue is studied and a relevant theoretical model is built in this paper. Besides, we present an experimental method by which the distributions of the distance-dependent intensity in different directions of light in Intralipid-10% sus-

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pension can be measured by the fibre. Theoretical and experimental results are analysed, which shows that the theoretic calculations based on our diffusion model are in good agreement with the experimental results beyond and in the areas around the light source, and the distribution of intensity in the incident direction follows approximatively the exponential attenuation. Here, the area around the light source is defined as the area around the incident point of the light beam. In addition, the characteristics of the changes of intensity in different directions of scattering light inside the biological tissue are studied in details by use of our model.

2. The diffusion approximate model

According to the DA theory, when a stable beam is incident on the scattering medium, the intensity $I(\boldsymbol{r},\hat{s})$ inside the scattering medium at a position vector $\boldsymbol{r}$ in direction $\hat{s}$ is the reduced incident intensity $I_{\rm ri}(\boldsymbol{r},\hat{s})$ plus the diffuse intensity $I_{\rm d}(\boldsymbol{r},\hat{s})$,[5] that is,

$$I(\boldsymbol{r},\hat{s}) = I_{\rm ri}(\boldsymbol{r},\hat{s}) + I_{\rm d}(\boldsymbol{r},\hat{s}), \tag{1}$$

for a collimation beam illuminating the medium, the reduced incident intensity is

$$I_{\rm ri}(\boldsymbol{r},\hat{s}) = F_0(\boldsymbol{\rho})\exp(-\mu_{\rm t}z)\hat{z}. \tag{2}$$

In Eq.(2), $F_0(\boldsymbol{\rho})$ is the radiant flux density of incident light, $\mu_{\rm t} = \mu_{\rm a} + \mu_{\rm s}$ is the total attenuation coefficient. For the first order diffusion approximation, the diffuse intensity $I_{\rm d}(\boldsymbol{r},\hat{s})$ can be expressed as

$$I_{\rm d}(\boldsymbol{r},\hat{s}) = \frac{1}{4\pi}\phi_{\rm d}(\boldsymbol{r}) + \frac{3}{4\pi}\boldsymbol{F}_{\rm d}(\boldsymbol{r})\cdot\hat{s}. \tag{3}$$

In Eq.(3), the diffuse photon fluence rate in a medium $\phi_{\rm d}(\boldsymbol{r})$ is defined by

$$\phi_{\rm d}(\boldsymbol{r}) = \int_{4\pi} I_{\rm d}(\boldsymbol{r},\hat{s})\mathrm{d}\Omega, \tag{4}$$

and the diffuse flux vector $\boldsymbol{F}_{\rm d}(\boldsymbol{r})$ is defined by

$$\boldsymbol{F}_{\rm d}(r) = \int_{4\pi} I_{\rm d}(\boldsymbol{r},\hat{s})\hat{s}\mathrm{d}\omega, \tag{5}$$

while the collimation light is incident on the parallel turbid medium with a thickness of d, $\boldsymbol{F}_{\rm d}(\boldsymbol{r})$ is given by[5]

$$\boldsymbol{F}_{\rm d}(\boldsymbol{r}) = \frac{\mu_{\rm s}gF_0(\boldsymbol{\rho})}{\mu'_{\rm t}}\exp(-\mu_{\rm t}z)\hat{z} - \frac{1}{3\mu'_{\rm t}}\nabla\phi_{\rm d}(\boldsymbol{r}), \tag{6}$$

