3-D Image Reconstruction in Optical Tomography

Xiaochun Yang and Berthold K.P. Horn

The Problem: Optical tomography (OT), as a potential diagnostic tool for detecting growths in translucent soft tissue, has been proposed and studied by several groups in recent years. Its principle is to use multiple movable light sources and detectors attached to the tissue surface to collect information on light attenuation, and to reconstruct the internal 3-D absorption and scattering distributions. Unusual growths inside the tissue may be discerned from the recovered optical densities because tumorous tissue has different scattering and absorption properties.

Our goal is to develop algorithm to image the otherwise inaccessible scattering and absorption distribution inside the illuminated tissue. To provide the necessary data, we also need to design suitable information collection strategies, and explore the underlying mathematics of our model for the scattering and absorption process. We also hope to delimit the circumstances in which this inverse problems is reasonably well-posed.

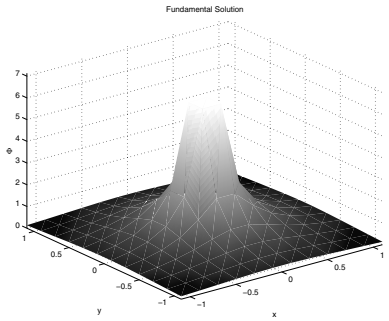
Motivation: Experiments have shown that visible and near infrared light, though highly attenuated, however detectable can travel through soft biological tissues, e.g. human brain and breast. Its non-invasiveness, low cost, non-ionizing nature, safety, and the potential clinical applicability brought by the current state of the art in instrumentation and large scale computation make it well worth continued and focused efforts aimed at advancing to a higher level of technical maturity.

Previous Work: The physical modeling in describing photon traversing through tissue-typed media is the diffusion model derived from the general radiative transport theory. Consideration of time dynamics adds an extra dimension to the problem and allows many different photon-measurement schemes and thus various image recovery methods to be derived.

Much pioneering work has been done by Simon Arridge and his group in this area. Theoretical work includes analytical formulation of the photon-measurement density function (PMDF) in some simple geometries [1]. Their tomographic reconstruction is implemented on a finite element grid where they use the iterative nonlinear gradient descent method to estimate the true absorption and scattering coefficients by minimizing the residue norm [2].

The most extensive survey on the development of optical tomography can be found in [3]. However, due to the mathematical difficulty in handling the severe ill-posed nature of the inverse problem, reconstruction algorithm remains inaccurate and computationally very expensive. So far no regularization scheme has been adapted to the 2-D or 3-D anatomical image data structure. The problem of experimental design waits for close investigation.

Difficulty: When compared with Computed Tomography, Magnetic Resonance Imaging, Position Emission Tomography and ultrasound imaging, OT reconstruction encounters certain difficulties because photon density drops fast as light travels away from the source. This is characterized by the governing equation. The rapid attenuation of the light can make reconstruction problems ill-posed, and make it hard to obtain good signal-to-noise ratios in measurements.



Fundamental Solution of the Diffusion Equation $-\nabla \cdot (\mu_d \nabla \Phi) + \mu_a \Phi = f$ *in Homogeneous Media*

Also, the physics of scattering and absorption bear a fair amount of similarity at the microscopic scale. Intuitively, a slab of material may be highly absorptive overall either because it just has a high coefficient of absorption, or because high scattering prevents the photons from leaving the volume as rapidly, thus increasing their chance of being absorbed. Thus separating the contributions to the light attenuation due to spatial variations in scattering and absorption properties is intrinsically difficult. This topic is given particular considerations in literature and it has been suggested that investigation of the time resolved photon migration may lead to a resolution. However, this technique requires extremely sensible source and detector, causing excessive cost to the entire system.

Approach: We will focus on the steady state source to detector approach — in part because of its very much simpler instrumentation requirements. As we notice the distribution of photon flux is sensitive to the ratio of the absorption coefficient μ_a and the diffusion coefficient μ_d, but not as sensitive to changes in the scattering and absorption that leave this ratio constant. It is the recovery of this ratio — based on the assumption that diffusion coefficient varies smoothly — lies at the core of our recent study.

A resistive circuit model has been used to simulate the physics of photon migration in the tissue-typed media in some simple geometries. The absorption and scattering coefficients are mapped to the horizontal and grounding conductances. We treat the tomographic reconstruction as a statistical parameter estimation problem. Parameters are chosen to minimize the misfit of the predictions and the observations. Our generalized EM-algorithm is a Bayes approach capable of incorporating the prior knowledge about the tissue image of interest. The special handling of the multi-response variable enhanced the regularization performance because the parameters to be estimated are able to preserve their high dimensional data structure and neighboring coherence. A prior information could be obtained from some other imaging modality, i.e. MRI. Via this simple circuit model, we could study what finite set of experiments and measurements lead us to a higher resolution. It suggests that certain oscillating behavior in the incoming pattern can greatly improve the conditioning of the inverse reconstruction. The current implementation support numerical simulation in rectangular, circular, cubic, spherical and cylindrical objects on regular tessellation.

We are extending our work to a finite element grid in order to handle more complicated geometries and the internal interfaces caused by the discontinuities in the optical property within the tissue. The grid is adaptive and reflects the anatomical structure of the tissue. This is being achieved iteratively by finite element error analysis.

Future Work: More tests should run against the available analytical results. Further study in experimental design, improving the resolution at the center of the object and the recoverability of both absorption and scattering coefficients are desired, as well as the effective computational techniques.

References:

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[3] .A. Benaron, G. Muller, B. Chance, *Medical perspective at the threshold of clinical optical tomography*, Medical Optical Tomography: Functional Imaging and Monitoring, SPIE Vol. IS11, 1993. pp. 3-9