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The Photoacoustic Spectral Reconstruction Method

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Abstract

We describe a spectral approach for inversion of photoacoustic data with multi-wavelength pulsed laser illumination. Multi-spectral photoacoustic tomography (PAT) provides a means of recovery of different chromophore concentrations and ultrasound velocity simultaneously and directly by incorporating prior spectral information into the image reconstruction process. It is demonstrated from clinical experiments that the multi-parameter recovery based on multi-spectral PAT is reliable and accurate. The reconstructed multiple parameter images may provide us a key tool to quantify physiological function, disease progression, or response to intervention.

Keywords: PAT; Multi-spectral optical imaging; Reconstruction methods; Transducers

Introduction

Biomedical PAT is a potentially powerful modality that can offer high resolution structural and functional imaging of tissues [1-6]. In PAT, a short-pulsed laser source is used to irradiate the tissue of interest. The laser-produced temperature rise and subsequent thermo elastic expansion of tissues generate acoustic wave which is detected by ultrasound transducers along multiple boundary positions. A reconstruction algorithm is used to recover the photoacoustic (PA) images. In this study, we describe a new spectral approach that allows for direct simultaneous reconstruction of tissue chromophores and acoustic velocity using multiple-wavelength laser illumination. Due to the use of multiple laser wavelengths, this approach provides more accurate physiological parameter reconstruction, especially for acoustic velocity and direct recovery of functional parameters. We will demonstrate this multispectral PAT approach using *in vivo* experiments.

Photoacoustic Spectral Reconstruction Method

In multi-spectral PAT, frequency-domain Helmholtz wave equation in an acoustically heterogeneous medium is written in consideration of Beer's law equation, [4-7]

$$\nabla^2 p(r,\omega,\lambda) + k_0^2(1+O)p(r,\omega,\lambda) = ik_0 \frac{v_0\beta\sum_{i=1}^{3}\varepsilon_i(\lambda)c_i\phi(r,\lambda)}{C_p} \quad (1)$$

where c_i is the concentration and $\varepsilon_i(\lambda)$ is the extinction coefficient of the ith chromophore (HBO_2, HbR and H_2O) at wavelength λ. And the inverse solution can be obtained by solving the following equation:

$$(\boldsymbol{J}^T\boldsymbol{J} + \xi\boldsymbol{I})\Delta\chi = \boldsymbol{J}^T(\boldsymbol{p}^o - \boldsymbol{p}^c) \quad (2)$$

in which $\Delta\chi = (\Delta O_1, \Delta O_2, \cdots, \Delta O_n, \Delta c_{1,1}, \Delta c_{1,2}, \cdots, \Delta c_{1,n}, \Delta c_{2,1}, \Delta c_{2,2}, \cdots, \Delta c_{2,n}, \Delta c_{3,1}, \Delta c_{3,2}, \cdots, \Delta c_{3,n})^T$ is the update vector for chromophores and acoustic velocity; ξ is the regularization parameter determined by combined Marquardt and Tikhonov regularization schemes; $\boldsymbol{p}_i^o$ and $\boldsymbol{p}_i^c$ are measured and calculated data for i=1,2,…M boundary locations and are written as for each acoustic frequency ω within each incident optical wavelength λ,

$$\boldsymbol{p}^o = (p_1^o, p_2^o, \cdots, p_M^o)^T|(\omega,\lambda),\ \boldsymbol{p}^c = (p_1^c, p_2^c, \cdots, p_M^c)^T|(\omega,\lambda) \quad (3)$$

The Jacobian matrix, J is denoted as $\boldsymbol{J} = [\tilde{\boldsymbol{J}}_{O,\lambda,\omega}, \tilde{\boldsymbol{J}}_{c_i,\lambda,\omega}]$, where $\tilde{\boldsymbol{J}}_{O,\lambda,\omega}$ and $\tilde{\boldsymbol{J}}_{c_i,\lambda,\omega}$ represent the Jacobian submatrix for acoustic velocity and different chromophores, respectively.

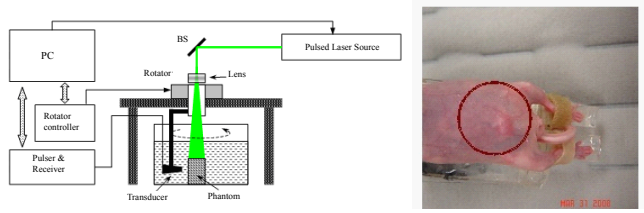

Figure 1: Schematic demonstration of our PAT system. BS: beam splitter; PC: personal computer (left); photograph showing the imaging region for a mouse with an implanted subcutaneous tumor (right).

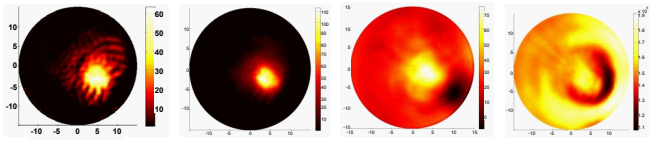

Figure 2: Reconstructed *in vivo* images of Hb (a), HbO_2 (b), H_2O (c) and acoustic velocity (d) from a mouse with a subcutaneous tumor.

Results and Discussion

In this section, we evaluate the multi-spectral PAT approach using small animal experiments. Multispectral PAT was performed on a mouse with an implanted subcutaneous tumor (see Figure1). The PAT imaging setup has been described elsewhere. Five optical wavelengths (755, 800, 860, 900 and 930 nm) were used from the Ti: Sapphire laser source. Figures 2a-2d present the reconstructed *in vivo* HbR, HbO_2, H_2O and acoustic velocity images. We see that he tumor is remarkably imaged with the highest contrast in HbR and HbO_2 images.

The multi-spectral PAT approach presented provides an efficient means of concurrent reconstruction of multiple parameters including different chromophore concentrations and acoustic velocity. Nonetheless, the ability of reconstructing multiple parameter images

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