where g is the anisotropy factor, and $F_0(\boldsymbol{\rho})$ is a constant for planar wave. When a Gauss beam is incident on the medium, $F_0(\boldsymbol{\rho}) = F_0\exp(-\rho^2/R^2)$, where R is the waist radius of Gauss beam, with $1/e^2$ times the width of the peak intensity, and $\mu'_{\rm t} = \mu_{\rm a} + (1-g)\mu_{\rm s}$ is the transport attenuation coefficient, $\hat{z}$ is the unit vector in the incident direction. Once the fluence rate $\phi_{\rm d}(\boldsymbol{r})$ in the medium is given, the diffuse flux $\boldsymbol{F}_{\rm d}(\boldsymbol{r})$ can be obtained by Eq.(6), and then diffuse intensity $I_{\rm d}(\boldsymbol{r},\hat{s})$ can be work out by Eq.(3), finally, the total intensity $I(\boldsymbol{r},\hat{s})$ can be acquired by Eq.(1). The thickness d of the medium is assumed to be more than hundreds photons average free paths, and Eq.(6) is valid for the incident collimation beam on a semi-infinite turbid medium.

When an infinitely narrow collimation beam is incident on a semi-infinite biological tissue under an extrapolated boundary condition (EBC), the fluence rate $\phi_{\rm d}(\boldsymbol{r})$ in a cylindrical coordinate system is[6]

$$\phi_{\rm EBC}(\boldsymbol{r}) = \frac{1}{4\pi D}\left(\frac{\exp(-\mu_{\rm eff}r_1)}{r_1} - \frac{\exp(-\mu_{\rm eff}r_2)}{r_2}\right), \tag{7}$$

where

$$r_1 = \left[(z-z_0)^2 + \rho^2\right]^{1/2},$$

$$r_2 = \left[(z+z_0+2z_b)^2 + \rho^2\right]^{1/2},$$

$$D = [3(\mu_{\rm a}+\mu'_{\rm s})]^{-1}$$

is the diffusion constant, $\mu'_{\rm s} = (1-g)\mu_{\rm s}$ is the reduced scattering coefficient, $\mu_{\rm eff} = \sqrt{3\mu_{\rm a}(\mu_{\rm a}+\mu'_{\rm s})}$ is the effective attenuation coefficient, $z_0 = (\mu_{\rm a}+\mu'_{\rm s})^{-1}$, $z_b = 2D(1+R_{\rm eff})(1-R_{\rm eff})^{-1}$, ρ is the radial distance taking the incident point as its origin, and z is the axial distance normal to the medium boundary. When the refractive index of tissue n=1.4, the fraction of photons reflected internally at boundary is $R_{\rm eff}$=0.493.[7] In a cylindrical coordinate system, we have the following equation:

$$\nabla\phi_{\rm d} = \frac{\partial\phi}{\partial\rho}\hat{\rho} + \frac{1}{\rho}\frac{\partial\phi}{\partial\varphi}\hat{\varphi} + \frac{\partial\phi}{\partial z}\hat{z}, \tag{8}$$

where $\hat{\rho}$, $\hat{\varphi}$ and $\hat{z}$ are unit vectors in radial, angle and incident directions, respectively. Since the intensity distribution is axially symmetric for a narrow collimation beam perpendicularly incident on a semi-infinite biological tissue, thus, we have $\dfrac{\partial\phi}{\partial\varphi} = 0$, and

$$\nabla\phi_{\rm d} = \frac{\partial\phi}{\partial\rho}\hat{\rho} + \frac{\partial\phi}{\partial z}\hat{z}. \tag{9}$$

Substituting Eq.(7) into Eq.(9), we obtain the following equation:

$$\nabla\phi_{\rm d} = \frac{\rho}{4\pi}\left(-\frac{(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}+\frac{(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\hat{\rho} + \frac{1}{4\pi}\left(-\frac{(z-z_0)(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}+\frac{(z+z_0+2z_b)(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\hat{z}. \quad (10)$$

