Optimized Wavelength Selection and Normalization in Spectral Near Infrared Tomography

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Abstract: Multi-spectral near infrared tomographic imaging has the potential to provide information about patho-physiological function of soft tissue. However, the specific choice of wavelengths used is crucial for the accurate separation of such parameters. Determination of a set of optimized bands of wavelengths is presented and tested using experimental data. The optimization method achieves images as accurate as using the full spectrum, but improves cross talk between parameters. A Jacobian normalization technique is presented which takes into account the varying magnitude of different optical parameters creating a more uniform update within a spectral image reconstruction model.

OCIS codes: (100.3190) Inverse problems; (170.3660) Light propagation in tissues;

1. Introduction

Near Infrared (NIR) Diffuse Optical Tomography (DOT) is a non-invasive imaging tool used for the diagnosis and characterization of breast cancer [1] and quantifying brain function [2]. Typically in spectral DOT, NIR light between 650 nm and 950 nm is propagated through the tissue being imaged with the emerging *'boundary data'* used in a light propagation model to derive the functional parameters of hemoglobin, oxygen saturation, water content and scattering properties using a spectrally constrained image reconstruction approach [3]. It is accepted that using a continuous wave (CW) DOT system, whereby only the intensity of the NIR light travelling through tissue is measured, reconstructing optical absorption and scatter is non-unique. A method is presented to examine the viability of using large CW data sets containing many wavelengths to achieve a unique solution with a minimal cross talk between chromophores. Other tomographic studies have restricted spectral reconstruction to using small data sets (5 or 6 wavelengths) for image reconstruction due to technical limitations. Although using a small set will be computationally faster, the use of more wavelengths increases the amount of information available and is considered important in constraining the inverse problem further such that cross talk between chromophores can be reduced. However, to date, there has been little work into the investigation of an optimum set of wavelengths to provide a unique and well-conditioned solution, under the assumption that boundary data is available at all wavelengths between 650-930 nm.

The method proposed by Corlu et al [4] is used as the basis of the presented study. Rather than restricting the image reconstruction to the best 3 wavelengths which provide a better conditioned problem, a method is proposed which finds ranges, or 'windows', of wavelengths over the entire spectrum which contribute to producing highly conditioned and unique images. Additionally, optimization based image reconstruction in DOT utilizes the incorporation of a sensitivity (Jacobian) matrix that relates a small change in optical parameters within the imaging domain to small measurable changes in the boundary data. However, the magnitude and range of the sensitivity of different chromophore and scattering properties is varied and there has been little investigation of this effect on image reconstruction. In this work the Jacobian normalization method is investigated which attempts to overcome the low sensitivity seen for scattering parameters when reconstructing spectral images using a frequency modulated broadband system. A normalization technique is proposed which provides a more uniform update to the reconstructed chromophores which also removes hyper-sensitivity at the boundary and simplifies the required regularization. This method reconstructs images with higher qualitative and quantitative accuracy while removing image artifacts from the boundary.

2. Methods and Results

The choice of wavelengths for the spectral reconstruction is based on two considerations; (1) the absorption parameters must be separable from the scattering parameters and (2) the absorption chromophores must be separable from each other. These criteria have been established and are derived from Beer's law and a non-uniqueness proof for CW data [5]. These conditions provide two parameters that need to be optimized; (a) a residual which must be as large as possible to give a unique solution and (b) a condition number which must be as small as possible so that

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each chromophore has an equal contribution to the total absorption. Although this method has been formulated such that scattering amplitude can vary, it has been found difficult to reconstruct scatter power reliably using a CW system without additional information about NIR path-length in tissue. In this work, therefore, the assumption is still made that scatter power is known and kept at a constant.

Assuming that only 6 discrete wavelengths can be measured from the entire spectral range of 650 – 930 nm, with a separation of 4 nm (that is from a complete set of 71 wavelengths), there exists 1.4×10^8 combinations of '6 wavelengths sets'. Each set has a condition number and associated residual which is calculated using published values of extinction and scattering coefficients. In this work three chromophores have been assumed to vary (hemoglobin, oxy-hemoglobin and water) as well as the scatter amplitude, while scatter power is held constant and is equal to 1. A scatter plot of the calculated residual and condition number for each of these 1.4×10^8 combination '6 wavelength sets' have been calculated and are shown in Figure 1(a). Due to the large number of points, the results shown are limited to those sets with a residual above 0.35 and a condition number below 400. The sets of wavelengths of interest which provide the most adequate information about the problems are those in the proximity of the top left hand corner as these contain the sets which have the highest residual and lowest condition number.

