Comparisons Between Different Forward Models For Light Transport In Tissues

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Abstract: Calculations based on diffusion approximation, radiation transfer and Monte-Carlo methods are conducted and compared for transient light transport in multidimensional biological tissues. The results for the diffusion approximation are obtained by the finite element method using a commercial package FEMLAB, while the results for the radiation transfer are computed from the Discrete Ordinates Method (DOM). Comparisons between the three methods are performed over a broad range of parameters, such as the scattering and absorption coefficients, the heterogeneity of the tissues, the CPU time, etc. The radiation transfer is found to match closely the MC simulation.

Introduction

The method of imaging the biological tissues using near-infrared (NIR) light is gaining much attention these days, as it is promoted with advantages like cost effectiveness and also safe to apply over human skin. Imaging the optical properties of materials (generally called "Optical Tomography") using NIR light will give promising results to detect the embedded tumor position and also the nature of it. The tumors, generally consumes more blood, will produce the direct information of its intensity and position if we are able to track the high absorption region of deoxygenated blood. It became possible by transilluminating the tissues using NIR light and detecting the signal coming out at the surface. The signal collected from detectors placed at different locations is processed by a computer program to regenerate the tissue image without actual invasion.

The feasibility of regenerating computer program is measured with simulation experiments in which forward models are used to generate similar type of data obtained from detectors. These forward models, basically computer programs or software, will simulate the original tissue and observe the transilluminated signal.

Different forward models are available nowadays to generate the simulation effect. In this paper we discussed three important forward models and their efficiency over each other. The radiative transfer method uses the radiative heat transfer equation, which can be applied to almost all the electromagnetic radiation. The diffusion approximation method is controlled by a differential equation, which is derived from radiative transfer equation under certain boundary conditions and source-detector positions. Monte-Carlo method is the commonly used statistical technique for many engineering applications

Theoretical Formulations

The radiative transfer equation to describe the laser radiation transport in scattering, absorbing and emitting turbid media can be written as [1]

$$\frac{1}{c}\frac{\partial I(r,\hat{s},t)}{\partial t}+\hat{s}.\nabla I(r,\hat{s},t)=-(\sigma_a+\sigma_s)I(r,\hat{s},t)$$
$$+\sigma_a I_b(r,\hat{s},T,t)+\frac{\sigma_s}{4\pi}\int_{4\pi} I(r,\hat{s}',t)\Phi(\hat{s}'\rightarrow\hat{s})dw+S(r,\hat{s},t)$$

where I is the radiation intensity, ∇ the gradient operator, t the time, $\mathbf{r}$ the spatial location vector, $\hat{s}$ the unit vector in the direction of intensity, S the source term, σ_a the absorption coefficient, σ_s the scattering coefficient, ω the spatial solid angle and $\Phi(\hat{s}'\rightarrow\hat{s})$ the scattering phase function. The equation for radiative transfer is solved using Discrete Ordinates Method.

The expansion of radiative transfer equation in spherical harmonics and retention of only the first term result in diffusion approximation equation [2], which is

$$\frac{\partial\phi(r,t)}{c\partial t}=-\nabla.D(r)\nabla\phi(r,t)-\mu_a(r)\phi(r,t)+Q(r,t)$$

where c is the speed of light in the medium, $\phi(r,t)$ is the photon fluence rate defined by the integral of $I(r,s,t)$ over all solid angle.

The boundary condition for photon diffusion is given as the following equation which was taken by the condition at the surface that the total diffuse flux directed inward must be zero.

$$-D(r)\frac{\partial\phi(r,t)}{\partial n}=\frac{1}{2}\phi(r,t)$$

These diffusion approximation equations look similar to the conventional heat conduction equations, which are available in commercial software. We used FEMLAB software to solve the diffusion approximation. Details about the DOM and Monte-Carlo method are described in [1].

Simulations

In the simulation model we generated bodies having optical properties similar to those of human tissues and tumors. The experiments are conducted on both 2-D and 3-D models. In two-dimensional model, the tissue with dimensions of 35mm x 20.2mm size is used. The properties of tissue will be varying according to layers in human brain as shown in Fig. 1. The squares represent the detector positions and arrow represents the source of light.

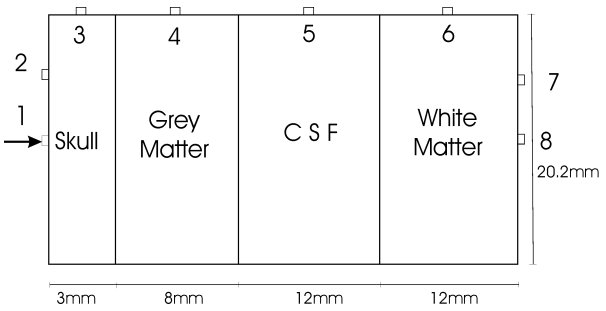

Fig. 1. 2D geometry and dimensions

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The absorption and scattering coefficients used for different layers are tabulated below:

Layer	μ_a (mm^{-1})	μ_s (mm^{-1})
Skull	0.005	1.6
Grey matter	0.015	0.6
CSF	0.001	0.01
White matter	0.01	1.2

In 3D case, a tissue of size 24x24x24mm is used and a tumor is placed at the center. Seven detector positions are selected around the cubic tissue as shown in Fig.2, considering the symmetry.

