

The Effects of Tissue Optical Parameters and Interface Reflectivity on Light Diffusion in Biological Tissues

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Abstract—In cancer progress, the optical properties of tissues like absorption and scattering coefficient change, so by these changes, we can trace the progress of cancer, even it can be applied for pre-detection of cancer. In this paper, we investigate the effects of changes of optical properties on light penetrated into tissues. The diffusion equation is widely used to simulate light propagation into biological tissues. In this study, the boundary integral method (BIM) is used to solve the diffusion equation. We illustrate that the changes of optical properties can modified the reflectance or penetrating light.

Keywords—Diffusion equation, boundary element method, refractive index

I. INTRODUCTION

THE prediction of light energy deposition in human tissues is essential during various biological applications [1-9]; much effort are being made in the study of light interaction with biological tissue due to the development and wide use of lasers for surgical and therapeutic applications. The rapidly increasing use of light in diagnostic and therapeutic medicine has created the need of exact determination of light distribution in tissues [10-15]. Human tissues are highly scattering and absorbing medium. After tissue illumination, some part of light penetrates into tissue that encounters several scattering and absorption events. So, these scattering and absorption events can modify the reflectance or transmitted light. In cancer progress, e.g. breast cancer, by change of cell morphology, the reduced scattering coefficient of tissue changes, in the other hand, by hyper-metabolism of tumor, the absorption of tissue changes. These changes of optical properties can be used as a marker for trace of the stage of cancerous. Therefore one of the most important subjects is to develop a model to study propagation of laser light in the biological tissue; such modeling can be used to calculate the intensity of transmitted or reflected light from the tissue. Diffusion equation usually is used to simulation of diffused light inside the biological tissues [2, 6]. The numerical methods such as, Finite Element Method (FEM), Finite Difference Method (FDM) and Monte Carlo Method (MC) have been used for numerical solving of diffusion equation [16-24]. The MC numerical method is time consuming, e.g. Boas used MC method for optical tomography whereas the computing time is more than 5 hours [25]. The FDM, FEM and FDTD are also time-consuming and their accuracy is lower than MC method.

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Recently, we have also used Boundary Element method (BEM) to solve diffusion equation in biological tissues [26]. As it was shown in ref [26], the BEM is faster than MC and those methods obtained on finite difference methods. The purpose of this investigation is to study of penetrating photons into biological tissues by BEM. In this study, distributions of diffused fluence versus depth in several tissues are calculated by BEM. We have also calculated the effects of refractive indices, anisotropic factor and scattering on diffused fluence inside several tissues.

II. OPTICAL PARAMETERS

Each turbid medium can be classified by two optical parameters, the absorption coefficient $a(mm^{-1})$ and the scattering coefficient $\sigma(mm^{-1})$. Also it is convenient to define an additional parameter, the optical albedo α , given by [20]:

$$\alpha = \frac{\sigma}{\sigma + a} \quad (1)$$

The albedo is a dimensionless parameter that gives the information of the scattering property of tissues, for example in case $\alpha = 0$, attenuation of light is completely due to absorption, while in the case of $\alpha = 1$ only scattering occurs. Another dimensionless parameter used in literatures is optical depth that it was written as [2, 27]:

$$od = (a + \sigma)d \quad (2)$$

Where d is path length.

In most biological tissues, it was found that the light is scattered in forward direction [24, 27]. For explanation of this phenomenon, a probability function $p(\theta)$ is defined that it states the probability of photon scattering by an angel θ . There is not an explicit form, for phase function but, it is usually characterized by a single parameter, called averaged cosine, g , given by [28]:

$$g = \int_{4\pi} p(\theta)\cos(\theta)\sin(\theta)d\theta d\varphi \quad (3)$$

This parameter is sometimes called the anisotropic coefficient and is a number between 1 and -1.

III. DIFFUSION EQUATION FORMALISM

Diffusion equation is widely used for study of photon migration in turbid medium [9, 26]:

$$-\nabla \cdot (D\nabla\phi(\vec{r})) + a\phi(\vec{r}) = S(\vec{r}) \quad (4)$$

Where $\varphi(\vec{r})$ is the fluence rate. In Eq.4, $D = \frac{1}{3(a + \sigma')}$ and $\sigma' = \sigma(1 - g)$ are diffusion and reduced scattering coefficients, respectively.