Supposing the narrow collimation beam with a unit power, that is, $F_0(\boldsymbol{\rho}) = F_0(0) = 1$, and substituting Eqs.(6), (7) and (10) into Eq.(3), the flowing equations are obtained:

$$I_{\rm d}(\boldsymbol{r},\hat{s}) = \frac{1}{16\pi^2 D}\left(\frac{\exp(-\mu_{\rm eff}r_1)}{r_1}-\frac{\exp(-\mu_{\rm eff}r_2)}{r_2}\right)+\frac{3}{4\pi}\times\frac{\mu_S g}{\mu_{\rm t}'}\exp(-\mu_{\rm t}z)\hat{z}\hat{s} + \frac{\rho}{16\pi^2 D\mu_{\rm t}'}\left(\frac{(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}-\frac{(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\hat{\rho}\cdot\hat{s} + \frac{1}{16\pi^2 D\mu_{\rm t}'}\left(\frac{(z-z_0)(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}-\frac{(z+z_0+2z_b)(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\hat{z}\cdot\hat{s}. \quad (11)$$

Supposing that θ is the angle included between unit vectors $\hat{s}$ and $\hat{z}$, Eq.(11) can be expressed as

$$I_{\rm d}(\boldsymbol{r},\hat{s}) = \frac{1}{16\pi^2 D}\left(\frac{\exp(-\mu_{\rm eff}r_1)}{r_1}-\frac{\exp(-\mu_{\rm eff}r_2)}{r_2}\right)+\frac{3}{4\pi}\times\frac{\mu_S g}{\mu_{\rm t}'}\exp(-\mu_{\rm t}z)\cos\theta + \frac{\rho}{16\pi^2 D\mu_{\rm t}'}\left(\frac{(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}-\frac{(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\sin\theta + \frac{1}{16\pi^2 D\mu_{\rm t}'}\left(\frac{(z-z_0)(\mu_{\rm eff}+r_1^{-1})\exp(-\mu_{\rm eff}r_1)}{r_1^2}-\frac{(z+z_0+2z_b)(\mu_{\rm eff}+r_2^{-1})\exp(-\mu_{\rm eff}r_2)}{r_2^2}\right)\cos\theta. \quad (12)$$

Based on the diffusion theory and considering an infinitely narrow incident light beam, we have two hypotheses:

(i) Beyond the area around the light source (for example $z > 2$mm), ignoring the function of reduced incident light $I_{\rm ri}(\boldsymbol{r},\hat{s})$, and supposing the equivalent source term of reduced incident light to be independent of angle, that is, the source is isotropic; solving the radiation transmission equation we obtain the diffuse flux vectors $\boldsymbol{F}_{\rm d}(\boldsymbol{r})$ and $\phi_{\rm d}(\boldsymbol{r})$ with the following relation:[5]

$$\boldsymbol{F}_{\rm d}(\boldsymbol{r}) = -D\nabla\phi_{\rm d}(\boldsymbol{r}), \quad (13)$$

and

$$I(\boldsymbol{r},\hat{s}) \approx I_{\rm d}(\boldsymbol{r},\hat{s}). \quad (14)$$

(ii) In the area around the light source, due to the photons undergoing scattering less times, the diffusion intensity $I_{\rm d}(\boldsymbol{r},\hat{s})$ is much smaller than the reduced incident light $I_{\rm ri}(\boldsymbol{r},\hat{s})$, thus, the radiant intensity is mainly determined by the reduced incident light $I_{\rm ri}(\boldsymbol{r},\hat{s})$, that is,

$$I(\boldsymbol{r},\hat{s}) \approx I_{\rm ri}(\boldsymbol{r},\hat{s}). \quad (15)$$

