Source and detector fiber optimization for depth sensitivity in endoscopic near infrared tomography

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Abstract: NIR optical tomography in endoscopic imaging geometry is a novel technique for non-invasive tissue-specific cancer detection in internal organs. The arrangement of source and fiber detection system is an important aspect in maximizing depth sensitivity in particular for axial imaging. This study demonstrates that using multiple arrays of fibers within an elliptic shaped probe increases depth resolution as compared to single array of fibers within a cylindrical shaped probe.

OCIS codes: (170.6960) Tomography; (100.3010) Image reconstruction techniques; (100.3190) Inverse problems

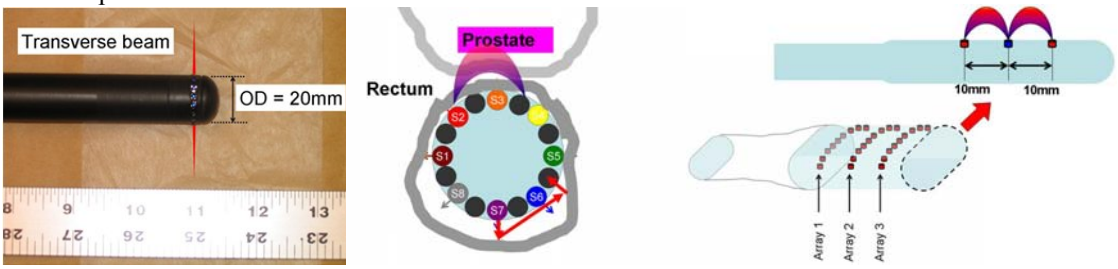
1. Introduction

Near-infrared (NIR) optical tomography is a non-invasive functional imaging technique that has shown the potential of acquiring unique tissue-specific functional contrast by using tomographic measurement of NIR attenuation within tissue. The high contrast of NIR optical tomography originates from the stronger light attenuation of hemoglobin relative to water in parenchymal tissue at the 650-900 nm range, as well as the distinct spectral differences of hemoglobin between the oxygenated and deoxygenated states. Contrast as high as 300 percent has been demonstrated in NIR tomography for vascular densities of only 2 percent [1]. Such high blood-based contrast allows pathognomic diagnosis of increased vascularity in malignant tissues and hemodynamic imaging of tissue function and physiology.

Over the past two decades, NIR optical tomography has been advanced steadily by investigating and clinical testing of key applications in the characterization of breast cancer [2], the assessment of brain functionality [3] and the evaluation of extremity abnormality [4]. The majority of applications to date have focused on using external applicator arrays. Specifically, most applications have used a method by which NIR light is directed into tissue using optical fibers at the external surface of the imaging volume and measuring the emitting light at other points on the same surface using either seperate fibers or a non-contact imaging detector array. The potential of imaging internal organs like prostate has driven the growing interest that extends NIR optical tomography to endoscopic or transrectal geometries. The key factor in attempting NIR tomography of internal organs has been the development of appropriate applicator arrays. Recently, novel applicator array was constructed and demonstrated as an NIR optical tomography system that allows two dimensional (2D) NIR contrast mapping of internal organs using a non-invasive internal interrogation [5]. The technique incorporates a broadband light source with spectrometer-based detection. The broadband light that disperses with a grating and passes a collimating lens forms a one-dimensional linear distribution of the source spectrum, which is coupled to the tissue by linearly aligned fibers. The fibers are arranged into a circular geometry inside an endoscope probe, Figure 1(a) and (b), where either a coated cone prism or a set of microoptics assembly is used for circumferential light deflection. The wavelength separation coupled to each fiber generates spread-spectral-encoding of the illumination over to the tissue, which accommodates concurrent sampling of all source-detector pairs when using a spectrometer and CCD in the detection. This design enables both the probing in transrectal geometry and the rapid sampling for NIR optical tomography.