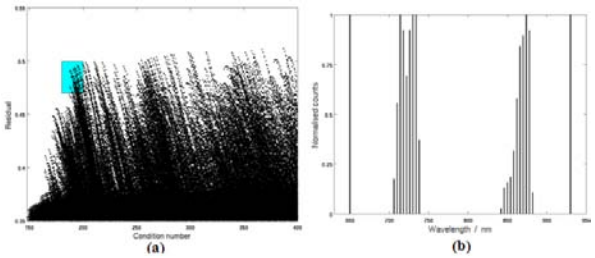

Figure 1. (a) Scatter plot of the residual and condition number calculated for 3 chromophores, hemoglobin, deoxy-hemoglobin and water. (b) Histogram of optimized wavelength.

Figure 1(b) shows a histogram of the distribution of optimal wavelength sets with high residual (>0.47) and low condition number (<200) criteria. The histogram is formed by counting the frequency that a particular wavelength appears for each of the six wavelength choices (or bins), normalized to the most frequently appearing wavelength for that specific bin. There are four clear spectral regions (or windows) which contribute to the high residual and low condition criteria and these are distributed around 650nm, 736nm, 874nm and 930nm. This shows that the wavelengths within the optimized sets which meet the residual and condition calculation are confined to narrow spectral windows. For a spectral model a larger number of wavelengths confines the inverse problem by reducing the ill-posed nature.

To test the feasibility of the optimization method for wavelength selection for an experimental system, measured data has been used in reconstruction of a simple gelatin based phantom. The cylindrical tissue simulation was designed with a radius 43mm and length 88mm. A cylindrical anomaly of radius 12.5mm is placed 25mm from the centre. The background hemoglobin concentration is 0.011mM while the anomaly has hemoglobin concentration of 0.027mM. Wavelengths between 690nm and 840nm with 5nm separation, excluding 760nm, were collected giving a total of 29 wavelengths using a frequency domain system incorporated with a mode locked Ti:Sapphire laser for the source between 690 and 850 nm wavelengths, described elsewhere [6]. Using the same method defined above windows of wavelengths of 695nm, 715nm to 735nm, 755nm, 765 to 770nm and 800nm to 810nm can be calculated as the wavelength set (12 wavelengths in total). Figure 2 shows the reconstructed images with the full spectrum (695nm to 840nm) denoted by 29 wavelengths, the windows method and a selection of 5 wavelengths from across the spectrum (700nm, 750nm, 800nm, 830nm and 840nm). The reconstructed images using 5 wavelengths show an overestimate in the total amount of Hb by 30% while the number artifacts is also high for SO_2, H_2O and scattering amplitude. This shows that a lack of information or non-optimized wavelength sets do not give accurate results. The reconstructed images using the full spectrum have reconstructed the total Hb qualitatively well while artifacts can be seen in the scattering amplitude. This could be because using the full spectrum in this case over-constrains the problem. The windows method reconstructed the peak in the Hb as well as reducing artifacts in the other images.