3. Experimental methods and materials

Intralipid is a fat emulsion that is used clinically as an intravenously administered nutrient. Investigations have shown that Intralipid is of almost purely scattering and low absorption.[7,8] The aqueous mixture of Intralipid and India ink is a good biological tissue phantom, and due to the mixture liquid having a good uniformity property, the optical parameters of the phantom medium can be selected at a wider range by varying the concentrations of Intralipid and ink in the dilute solution. Therefore, this liquid is used as the simulated material of biological tissue to study the optical characteristics of bio-tissue. Here we chose Intralipid-10% suspension as the simulated material of biological tissue. The asymmetry factors g of Intralipid-10% suspensions were in the range from 6.8 to 7.1,[8,9] which were determined by experiment and calculation. In the experiment, we prepared the phantom solution that was the pure Intralipid-10% dilute solution with a concentration of 5.18%, the scattering coefficient of $\mu_{\rm s1}$=2mm^{-1} and absorption coefficient of $\mu_{\rm a1}$=0.003 mm^{-1}.[8]

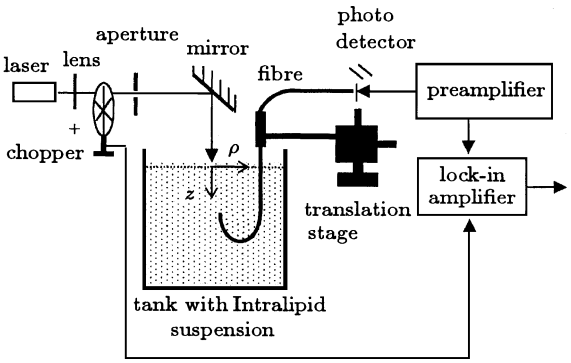


Fig.1. Experimental setup for determining the distribution of intensity of light in Intralipid-10% suspension.

The experimental setup is shown in Fig.1. A semiconductor laser beam (20mW; 650nm), whose divergence angle is less than 0.3 mrad, was collimated with a lens and then was chopped (2kHz) before going through an aperture. The beam was reflected by a mirror, and then normally incident on Intralipid -10% phantom. A plastic container (18cm×18cm×16cm) was filled with 5-L diluted Intralipid-10% suspension. The inner surface of the container had a very small reflection, thus the influence of the inner surface on the light distribution in the phantom could be almost neglected. The refractive indices of the Intralipid-10% suspension and air were mismatched. The diffusion light signal in the solution received by the optical fibre probe (fibre 300μm; N.A. 0.3; multimode) was transmitted to a photodiode. The photoelectrical signal of the photodiode was fed into a preamplifier and a lock-in amplifier (Model SR830, Stanford Research Systems, Sunnyvale, California). A fibre translation stage was used to move the optical fibre probe along the z and ρ directions with an error of less than 0.01mm. In order to bend the fibre, the fibre was fixed on a thin copper wire which can crook easily (diameter 0.8mm), and the detecting side of the fibre was about 3mm longer than the copper wire. Here the radius of the bent fibre was about 25mm. The detection system was carefully checked before detection. The sensitivity and linearity of this photoelectric detection system were satisfactory to the measurement. The influence of the bending of the fibre on the transmission of light was checked for the three bent versions of the fibre, as shown in Figs.2–4, in air and solution, respectively. By comparing the results measured by the fibres with and without the three bent version, the errors were found to be less than $< 1\%$. We used a cylindrical system to do the experiment and calculation. Here, z was the optical axis of the incident beam and ρ represented the radial direction. The light intensities were detected by the fibre in the three directions respectively (see Figs.2–4), and the results were obtained from the detected intensities of forward-scattering light in the z direction, horizontal scattering light in the ρ direction and backscattering light in the z direction, which are expressed by the relative intensity I_{r}. Adjusting the fibre position along with z and ρ directions, respectively, the relative intensity I_{r} was recorded, which is the ratio of the scattering light intensity I_{s} in the scattering medium to the incident beam intensity I_{i} on the medium's surface. (Due to the aperture angle of the fibre being small, through which the detection light was received, it can be considered that the detected intensities were approximatively measured in the same direction.)

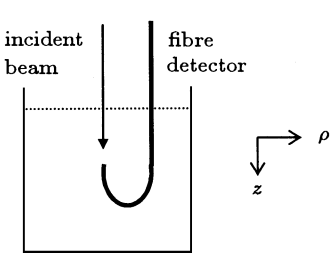


Fig.2. Detection of forward-scattering light.