Imaging in trans-rectal geometry gives little flexibility to the placement of optodes when axial imaging is aimed for. Little work has been done to investigate the optimum arrangement of the optodes for the excitation and detection of the NIR signal, within the compact transrectal geometry. The current method uses a cylindrical design with 8 sources and 8 detectors placed uniformly around a single ring of the probe, Figure 1. Upon the excitation of tissue using the sources (S in Figure 1(b)), measurements are made at all 8 detectors, simultaneously, to reconstruct cross-sectional images of optical perturbations within the region being imaged. One limitation that may exist with this 2D single plane measurement scheme is in the depth resolution and sensitivity. It is therefore important to investigate the merits and benefits of using multiple plane source and detection arrays, mounted within the cylindrical probe to assess any improvement possible in depth sensitivity of the measured signal.

In this work, sensitivity analysis of multiple detection systems in terms of increasing the number and configuration of source / detect arrangements will be investigated for the current cylindrical probe, in three dimensions (3D) as well as exploring the use of non-cylindrical, elliptic probe designs that may offer alternative improvements in depth resolution.



(a) **(b)** **(c)**

Figure 1. (a) The cylindrical transrectal probe and (b) 2D cross-section showing the source and detector arrangements. (c) proposed elliptical probe design consisting of either a single layer of source and detectors in a single array, or two array of detectors with a single array of sources in between.

2. Methods

The first probe design cylindrical shape is shown in Figure 1(a) and (b). This probe is modeled as a cylinder of length 40mm (-20mm ≤ z ≤ 20mm) with inner radius 10mm and outer radius 20mm. Two different data collection strategies are considered: (a) 8 sources and 8 detectors distributed evenly in a single ring of fibers at z = 0 mm and (b) three separate rings of 8 sources and 8 detectors, at z = 0 mm, 10 mm and -10 mm. In this case, the depth of tissue modeled as surrounding the probe is set at 10 mm. This design is better suited for imaging through a lumen that can enclose the probe completely without much airgap between the probe surface and surrounding tissue.

The second probe design, shown in Figure 1(c) is an elliptical shaped probe. The probe is an elliptical cylinder of length 40mm (-20mm ≤ z ≤ 20mm) with major radius 20mm and minor radius 10mm surrounded by a cylindrical mesh of radius 30mm. This design of placing the arrays of sources and detectors on just one side of the probe is better fitted to imaging prostate through rectal wall. The three arrays have a longitudinal separation of 10mm and placed along the minor axes at positions z = -10 mm, z = 0 mm and z = 10 mm about x = 0 mm. Two different data collection strategies are considered: (a) 5 sources and 4 detectors interleaved in a single line (Array 2 in Figure 1(c)), and (b) three separate rings of 8 sources (Array 2) at z=0mm and 8 detectors (Array 1 and 3) at z =10 mm and -10 mm. In this case, the depth of tissue modeled as surrounding the probe is set at 20 mm in the short axis and 10 mm in the long axis. The angular separation of each channel in both cases is 8º. The accuracy of diffusion approximation can be maintained for array setup of (b), while it may be comprised in array setup of (a).

To simulate the propagation and hence the sensitivity of the NIR signal throughout the volume of interest, a finite element model is used for each probe design. The propagation of light within the surrounding tissue was calculated using the diffusion approximation and the total sensitivity of intensity data to absorption changes within the model, for all source and detector combination was calculated.

3. Results

The normalized total sensitivity of each probe design and fiber arrange strategy is shown in Figure 2. Note that for the cylindrical case the depth of tissue modeled as surrounding the probe is set at 10 mm, where as in the elliptic case the depth of tissue modeled as surrounding the probe is set at 20 mm in the short axis and 10 mm in the long axis. It is evident that by the use of a single array of fibers, the total sensitivity of measured intensity data to small changes in absorption rapidly decays as a function of distance away from the source and detector array. In each of the models, the maximum sensitivity is seen directly above the detector fibers and for the elliptical probe, the sensitivity is more uniform within the tissue being sampled.