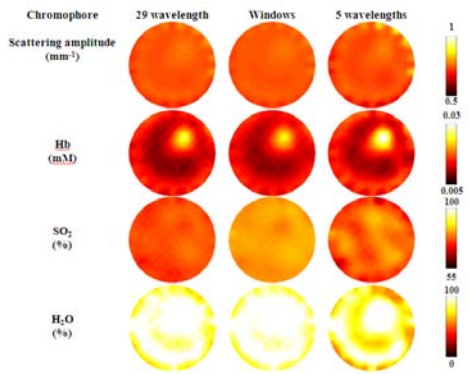

Figure 2. Reconstructed images with three different wavelength selections

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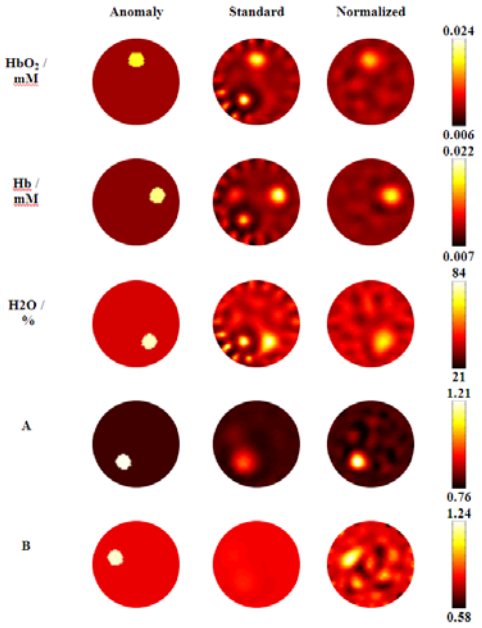

Figure 3. Reconstructed images with 1% noise.

To overcome the differences in the variation in sensitivity at each wavelength for each parameter, the Jacobian can be row and column normalized. This will ensure that the maximum sensitivity of each chromophore is normalized to unity as well as the sensitivity over all measurements. Pre-multiplying the Jacobian by a diagonal matrix **G** where each non-zero element is the inverse of the largest value in each column, the transformed Jacobian matrix has the form $\mathbf{J}_{CN} = G\mathbf{J}$ where $G_{j,j} = \frac{1}{\max(J_{i=1:nm,\,j})}$. Post-multiplying the normalized matrix by a diagonal matrix **F** where each non-zero element is the inverse of the maximum of each row of the column normalized matrix, the fully transformed Jacobian matrix has the form $\tilde{\mathbf{J}} = \mathbf{J}_{CN}\mathbf{F}$ where $F_{i,i} = \frac{1}{\max(J_{CN\,i,\,j=1:nn})}$ and the update equation becomes $\mathbf{F}\left(\tilde{\mathbf{J}}^T\tilde{\mathbf{J}} + \alpha\mathbf{I}\right)^{-1}\tilde{\mathbf{J}}^T G\delta\Phi = \delta\mu$. To study the effect of Jacobian normalization, simulations were carried out using a 2D circular model. Sixteen optical fibers are modeled equidistant from the centre of the mesh and were used for the data collection with a modulation frequency of 100MHz giving rise 480 measurements of phase and amplitude per wavelength. The background has a Hb concentration of 0.01 mM, a HbO_2 concentration of 0.01 mM, H_2O content of 40%, a scattering amplitude of 0.9 and a scattering power of 0.9. Anomalies are placed uniformly around the model of radius 7.5 mm as shown by Figure 3. Data was simulated using the forward model and random noise is added accordingly. It is found that the normalized method reconstructs images which are quantitatively and qualitatively more accurate than the non-normalized method. There are image artifacts around the periphery for the standard method for all absorption chromophores which are not present when using the normalization method. The reconstructed images using the standard method are qualitatively and quantitatively worse than the normalized method with more image artifacts and higher cross talk between chromophores. The standard method is particularly poor at reconstructing scattering parameters. The normalization technique reconstructs all chromophores and scattering parameters well with few image artifacts and smaller crosstalk. Similar is found for larger amounts of added noise.

3. Discussion

The use of large wavelength sets in NIR imaging can help optimize the inverse problem and are especially useful for systems where the magnitude of measurement noise is large. Using an optimized set of a small number of wavelengths is computationally more efficient and can provide unique images using continuous wave measurements. Reconstructed images have shown that by adequate optimization, the total number of required wavelengths can be reduced without loss to image quality or accuracy, but with the added advantage of reducing both data collection and image reconstruction time. A method to treat the Jacobian by row and column normalization has been presented which ensures that the sensitivity of each optical parameter to be reconstructed using multi-wavelength is of the same order of magnitude. Using this method, the regularization used within Newton-type optimization allows for comparable smoothing across all parameters within the image reconstruction, without having bias with respect to magnitude or range of the sensitivity.

4. Acknowledgements

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5. References

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