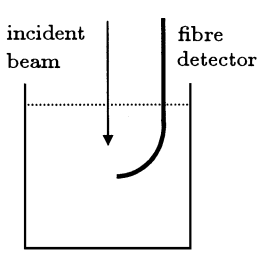


Fig.3. Detection of horizontal scattering light.

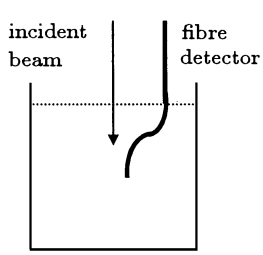


Fig.4. Detection of backscattering light.

4. Results and analyses

According to Eq.(12) and our two hypotheses, the theoretical results are denoted in the Figs.5(a)–5(h) by solid curves, and the experimental results are represented by circles, where the theoretical results are for forward-scattering light I_{forward}, horizontal scattering light $I_{\mathrm{horizontal}}$ and backscattering light I_{back} respectively at angles θ=0°, 90° and 180° based on Eq.(12). In order to compare with the distribution of fluence rate $\phi_{\mathrm{d}}(\boldsymbol{r})$, Fig.5 also shows the results of $\phi_{\mathrm{d}}(\boldsymbol{r})$ based on Eq.(7) (see dashed curves in Fig.5).

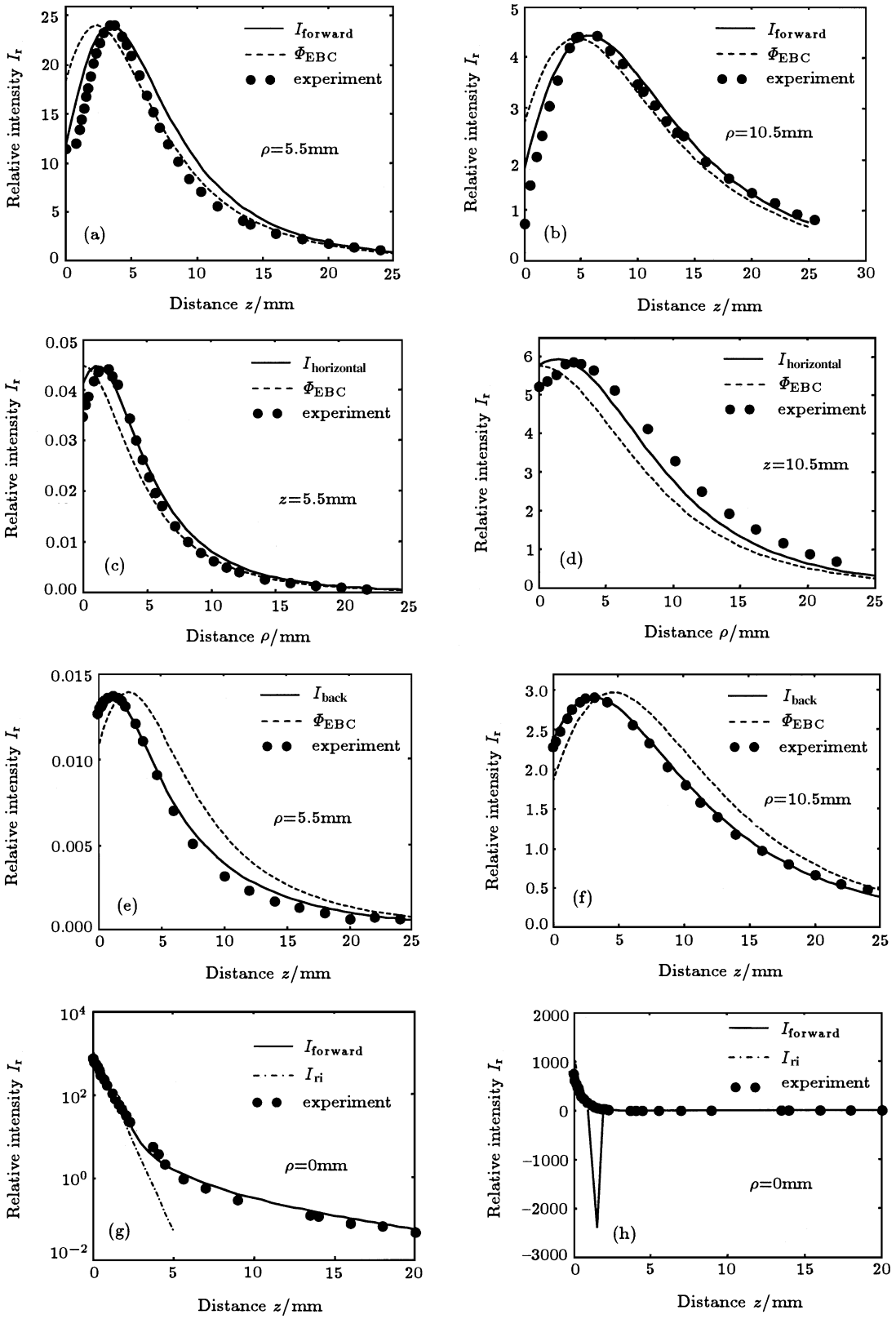


Fig.5. Comparison between theoretical results and experimental data for forward scattering light, horizontal scattering light and back scattering light in Intralipid suspension.

Figures 5(a)–5(f) show that the theoretical and experimental results of I_{forward}, $I_{\text{horizontal}}$ and I_{back} have some differences in the area around the light source. Here the differences of $I_{\text{horizontal}}$ are obvious (see Figs.5(c) and 5(d)); the differences of I_{forward} are a little, (see Figs.5(a) and 5(b)); and the differences

of $I_{\rm back}$ are very little (see Figs.5(e) and 5(f)); Beyond the area around the light source, the theoretical results are in good agreement with experimental results, therefore, the first hypothesis is reasonable. In the area around the light source, there are larger differences between the distributions of fluence rate and the radiation intensity in either the z or ρ direction. However, in the area apart from the light