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The numerical and experimental study of photon diffusion inside biological tissue using boundary integral method

Mohammad Ali Ansari *, Saeid Alikhani, Ezeddin Mohajerani, Reza Massudi

Laser and Plasma Research Institute, Shahid Beheshti University. G. C., Evin, Tehran, Iran

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ABSTRACT

In this study, the diffusion of photons in turbid media, like biological tissue has been studied. Due to scattering and absorption of photons in such media, the study of photon propagation in biological tissue is complicated. The several numerical methods have been presented to simulate the behavior of diffused photons. Recently, Boundary Integral Method (BIM) has been offered to simulate photon migration inside biological tissues. This method has advantage, e.g. lower computational time in compared with other numerical methods. In this study, the accuracy and precision of BIM compares with another numerical method like Monte Carlo technique and finite difference method, and also the calculated results obtained by BIM and Monte Carlo method evaluate with measured results. Furthermore, the effects of scattering and absorption coefficient of tissue on the measured signal are studied.

1. Introduction

Diffuse optical tomography (DOT) is a new optical imaging technique which is used for imaging of breast and neonate brain [1–8]. Optical imaging provides non-ionizing and safe radiation for medical imaging, and also the cost of this method is less than magnetic resonance imaging (MRI). Moreover, optical scattering spectra provide information about the size of optical scatterers like cell nuclei [1]. The study of diffused photons in biological tissues is the key problem in DOT [1,9–11]. Photon migration in biological tissues can be studied by diffuse equation [1]. The diffuse equation can be solved by analytic and numerical methods [12–21]. The analytics methods are available for simple geometric like slab, cylinder and sphere, but numerical methods are used for complicated geometry or heterogeneous distribution of optical properties [3,17]. The majority of numerical methods are based on Monte Carlo or finite element approaches. They are time consuming and their accuracy depends on mesh resolution [14,17]. Recently, boundary integral method (BIM) has been presented to solve diffuse equation [14,18,21–25]. The computational time of BIM is less than other methods such as Monte Carlo and finite difference approaches [18,21,22]. In addition, its accuracy is better than finite element approaches [14,21]. We have numerically shown that BIM can be applied to simulate photon migration in biological tissue, and also the effects of scattering and anisotropic properties of tissue on the reflectance and transmittance optical signal studied in Refs. [14,21,22]. Srivanssan et. al. described that scattering coefficient of the phantom like breast tissue can be determined by BIM [23–25].

In Refs. [14,21,22], the ability of BIM to assess the light-tissue interaction has been numerically presented. In the current study, the accuracy of BIM for light diffusion in turbid media is investigated by experimental methods. Also, the effect of variation of anisotropic property of sample on detected signal is inspected; because the variation of absorption and anisotropic properties of tissues is important for tumor detection in DOT [27].

In this study, the diffuse equation is solved by BIM. First, the appropriate green function to convert diffuse equation to integral form by using the green second theorem is found [18,26]. In this method, one should only discretize surface of the sample. Next, the surface integral is discretized and the resulting integral is numerically solved. Using this technique we have calculated intensity of diffusely reflected signal from tissue. After that the precision of these results is compared with the results obtained by Monte Carlo and experimental methods. For experimental verification, the several phantoms made by Intralipid and Indian ink are used. The phantoms are illuminated by laser light, and then diffused signal on the phantoms is measured, these signals are used for evaluation of results obtained by BIM.

2. Materials and methods

2.1. Review of theory

The diffusion of photons in biological tissues can be studied by diffuse equation [21,27]:

$$-D\nabla^2\phi\left(\vec{r},t\right)+\mu_a\phi\left(\vec{r},t\right)+\frac{\partial\phi\left(\vec{r},t\right)}{\partial t}=S\left(\vec{r},t\right). \quad (1)$$

* Corresponding author.
E-mail address: m_ansari@cc.sbu.ac.ir (M.A. Ansari).

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Here, $\vec{r}$ denotes position, t denotes time, and $\phi\left(\vec{r},t\right)$ is fluence rate defined as the energy flow per unit area per unit time. The constant D is referred to as the diffusion coefficient:

$$D=\frac{1}{3(\mu_a+\mu'_s)} \tag{2}$$

where μ_a and $\mu'_s=\mu_s(1-g)$ are absorption and reduced scattering coefficient, respectively. The anisotropic factor g, defined as $\langle\cos\theta\rangle$, has a value between -1 and 1. A value of zero indicates isotropic scattering, and a value close to unity indicates dominantly forward scattering. For most biological tissues, g is ~0.9 [28]. $S\left(\vec{r},t\right)$ is the isotropic source term at position $\vec{r}$ and the moment t. In this study, the pump source is continuous, so the diffuse equation can be applied stationary.

When the ambient and biological tissue has different indices of refraction, the bounder, Γ_s, between them is referred to as a refractive-index-mismatched boundary. In this condition, the boundary condition is presented as follows owning to Fresnel reflections [18,19]:

$$\phi\left(\vec{r}\right)-2C_R D\frac{\partial\phi\left(\vec{r}\right)}{\partial n}=0 \qquad \vec{r}\in\Gamma_s \tag{3}$$

that $C_R=(1+R)/(1-R)$ where R is Fresnel reflection coefficient. In BIM, diffuse equation can be solved by appropriate green function. Really, green function is a solution of diffuse equation in absence of source term. The appropriate green function for this equation has been derived as following [26]:

$$G\left(\vec{r},\vec{r}\,';\omega\right)=\frac{1}{4\pi\left|\vec{r}-\vec{r}\,'\right|}\exp\left(ik_x\left|\vec{r}-\vec{r}\,'\right|\right) \tag{4}$$