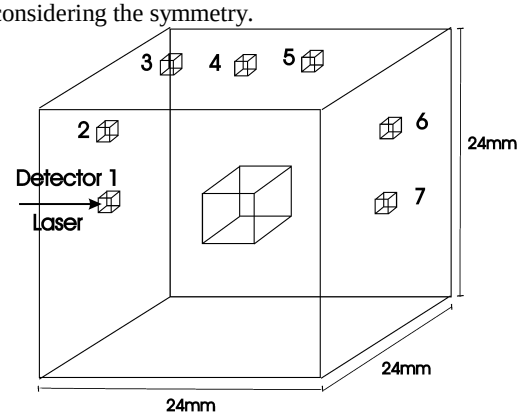
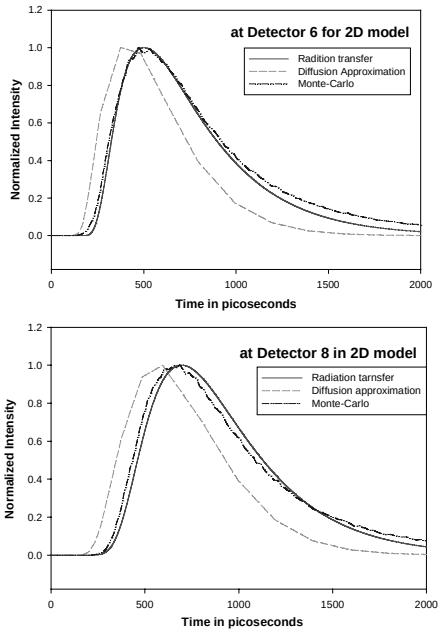


Fig. 2. 3D geometry and detectors

The optical properties of tissue were taken as μ_a=0.001mm^{-1} and μ_s=1mm^{-1} and for tumor μ_a=0.1mm^{-1} and μ_s=1mm^{-1}. The results of the three methods are compared and graphs are drawn against each other.



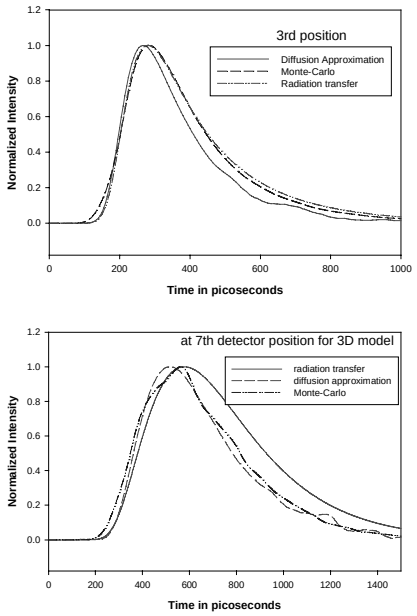
(a)

Fig.3 Normalized intensities in 2D model.

Results and Discussion

For 2D case, results are retrieved at 8 different detector positions and comparisons of predictions for the forward models are drawn in Figs. 3(a) and 3(b) for 6th and 8th detector positions respectively. We found that all the methods are giving almost same sort of temporal results for signal propagation but the time taken for max signal varied according for each method. While radiative transfer method produced smooth curves, diffusion approximation produced a bit straight lines at some detectors. Monte-Carlo method produced slightly jagged curves for almost all detectors.

Similar graphs are drawn and studied for 3D modeling at 7 different detector positions. The graphs in Figs. 4(a) and 4(b) are drawn at the 3rd and 7th detector positions in which all three methods are compared with each other. The jagged profile for diffusion approximation is resulted due to the restriction on the size of tissue body chosen. It is observable from the graphs that both radiation transfer and Monte-Carlo method match closely, but diffusion approximation differs from the other two. The rising is much fast in the Monte Carlo prediction.



(a)

(b)

Fig. 4. Normalized intensities in 3D model

CPU times

Diffusion approximation: 15-20min for 2D
60-90min for 3D
Radiative transfer (S_{10} method): 8 hrs for 3D
Monte-Carlo method: 4 hrs for 2D
10 hrs for 3D

Conclusion

Predictions from the results are showing that radiation transfer gives better results. Monte-Carlo method looses its efficiency in thick media. Diffusion method can be successfully used in thick tissue materials when no low scattering region exists.

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References

[1] Zhixiong Guo, "Ultrashort Laser Transport in Turbid Media"-Dissertation at Polytechnic University, June 2001.
[2] Yukio Yamada and Yasuo Hasegawa, Proceedings of SPIE, Vol. 1888, 167-178, Jan 1993.