Propagation of light in a highly diffuse domain Ω with boundary $\partial\Omega$ can be modeled by using Eq.4 and appropriate boundary conditions, called Robin's boundary condition [10]:

$$-\hat{n} \cdot (D\nabla\varphi(\vec{r})) + b\varphi(\vec{r}) = p(\vec{r}) \quad (5)$$

Where $b = \frac{2(1+R)}{(1-R)}$, which R is Fresnel reflection, and $p(\vec{r})$ is the source flux on the boundary. The method of BEM solution is similar to ref [26].

IV. NUMERICAL RESULTS

We use BEM to solve the diffusion equation numerically and to obtain the fluence distribution at various depths for different type of tissues. The accuracy and precision of the BEM code was investigated in ref [10]. The biological domain Ω is assumed to be a semi-infinite slab illuminated by a flat-top beam. In this paper, we have studied the effects of refractive indices, anisotropic factor and scattering on diffused light in human tissues from far IR to UV wavelengths.

The reflective index of biological tissue affects on reflectance; to study this effect, we have calculated the value of fluence at depth of 0.26 mm inside the tissue. Fig.1 depicts diffused fluence versus refractive index. Due to the high concentration of water in biological tissues, the optical properties of tissues can be evaluated by optical properties of water [2]; so, in the Fig. 1 the results were calculated from $n = 1.0$ to $n = 1.4$.

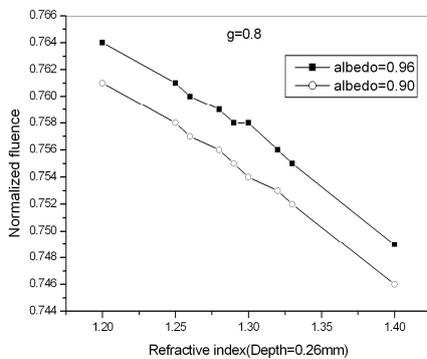


Fig. 1 Calculated fluence as a function of refractive indices for different albedo

Fig. 1 shows that by an increase of refractive index the fluence is decreased. This decreasing can be explained by the following explanation, since an increase of refractive index results in an increase of reflectance on interface between air and tissue; hence the transmitted fluence is decreased. For example, the refractive indices of water at wavelengths 0.2 nm and 10.0 nm are 1.396 and 1.218, respectively [2]; the value of reflectance for these two wavelengths are 0.027 and 0.010, respectively. The calculated fluence for 10.0

nm is 1.02 times greater than wavelength 0.2 nm. In Fig. 1, two tissues with different albedo and same anisotropic factor are considered. For lower albedo tissue, the absorption effects is stronger than other one, hence the fluence for lower albedo is lower than another sample. The effect of variation of the anisotropic factor on the diffused fluence is illustrated in Fig. 2. In this figure, one can see that when anisotropic factor increases, the most of transmitted light scatters forwardly and hence the intensity of light along "incident direction" is increased and the beam can penetrate to the deeper layer and as a result the local absorption near the top of tissue decreases.

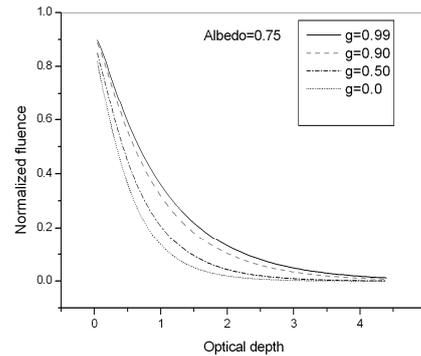


Fig. 2 Normalized fluence as a function of anisotropic factor

To more study of the anisotropic factor effect, we have calculated the fluence at depth 0.04 mm for high scattering media, $\alpha = 1$, (see Fig. 3). The behavior of diffused fluence versus anisotropic factor is shown in this figure, and one can observe that the graph decreases for forward scattering with high anisotropic factors, so the relative difference between the values of maximum and minimum of fluence is 1.18%.

