

Wave optical simulation of optical imaging using experimentally acquired sample refractive index maps

En Lu¹, Paweł Ossowski², Szymon Tamborski², Brendan F. Kennedy², Dhani Tracey-White³, Colin J. Chu³, Marinko V. Sarunic^{1,3}, Silvia Cipiccia¹, Maciej Szkulmowski², and Peter R.T. Munro¹

¹Department of Medical Physics and Biomedical Engineering, University College London, UK

²Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziadzka 5, 87-100 Toruń, Poland

³Institute of Ophthalmology, University College London, UK

ABSTRACT

Simulation of light propagation in biological tissue is gaining importance in understanding how biological tissues scatter light and in interpreting optical images of such tissues. The development of light scattering simulation techniques, which include finite element, finite difference and volume integral methods, has remained advanced relative to the acquisition of three-dimensional refractive index distributions of biological tissues. Such refractive index distributions are required for light propagation simulations to obtain new insight into scientific and medical applications. Until the recent development of robust implementations of optical diffraction tomography, there has been a relative scarcity of such data. In this talk we demonstrate how advanced optical modelling, in combination with advanced refractive index models of mouse retina, can be used to simulate optical coherence tomography image formation of mouse retina. We will investigate whether such data, which still has resolution limited by the optical diffraction limit, contains sufficient information to generate realistic optical coherence tomography images.

Keywords: Optical Coherence Tomography, Simulation, Maxwell's Equations, Numerical Modelling, Optical Microscopy, Quantitative Phase Imaging

1. INTRODUCTION

Simulation offers a practical alternative where experiment may be infeasible or even impossible. For instance, accurately predicting the formation of optical coherence tomography (OCT) images for three-dimensional refractive index distributions is highly relevant. A realistic model of OCT image formation, based on three-dimensional solutions of Maxwell's equations, has numerous potential applications. For example, it enables exploration of image formation for features that are near or below the resolution limit of an OCT system, facilitates solving inverse scattering problems without relying on the first-order Born approximation, and offers a reliable benchmark for verifying various quantitative techniques.

The finite-difference time-domain (FDTD) and pseudo-spectral time-domain (PSTD) methods show promise for simulating OCT image formation. One reason for this is their ability to simulate light scattering for all wavelengths in the spectrum simultaneously. A number of such models, including our own, have been reported.¹⁻⁵ These models, however, require a three-dimensional refractive index map of the sample refractive index. There are multiple challenges associated with acquiring such a model, which include the need to acquire such a map with resolution potentially at or below the optical diffraction limit and the impossibility of doing so in vivo. As a first step towards achieving this goal we have acquired a three-dimensional map of the refractive index of fixed mouse retina. We have used this map to simulate image formation of an OCT B-scan. In this talk we will use this simulated B-scan to investigate the realism of the refractive index map.

Further author information: Send correspondence to p.munro@ucl.ac.uk

2. THE MODEL

Simulations of image formation are performed using the Time Domain Maxwell Solver (TDMS).⁶ TDMS includes illumination⁷ and detection⁸ models, integrated into the FDTD and PSTD methods and is thus highly flexible. The FDTD and PSTD methods account for the bulk of the computation as they calculate how light is scattered by the sample. The PSTD method is, in general, preferred to the FDTD method for OCT simulations due to the need to simulate sample spaces which are large compared with the wavelength of light. This is because the PSTD method uses the discrete Fourier-transform to evaluate the spatial derivatives of fields as: $f'(x) \approx \mathcal{F}^{-1}\{ik\mathcal{F}\{f(x)\}\}$, where \mathcal{F} and \mathcal{F}^{-1} are Fourier and inverse fast Fourier transforms, respectively, k is the reciprocal Fourier variable associated with x and i is the imaginary unit. This approach enables the PSTD to employ a spatial grid sampled at near the Nyquist limit of $\lambda/2$. The PSTD and FDTD methods both have the advantage of being broadband, meaning that all frequencies of interest can be calculated in a single simulation, significantly reducing the computational burden.

3. EXAMPLE

Figure 1 shows an example of a simulated OCT image of mouse retina, including the magnitude of the focused beam propagating through the sample (a), an example spectrometer current (b), the associated A-scan magnitude (c) and a B-scan (d). This example is sub-optimal since the axial resolution is of the order of $10 \mu\text{m}$, which is larger than would ordinarily be used to inspect mouse retina.

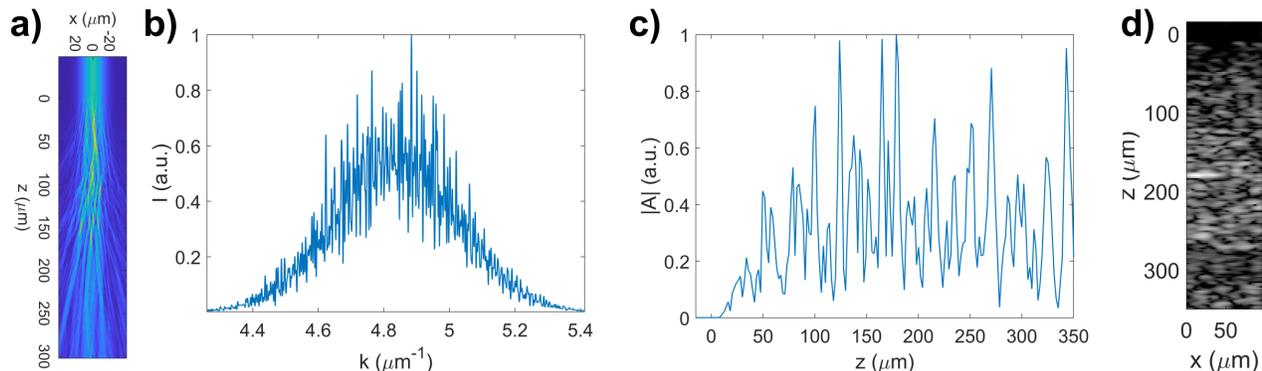


Figure 1. Images illustrating different outputs of the TDMS model used to simulate B-scan formation. In particular, a) shows the field magnitude of a focussed beam propagating through a retina; b) shows the spectrometer signal as a function of wavenumber; c) shows the A-scan magnitude corresponding to a) and b); d) shows a B-scan shown on a log scale.

4. CONCLUSIONS

We have demonstrated how realistic retinal OCT B-scans can be simulated using experimentally acquired refractive index maps and the open-source TDMS software package (<https://github.com/UCL/TDMS>).

REFERENCES

- [1] Brenner, T., Munro, P. R. T., Krüger, B., and Kienle, A., *Sci. Reports* **9**, 12189 (2019).
- [2] Brenner, T., Reitzle, D., and Kienle, A., *J. Biomed. Opt.* **21**, 45001 (2016).
- [3] Munro, P. R. T., Curatolo, A., and Sampson, D. D., *Opt. Express* **23**, 2541–2556 (2015).
- [4] Munro, P. R. T., *Opt. Express* **24**, 27016–27031 (2016).
- [5] Wang, Z., Zhang, Y., and Hsu, C. W., <https://doi.org/10.48550/arXiv.2308.07244> (2023).
- [6] Munro, P. R. T., Cunliffe, S., Giordano, M., Graham, W., Kriezis, E., Török, P., and Young, T., 10.5281/zenodo.7950604 (2023).
- [7] Munro, P. R. T., *J. Biomed. Opt.* **23**, 1 (sep 2018).
- [8] Munro, P. R. T., *Opt. Express* **23**, 30603–30617 (2015).