Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2014 February 1; 8931: . doi:10.1117/12.2040200.

Diffuse optical tomography using multichannel robotic platform for interstitial PDT

Anna V. Sharikova^{*}, Xing Liang, and Timothy C. Zhu

Dept. of Radiation Oncology, University of Pennsylvania, 3400 Civic Center Blvd, Philadelphia, PA USA 19104

Abstract

In the operating room, time is extremely precious, and the speed of one's data acquisition system often determines whether the data will be taken or not. Our multichannel robotic platform addresses this issue by optimizing source and detector scanning procedures. Up to 16 fibers can be moved independently with resolution of 0.05 mm and speed of 50 mm/s using motors with position feedback. The initial fiber alignment employs a light beam/optical detector system for identical positioning of all motors. Peak and edge detection algorithms, for point and linear sources, are used with multiple fibers simultaneously for fast realignment of sources and detectors. The robotic platform is used to perform Diffuse Optical Tomography (DOT) measurements in solid prostate phantoms with both homogenous and inhomogeneous Optical Properties (OP). Correct positioning is critical for the accurate recovery of the OP. The light fluence rate distribution is determined by scanning multiple detector fibers simultaneously along lit linear sources placed throughout the phantom volume inside catheter needles. The scanning time for the entire DOT is about 10 seconds after the initial alignment. The OP distribution reconstruction is based on the steady-state light diffusion equation. The inverse interstitial DOT problem is solved using NIRFAST. The optical properties are recovered by iterative minimization of the difference between measured and calculated light fluence rates. Recovered OP agree with the actual values within 10%. The OP corrections are used to significantly improve light fluence accuracy for the entire volume of bulk tumor.

Keywords

photodynamic therapy; dosimetry; robotic platform; diffuse optical tomography; PDT; DOT

1. INTRODUCTION

Photodynamic therapy (PDT) is a treatment modality for localized diseases, most notably cancer. The treatment light, usually from a visible or near-IR laser source, excites a photosensitizer administered to a patient prior to PDT treatment, and photosensitizer interacts with ground state oxygen ($^3\text{O}_2$) to generate a cytotoxic molecule: singlet oxygen ($^1\text{O}_2$). The singlet oxygen then destroys nearby cells¹.

During the interstitial PDT, the source and detector fibers are inserted into catheters placed inside a prostate using a template. The target volume must receive the prescribed amount of light fluence. The robotic platform, being a second generation clinical scanner²⁻³, allows fast delivery of a uniform PDT light dose through optimized source positioning and continuous dosimetry during treatment.

Optical properties of tissues (absorption and scattering) play a major role in light fluence distribution. That, in turn, determines the treatment dose delivered to each point, and, therefore, treatment efficacy. The OP values depend on the patient and the site, and their distributions must be measured swiftly and dependably in clinical treatment. Since the source and detector fibers move in a coordinated fashion when robotic platform is utilized, the entire measurement set can be done in a fraction of a minute⁴.

The solution to the inverse diffuse optical tomography (DOT) is based on diffusion equation and utilizes adjoint model. The DOT reconstruction algorithms⁵⁻⁶ for the OP calculations are using NIRFAST code⁷⁻⁸ customized for the interstitial case.

The spatial distributions of absorption and reduced scattering coefficients in tissue-mimicking phantoms were determined based on the light fluence distribution produced by linear source fibers spaced uniformly throughout the phantom volume.

2. METHODS AND MATERIALS

2.1 Multichannel robotic platform

The robotic multichannel platform^{3,9} developed in our lab has 16 independently operating channels, each equipped with encoder feedback and interchangeable fiber holder (Fig. 1). Positioning resolution is 0.05 mm, effective travel range is 200 mm, and maximum speed is 50 mm/s. An optical diode and receiver system allow automatic home position alignment.

Automated motor control routines implemented in VB6 include home positioning, travel limits, detector scanning range adjustment, and detector and source alignment for OP scanning among others. Fig. 2 shows how detector scanning range adjustment results in source position alignment for multiple detectors.

2.2 Phantoms

Phantoms used in our experiments were designed to imitate typical optical properties of tissues. Solid PVC inclusions¹⁰ were used to introduce inhomogeneities in the uniform liquid phantom (Fig. 3). The optical properties of the phantoms are summarized in Table 1. The first phantom is liquid without any inclusions, and the second one has two inhomogeneities.

2.3 DOT algorithm

Diffuse optical tomography was used to determine spatial distribution of absorption and reduced scattering coefficients from the fluence rate distribution produced by linear source fibers. NIRFAST freeware has been used to solve the inverse problem for the interstitial DOT, which is based on the steady-state light diffusion equation:

$$\mu_a(\vec{r})\Phi - \nabla(D(\vec{r})\nabla\Phi) = S \quad (1)$$

where μ_a is absorption coefficient, D is diffusion coefficient, Φ is the photon fluence rate, and S is an isotropic source term. In Finite Element Formalism (FEM), fluence Φ is represented by a piecewise continuous polynomial function⁷. The inverse problem is concerned with recovery of optical properties at each FEM node within the domain using measurements of light fluence. It is achieved by iterative minimization of the difference between measured and calculated light fluence. The first iteration calculates light fluence based on the initial OP values, while consequent steps employ Jacobian matrix calculated via adjointed method⁷⁻⁸:

$$(J^T J + \lambda I)^{-1} J^T \delta\Phi = \delta\mu \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Total light fluence

The total light fluence rates at detector positions for a homogeneous and inhomogeneous phantom are shown in Fig. 4.

