Comparison of Diffusion and Transport in human head

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Abstract

Two well-known forward models for light propagation in adult human head are compared: Monte Carlo and Finite-Difference. The main advantage of a diffusion based method is the low computational cost at the expenses of accuracy.

1. Introduction

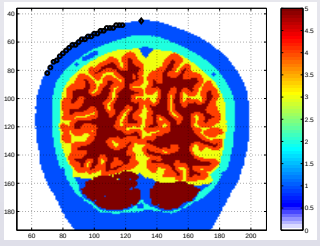
Diffuse Optical Imaging (DOI) is a relatively new method used to image blood volume and oxygen saturation in vivo. We compare two well-known forward models for photon migration in the human head: Monte Carlo (MC) of the transport equation and Finite-Difference of the diffusion equation (FD). Due to the long processing time associated with Monte Carlo, it is advisable to adopt a faster alternative forward model with comparable accuracy. The low scattering properties of the Cerebral Spinal Fluid (CSF) filling the space between the brain and the skull has been of particular concern in the development of an accurate photon migration forward problem for the human head as the diffusion equation is known to provide inaccurate solutions under such circumstances. The roughness of CSF is of particular interest as it limits the average straight-line distance that a photon would travel in the "void" region. Thus, even if the "void" region does not scatter light, we could treat it as if it had an effective scattering coefficient such that the typical scattering length is greater than the average straight-line distance through the "void" region. A sufficiently accurate solution from the diffusion equation would significantly increase the solution of the inverse problem for DOI.

2. Methods

The head model we employ is provided by MRI segmented data. With such adult head geometry we can specify up to five tissue types (scalp, skull, CSF, gray and white matter) but for most of our test we use three (as described in Table 1). The whole volume is voxelized in a cube with 256 voxel each side (2563 voxel in total, 1 mm^3 each) or 1283 voxels, 2 mm^3 each; two different resolution is used in order to enhance each forward model performance. The interesting tissue types are immerged into air (tissue type 0). The optical properties are lined out in the below table

Tissue Type	Scattering coefficient [mm^{-1}]	Absorption coefficient [mm^{-1}]
Scalp and Skull	0.86	0.019
CSF	0.001, 0.01, 0.1, 0.2, 0.3, 0.7, 1.0	0.004
Brain	1.11	0.01

Optical properties of the adult head model



MRI segmented 3D head model: display of the probe

We use a 3D head model from MRI data and we define a sub-region of 81 mm^3 starting at the single source is cropped out of an air tissue type background in order to reduce the size of the head and reduce the computational cost. We use index of refraction n = 1 and scattering anisotropy g = 0.01.

Let's call:
Model 1 the adult head model where CSF μ_s is 1.0 mm^{-1} and the remaining optical properties are as in the optical properties table.
Model 2 the adult head model where CSF μ_s is 0.1 mm^{-1} and the remaining optical properties are as in the optical properties table.

3. Results and discussion

We run several tests (such as Partial Optical Path length Factor (PPF) in time domain and continuous wave, Temporal Point Spread Function, Spatial Sensitivity Profile) using Monte Carlo simulation in order to investigate the importance of a good characterization of CSF reduced scattering coefficient.

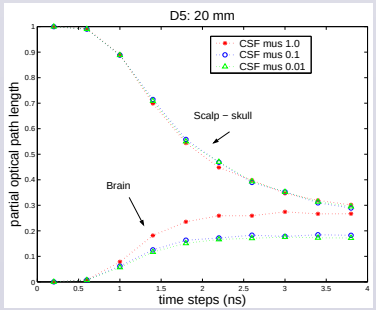


Fig. 1

Comparison of MC PPF in TD. **Difference between CSF scattering 0.001 and CSF scattering 0.1 is small (green and blue lines).** Noticeable difference in the brain when we choose a too large (non effective, i.e. larger than 0.3) scattering for CSF.

Relationship between fluence and changes in CSF scattering coefficient: small changes are observed for μ_s changes up to 0.3 mm^{-1}.

This test prove our point that if we change CSF μ_s within the effective value (i.e. inverse of tissue thickness) the fluence will not be greatly affected.