In order to evaluate the increase in depth sensitivity, the cross sectional profile of the sensitivity as a function of depth was calculated for each of the models and is shown in Figure 3. It is seen that the use of multiple fiber arrays improves the depth sensitivity of both probe designs, with the greater depth seen using the elliptical probe. The use of elliptical probe with a single detection array does not provide additional depth sensitivity, whereas the addition of multiple arrays to the elliptical probe, not only increased the depth sensitivity, but also provides a more uniform sensitivity at lower decay rate as a function of depth.

4. Discussion

In this paper we have shown that for axial imaging geometry the use of an elliptic shaped probe together with 3 arrays of detection system improves the depth sensitivity of measured intensity signal to absorption changes

within the tissue being sampled. This increased sensitivity is crucial when designing a non-invasive axial imaging probe for endoscopic NIR tomography imaging of internal organs such as the prostate to detect and characterize abnormal lesions.

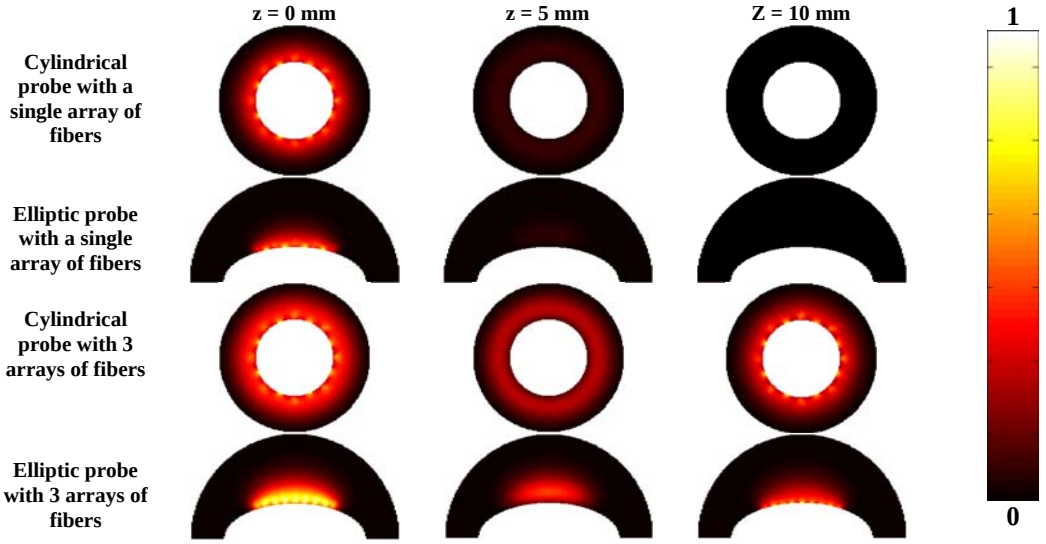


Figure 2. The normalized sensitivity of each probe design and fiber arrangement strategy. The images presented are coronal cross-sections of the 3D model at different sections. Note that for the cylindrical case the depth of tissue modeled as surrounding the probe is set at 10 mm, where as in the elliptic case the depth of tissue modeled as surrounding the probe is set at 20 mm in the short axis and 10 mm in the long axis.

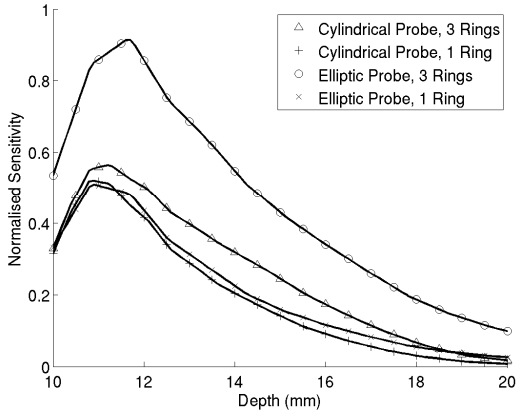


Figure 3. Cross sectional normalized sensitivity profile for each probe design as a function of depth

5. Acknowledgements

This work has been partially supported by Congressionally Directed Medical Research Program through grant PC060814.

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