The difference is most drastic for detector points inside inhomogeneities, where fluence rate is decreased by roughly an order of magnitude. Since achieving prescribed PDT dose within entire treatment volume is critical for the efficacy of the treatment, locating such inhomogeneities during treatment and adjusting light dose accordingly should have significant effect on PDT treatment.

3.2 Phantom optical properties

A mesh generated for the phantom inverse DOT is shown in Fig. 5. It includes different OP settings for “normal tissue” and heterogeneities, as well as source and detector locations. The distribution of optical properties through the center of inhomogeneities in two different planes is shown in Figs. 6 and 7. The values of absorption coefficient are reconstructed accurately within 10%.

4. CONCLUSION

The robotic multichannel platform is faster than dual motor system (less than 1s for a single OP scan), has home location accuracy within 0.1 mm, and repeated measurements agree within 0.3%. The optical properties measurements agree with dual motor data within uncertainty⁹.

The ability to separate absorption and scattering coefficients depends on the accuracy of the light fluence source measurement. We have observed the difference between initial and reconstructed fluence rates to be within 10%. DOT allows reliable recovery of the absorption coefficients.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Hamid Dehghani for revising NIRFAST code to accommodate finite length fiber sources, and both Dr. Brian Pogue and Dr. Dehghani for providing the NIRFAST software. We thank Dr. Jarod Finlay for help with Robotic platform code modifications and Dr. Andreea Dimofte for help making and measuring phantoms. This work is supported by NIH grants P01 CA87971 and R01 CA154562.

REFERENCES

1. Brown SB, Brown EA, Walker I. The present and future role of photodynamic therapy in cancer treatment. *The Lancet Oncology*. 2004; 5(8):497–508. [PubMed: 15288239]
2. Zhu TC, Dimofte A, Finlay JC, Stripp D, Busch T, Miles J, Whittington R, Malkowicz SB, Tochner Z, Glatstein E, Hahn SM. Optical properties of human prostate at 732 nm measured in vivo during motexafin lutetium-mediated photodynamic therapy. *Photochem. Photobiol.* 2006; 81:96–105. [PubMed: 15535736]
3. Sharikova AV, Finlay JC, Dimofte A, Zhu TC. A robotic multichannel platform for interstitial photodynamic therapy. *Proc. SPIE*. 2013; 8568 85680Q1-Q6.
4. Hu Y, Finlay JC, Zhu TC. The design of a robotic multichannel platform for photodynamic therapy. *Proc. SPIE*. 2009; 7380:491–4911.
5. Arridge SR, Schweiger M. Photon-measurement density functions. Part 2: Finite-element-method calculations. *Appl. Opt.* 1995; 34:8026–8037. [PubMed: 21068901]
6. Liang X, Wang KK, Zhu TC. Characterization of tissue optical properties for prostate PDT using interstitial diffuse optical tomography. *Proc. SPIE*. 2012; 8210 0C1-0C8.
7. Dehghani H, Eames ME, Yalavarthy PK, Davis SC, Srinivasan S, Carpenter CM, Pogue BW, Paulsen KD. Near infrared optical tomography using NIRFAST: Algorithm for numerical model and image reconstruction. *Communications in Numerical Methods in Engineering*. 2009; 25:711–732. [PubMed: 20182646]
8. Jermyn M, Ghadyani H, Mastanduno MA, Turner W, Davis SC, Dehghani H, Pogue BW. Fast segmentation and high-quality three-dimensional volume mesh creation from medical images for diffuse optical tomography. *J. Biomed. Opt.* 2013 Aug 12;18(8) 086007.
9. Sharikova AV, Finlay JC, Liang X, Zhu TC. PDT dose dosimetry for pleural photodynamic therapy. *Proc. SPIE*. 2013; 8568 8568-39.
10. Spirou GM, Oraevsky AA, Vitkin IA, Whelan WM. Optical and acoustic properties at 1064 nm of polyvinyl chloride-plastisol for use as a tissue phantom in biomedical optoacoustics. *Phys. Med. Biol.* 2005; 50:N141–N152. [PubMed: 16177502]

Figure 1.
Robotic 16-channel platform.

Figure 2.
Automatic range adjustment.

Figure 3.
Liquid phantom with PVC inhomogeneities.

Figure 4.
Light fluence rates at detector positions for homogeneous (left) and inhomogeneous (right) phantoms..

Figure 5.
"Prostate" phantom mesh.

Figure 6.
Distribution of optical properties through the center of inhomogeneities in x-y plane (mm⁻¹).

Figure 7. Distribution of optical properties through the center of inhomogeneities in y-z plane (mm⁻¹).

Table 1

Phantom optical properties.

Optical propereties	Liquid phantom	First inhomogeneity	Second inhomogeneity
μ_a, mm^{-1}	0.03	0.05	0.09
μ_s', mm^{-1}	0.7	1.5	1.5