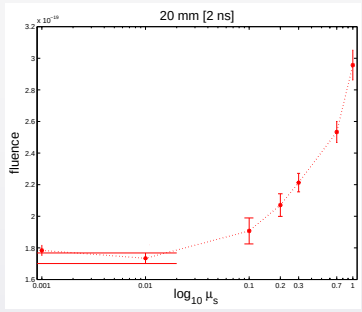


Fig. 2

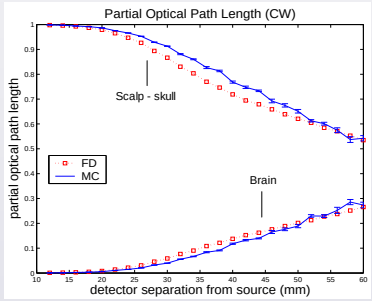


Fig. 3

PPF plot in CW [Fig. 3]. **Qualitatively the discrepancy between MC and FD appears small.** PPF is calculated using $\Delta\mu_a$ 0.001 mm^{-1}.

PPF CW quantitative plot. Relative sensitivity to absorption changes in scalp and skull [Fig. 4a]. The plot shows that **where MC SNR is strong enough (small error-bars) the percentage discrepancy between MC and FD is very small.**

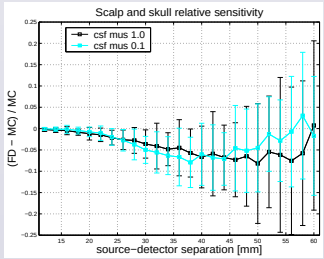


Fig. 4a

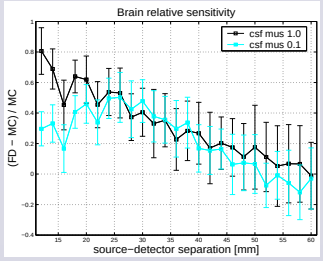


Fig. 4b

Error bars shown in Fig.6 and Fig.4 display the standard error calculated combining 11 independent MC run, each one simulating one hundred million photons.

PPF CW quantitative plot. Relative sensitivity to absorption changes in the brain [Fig. 4b]. Larger error-bars due to weaker signal reaching deeper tissues. **Larger discrepancy between MC and FD at small separation.**

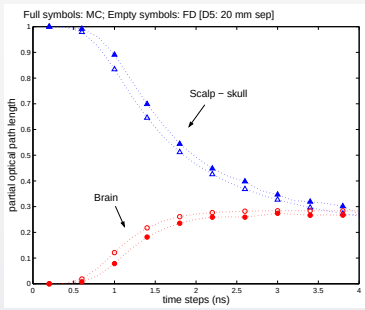


Fig. 5

PPF in TD for scalp-skull and brain. **FD is less sensitive to absorption changes in the brain than MC** [Fig. 5]. The question is: how big is this difference?

To answer such question we calculate the relative sensitivity to absorption changes in each tissue type.

In the brain FD and MC measure little disagreement at later time [Fig. 6a]. At early time the signal is zero: no photons coming from the brain have been yet detected.

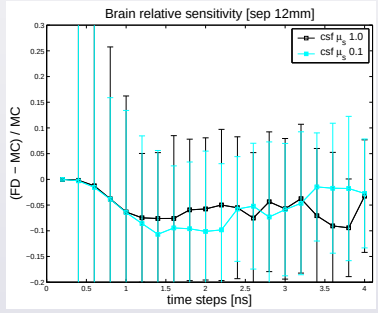


Fig. 6a

Quantitatively, **MC and FD exhibit little disagreement in sensitivity to absorption changes in scalp and skull at later time** [Fig. 6b]. At early time sensitivity of the two methods is small due to weak signal.

The discrepancy measured is almost always within the error bars.

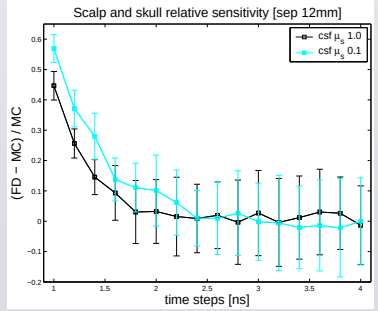


Fig. 6b

4. Conclusions

The data collected prove that the presence of CSF is important in an accurate head model but its scattering coefficient will not greatly affect Monte Carlo predictions if varying between 0.3 and 0.001 mm^{-1} (for a CSF layer not thicker than 4 mm).
Through qualitative and quantitative studies we established the limits of FD predictions and the constraints under which we can rely on FD. Comparing the Time Domain (TD) data versus the Continuous Wave (CW) we observe that the former are overall better than the latter because when integrating over time to calculate CW we are penalized by early times and late times outliers mostly due to poor SNR (signal detected at deep tissues like brain is weak) and diffusion inaccuracy at early times.

Acknowledgment

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