source, the differences tend to decrease. Figures 5 (c) and 5(d) show that the distributions of fluence rate $\phi_{\rm d}(\boldsymbol{r})$ decrease monotonically with ρ, and theoretical and measured radiant intensities each have a maximum; In addition, our experimental results show that the distribution of the backscattering light $I_{\rm back}$ over ρ has the maxima at z=5.5mm and z=10.5mm, but the forward-scattering light $I_{\rm forward}$ versus ρ appears to have the distribution decreasing monotonically.[10] And these experimental results are in good agreement with our theoretical results, which shows that there exist distinct differences of the distributions of the distance-dependent intensity of scattering light in different directions inside the tissue phantom.

Based on Fig.5 (g), the distribution of intensity I in the z-direction is observed from the light incident point (ρ=0mm), and the distribution of I_z is well described by Eq.(2) within the distance $z < 2.5$mm (see the dash-dotted curve in Fig.5 (g)), that is, in the area around the light source, I decreases exponentially as a function of z, therefore the second hypothesis is also reasonable. Moreover, beyond the area around the light source (z >2.5mm), theoretical results of diffuse intensify $I_{\rm d}$ are in agreement with experimental results, which is in accord with the first hypothesis. Based on Eq.(11) or (12), at the position of $z = z_0$, there appears a negative break (see Fig.5 (h)), which indicates that if the diffusion theory is used to explain the distribution of the intensity in the area around the light source, there appear big errors that are induced by the hypothesis of the source being isotropic. In addition, the differences between theoretical and experimental results are also induced by the experimental errors.

