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A Novel Monte Carlo Approach for Diagnostic Fiber Optic Probe Design

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Abstract: A radiative transport method based on efficient coupled forward-adjoint Monte Carlo simulations is used for the analysis of diagnostic fiber optic probes. Results are shown for various probe geometries within a layered tissue model.

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Within biomedical optics there is great interest to use fiber optics to probe superficial tissue structures on sub-millimeter length scales. The propagation of light in such mesoscopic tissue volumes, results in radiant profiles that possess highly anisotropic angular distributions. Thus conventional analysis based on the diffusion approximation to the radiative transport equation (RTE) is not applicable [1]. Diagnostic probes are employed to differentiate or isolate signals from specific volumetric tissue regions. Therefore, for the design of fiber optic probes, we are interested in mapping tissue sub-volumes from which a diagnostic signal originates. This spatial distribution of the detected signals origin defines an interrogation tissue volume and can be used to characterize fiber optic probe efficacy.

Utilizing reciprocity of the RTE, simulations are conducted from both the source (forward) and detector (adjoint) fibers. Interrogation maps are formed from these simulations using a surface coupling technique [2] with volume elements (voxels). Because the light field displays angular anisotropy, the surface of each voxel must be further discretized in angle. Mathematically the interrogation probability for each voxel is given by:

$$P\left(V \cap D\right)_{voxel} = \sum_{i=1}^{6} \sum_{j} \sum_{k} L_{i,j,k} \, J^{\star}_{i,j,k} \, \Delta A_i \, \Delta\mu_j \, \Delta\phi_k \qquad (1)$$

where $L_{i,j,k}$ is the forward radiance and $J^{\star}_{i,j,k}$ is the adjoint current passing the interface. Each simulation tallies the contributions to the (i, j, k) spatial angular bin.

Using this technique we have studied homogeneous and layered tissue geometries, exploring the impacts of source-detector separation, numerical aperture, and angle on the volume of tissue probed. Moreover, the impact of space-angle discretization of the tissue volume on the accuracy of the results is examined.

References

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