where

$$k_x=\sqrt{\frac{\left(\mu_a+\frac{i\omega}{c}\right)}{D}}. \tag{5}$$

For case of CW illumination, the modulation frequency ω equals zero. Applying boundary condition stated in Eq. (3), and doing some mathematics, we obtain [26]:

$$\phi\left(\vec{r}_{\partial\Omega}\right)=\int_\Omega G\,\tilde{S}.d\,\vec{r}-\int_{\Gamma_s}\left(-G\frac{\partial\phi}{\partial n}+\phi\frac{\partial G}{\partial n}\right)d\vec{r}_s \tag{6}$$

where $\vec{r}_{\partial\Omega}$ is the observation point vector on the boundary Γ_s. Then, the boundary Γ_s is discretized to square elements and the fluence ϕ is approximated as:

$$\phi\left(\vec{r}\right)=\sum_{j=1}^{m}N_j\left(\vec{r}\right)\phi_j\left(\vec{r}\right) \tag{7}$$

where index j refers to the node j^{th} and $N_i\left(\vec{r}_k\right)=\delta_{ik}$ is Kronecker symbol. If $\vec{r}_k$ spans all the nodes on the surface of the boundary, Eq. (1) can be modified as following:

$$H\psi+\Gamma\xi=\bar{S}. \tag{8}$$

Here, $\psi_{1\times N}$, $\xi_{1\times N}$ and $\bar{S}_{1\times N}$ are column vectors containing the nodal values of the fluence ϕ, its normal derivative $q=\partial\phi/\partial n$ and volume source S, respectively; and N is the number of nodes. The element of $\bar{S}_{1\times N}$ is given by:

$$s_j=\int_{\Gamma_s}G\left(\vec{r},\vec{r}\,'\right)S\left(\vec{r}\right)d\,\vec{r}\;. \tag{9}$$

The elements of matrices $H_{N\times N}=\{h_{i,j}\}$ and $\Gamma_{N\times N}=\{\iota_{i,j}\}$ are as:

$$\begin{aligned} h_{i,j}&=\delta_{ij}I+\int_{\Gamma_s}\frac{\partial G\left(\vec{r},\vec{r}\,'\right)}{\partial n}N_{kl}\left(\vec{r}\right)d\vec{r} \\ \iota_{i,j}&=-\int_{\Gamma_s}G\left(\vec{r},\vec{r}\,'\right)N_{kl}\left(\vec{r}\right)d\vec{r}. \end{aligned} \tag{10}$$

By locating observation point on different nodes and using Eq. (8), and consideration of boundary condition, a system of equations is obtained which gives the fluence at those surface points. By solving this set of equation, the fluence on the nodes can be found.

2.2. Preparing phantom and experimental setup

We have done experiments on different phantoms like tissue with absorption and scattering coefficients similar to human breast tissue [28,29]. The optical properties of phantoms have been measured by indirect method [30,31].

As mentioned in Refs. [27,28], in cancerous stages, the optical properties of tissues such as scattering and absorption coefficients vary simultaneously. In this study, the effects of variation of these parameters on the diffused reflectance are studied. Two different setups are designed with different illuminating source; first setup is used to study the effects of these optical properties on diffused reflectance separately. Another setup is applied to study the effect of simultaneous variation of these optical properties on the diffused reflectance.

Schematic of first experimental set up is illustrated in Fig. 1. A cylindrical glass bottle with height of 5 cm and diameter of 3.71 cm was used as container. The Intralipid 10% was filled into the bottle to achieve background scattering same as normal breast tissues.

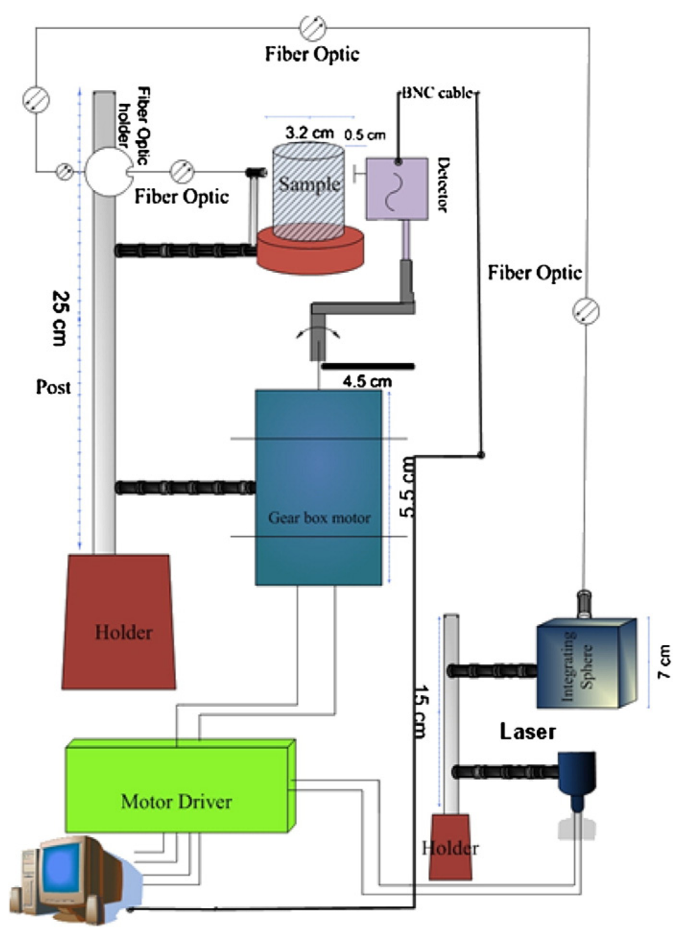

Fig. 1. A schematic of setup for investigate the diffusion of light in cylindrical sample.