Figures 6(a)–6(f) show that the radiation intensity $I_{\rm d}(\boldsymbol{r}, \hat{s})$ changes with θ based on Eq.(12). Figure 6(a) shows that the $I_{\rm d}(\boldsymbol{r}, \hat{s})$ changes with θ at the position of $\rho = 0$mm and $z = 3.5$mm. The forward-scattering characteristics are very obvious. When z increases ($z = 5$mm), forward-scattering characteristics become weak, and they further decrease in the area apart from the source ($z = 15$mm). The scattering in each direction finally tends to be uniform; Figure 6(b) shows the influences of anisotropy factor g on the distribution $I_{\rm d}(\boldsymbol{r}, \hat{s}) - \theta$. In the area apart from the source ($z = 12$mm), when $g = 0$, $I_{\rm d}(\boldsymbol{r}, \hat{s})$ in each direction is rather uniform, and when $g = 0.9$, the changes of $I_{\rm d}(\boldsymbol{r}, \hat{s})$ with θ have obvious forward-scattering characteristics. Figure 6(c) shows that at $z = 3$mm and $\rho = 3$mm, forward-scattering characteristics exist; at $\rho = 6$mm, the intensities of the forward-scattering and the backscattering are almost the same; at $\rho = 20$mm, the backscattering intensity is larger than the forward scattering intensity; these results are supported by experimental results,[10] and indicate that although the photons scattered in biological tissues exhibit the characteristics of the obvious forward-scattering, the backscattering characteristics still remain in some area. From Fig.6(d), we know that at $z = 0$mm, which is at the surface of the beam being incident on medium, the backscattering intensity is larger than the forward-scattering intensity for each ρ. And from Fig.6(e) in the area around the light source, ($\rho = 3$mm, $z = 2.5$mm), the maximum of $I_{\rm d}(\boldsymbol{r}, \hat{s})$ appears near to the horizontal direction ($\theta = 90^\circ$); in the area apart from the light source ($z = 20$mm), the maximum of $I_{\rm d}(\boldsymbol{r}, \hat{s})$ is almost the same as that in the incident direction ($\theta = 0^\circ$). Figure 6(f) shows that $I_{\rm d}(\boldsymbol{r}, \hat{s})$ is approximately isotropic in the area apart from the source. The analyses above demonstrate that the distributions of the diffuse intensity in biological tissue are quite dependent on the positions in biological tissue and the optical parameters of biological tissue.