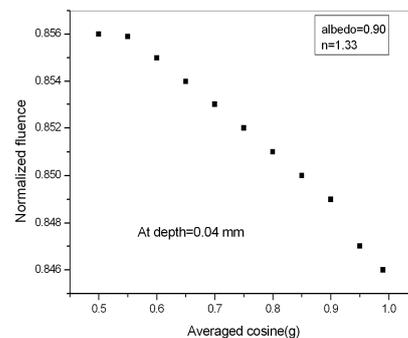


Fig. 3 Calculated fluence versus optical depth for several anisotropic factor (averaged cosine)

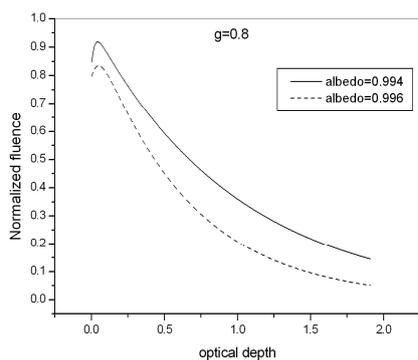


Fig. 4 Normalized fluence as a function of albedo at same anisotropic factor

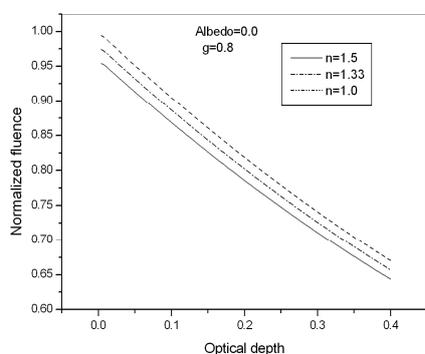


Fig. 5 Calculated fluence for isotropic tissue and zero albedo

Fig. 4 shows the result for a high scattering medium. In high scattering media, the light is scattered to greater optical depths due to anisotropic scattering effects. The optical layer is thick and absorption of incident light occurs in regions close to the top of sample and fluence increases in this region but it decreases more slowly with lower albedo.

Previous figures are calculated for nonzero albedo; for study the effect of refractive index and reflectance of tissue on photon migration in absorption dominant case, $\alpha = 0$, we have calculated fluence as a function of optical depth for different refractive index (see Fig. 5). In Fig. 5, the dependence of the diffuse fluence on optical depth is illustrated in the case of isotropic scattering and different refractive indices. For $\alpha = 0$, attenuation follows Lambert's law of absorption and the fluence obviously approaches smaller values for greater refractive indices, since the transmitted light for lower refractive index is greater than larger one.

It can be deduced from figures 1-5 that the photon migration inside turbid medium like a biological tissue depends on optical parameters of the tissue. So, we have calculated the diffused fluence inside brain (white) for three different wavelengths. The results are shown in Fig. 6. One observes that the fluence is decreasing dramatically for IR wavelength compared to visible wavelength, since the total attenuation

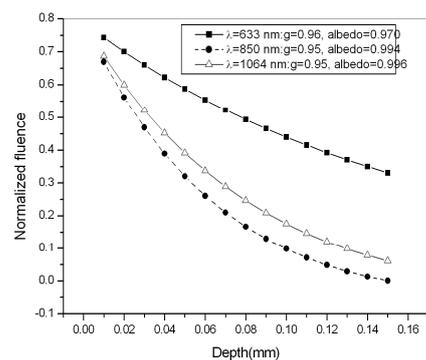


Fig. 6 Calculated fluence for different wavelengths inside brain tissue

coefficients for wavelength 850 and 1064 nm are three and two times greater than at wavelength 633 nm, respectively [2].

V. CONCLUSION

The BEM was used to calculate photon migration inside a semi-infinite layer of biological tissue, including scattering and absorbing. Results for different value of refractive indices illustrate the effects of interface reflections on diffused light inside turbid medium. The results show that by increasing of the value of refractive index, the diffused fluence decreases. An important result shown by our calculation is the occurring a peak of fluence near the surface of tissue for high scattering tissues.

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