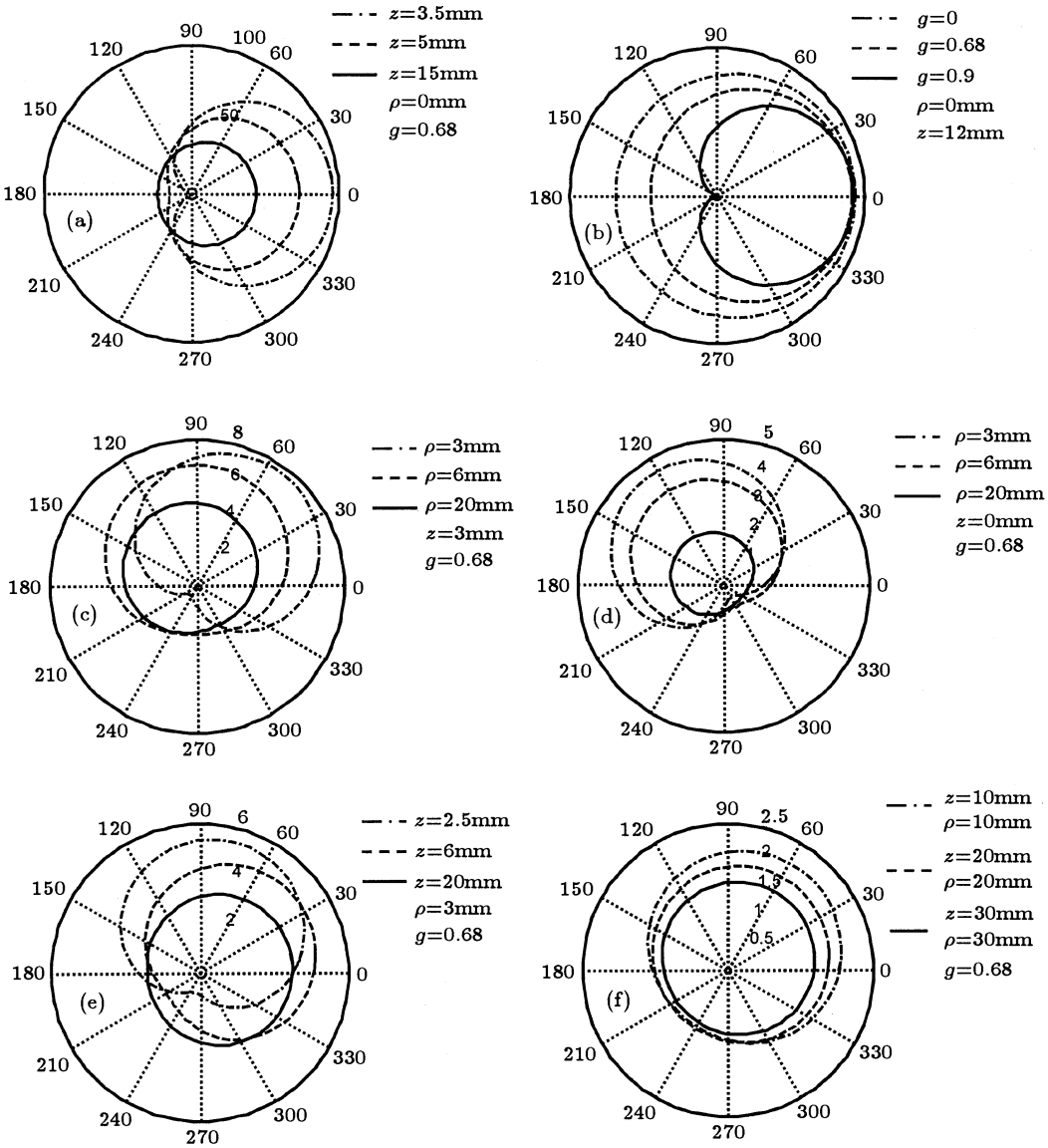


Fig.6. The changes of the relative intensity $I_{\mathrm{d}}(\boldsymbol{r}, \hat{s})$ in bio-tissue versus θ, θ is the angle between the direction $\hat{s}$ and the incidence light direction $\hat{z}$.

5. Conclusions

According to diffusion approximate theory (DA) and the results from Ref.[5], we propose the two hypotheses about the radiation intensity distribution of an infinitely narrow beam being incident on a semi-infinite biological tissue and build a relevant theoretical model as well. In order to verify the correctness of the theoretical model, we present a method of measuring the distributions of light intensity in the bio-tissue phantom Intralipid-10% and measure the distributions of the distance-dependent intensity in different directions by using the fibre. The theoretical and experimental results are analysed; their analyses indicate that our theoretical results from the diffuse model are in agreement with the experimental results well beyond the area around the light source, therefore, the theory has a high accuracy. In the area around the light source, the variation of intensity with the incident direction is approximatively in the exponential form. The study of the distributions of intensity in different directions by use of our model reveals the anisotropic characteristics of the scattering light in biological tissues. The results we obtained will help further study the propagation and scattering of light in biological tissues. At present, we are researching the feasibility of determining the optical parameters of biological tissues by using nonlinear regressions of our theoretical model to the experimental data.

The diffusion theory is used widely to study light transport in the turbid medium, but the theory itself has still some deficiencies in application to biophotonics, therefore it is necessary to be further improved and developed.

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