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ABSTRACT

Model-based reconstruction techniques have been successfully implemented in optoacoustic tomography and acoustic-resolution microscopy to retrieve improved image quality over delay-and-sum methods. In scanning optical resolution optoacoustic microscopy (OR-OAM), no reconstruction methods are employed while post-processing is usually limited to basic frequency filtering and envelope extraction with the Hilbert transform. This results in considerable deterioration of the acoustically-determined resolution in the axial (depth) direction. In addition, when OR-OAM is used for transcranial mouse brain imaging, the skull strongly attenuates high ultrasonic frequencies and induces reverberations, which need to be accounted for during the reconstruction process to avoid image distortions and further deterioration of the axial resolution. Here we show a basic implementation of a model-based reconstruction to increase the axial resolution in OR-OAM. The model matrix is calculated using Field II for free field conditions, taking into account the shape and bandwidth of the spherically focused transducer. Assuming the confinement of the optoacoustic sources within the limits of the optical focus, one may calculate the model matrix by assuming a line source of small absorbing spheres equal in size to the optical beam. In addition, a plate model used in the recently reported virtual-craniotomy deconvolution algorithm is incorporated into the model matrix to tackle the transcranial acoustic transmission problem. The free-field model-based results are compared against the plate model for transcranial brain data obtained *in-vivo*.

Keywords: optoacoustic microscopy, photoacoustic microscopy, image reconstruction, neuroimaging, skull, transcranial imaging, model-based reconstruction

1. INTRODUCTION

Reconstructing a meaningful image out of bipolar time-resolved signals is a crucial step in optoacoustic imaging. If a physical forward model of acoustic wave propagation is available, a linear system of equations can be built to retrieve an optical absorption image of biological tissue. Model-based reconstruction algorithms have been successfully applied in optoacoustic tomography[1,2] and acoustic-resolution optoacoustic microscopy,[3,4] showing improved image quality over delay-and-sum methods.[5–8] In scanning optical resolution optoacoustic microscopy (OR-OAM),[9–14] no reconstruction methods are employed, i.e. post-processing is limited to basic frequency filtering and envelope extraction with the Hilbert transform. Thus, the acoustically-determined resolution in the axial (depth) direction is considerable deteriorated in comparison with the optically-determined lateral resolution (Fig. 1(b)). Moreover, when OR-OAM is used for transcranial mouse brain imaging, the skull produces additional reverberations and low frequency filtering.[15,16] To avoid transcranial image distortions and further deterioration of the axial resolution, a dictionary learning[17] and a virtual craniotomy deconvolution[18] have been proposed. Here we propose a model-based reconstruction to improve the axial resolution in OR-OAM that could also be extended to tackle skull-induced distortions in transcranial OR-OAM.

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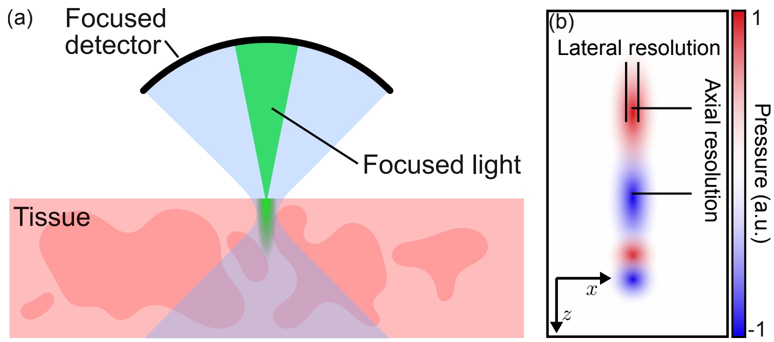

Figure 1. (a) Geometry considered for optical resolution optoacoustic microscopy. (b) Characteristic waveform detected from a small absorbing object. The axial resolution is much larger than the lateral resolution and some secondary peaks appear in the waveform.

2. METHODS

Because of the focused light delivery (Fig. 1(a)), we assume the acoustic wave could only be generated at a line located along the acoustic axis of the focused detector (Fig. 2(a)). Alternative geometries could be considered for different OR-OAM implementations.[9–14] We calculated the model matrix using Field II[19] in free field conditions for a spherically focused transducer of 6 mm in diameter and 7 mm of focal distance (Fig. 2 (b)) to model the PVdF transducer (30 MHz central frequency) used in the experiments. We implemented the linear system using Tikhonov regularization[20] for each position in the xy scanning plane (Fig. 2(b)). Thus, each pixel is treated independently and the model matrix is calculated once to process the whole dataset. We inverted the system using direct inversion and non-negative least squares.[21] We tested our method in a transcranial mouse brain dataset acquired *in-vivo*.

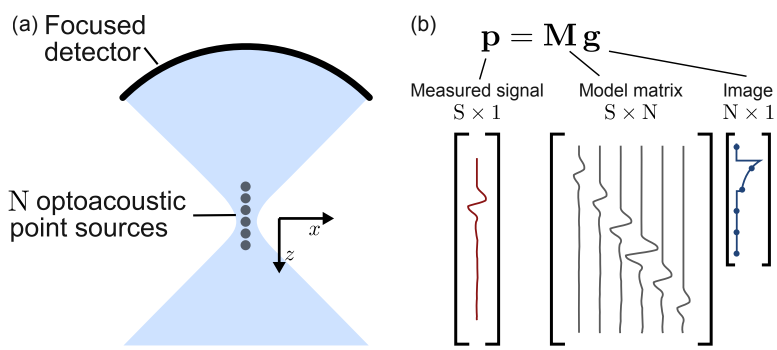

Figure 2. (a) Schematic of the position of the optoacoustic sources relative to the focused detector. (b) Linear system of equations for a single position in the scanning plane xy. The model matrix includes the spatial and frequency response of the detector.

3. RESULTS

Large reverberations and the bipolar nature of the OR-OAM raw data (Fig. 3) contrasts with the images retrieved by the model-based reconstruction. The reverberations can be partially removed and the bipolar nature of the signals corrected. For the direct inversion, negative values have been neglected, whereas the non-negative least squares method automatically retrieves positive values only. The skull bone can be included in the model matrix as a plate[16,18] using a simplified model that accounts for longitudinal and shear waves. The use of such physical model considerably increases the number of parameters required to build the forward model and additional imaging of the skull bone would be required.[18] Although the plate model does not seem to perform better than

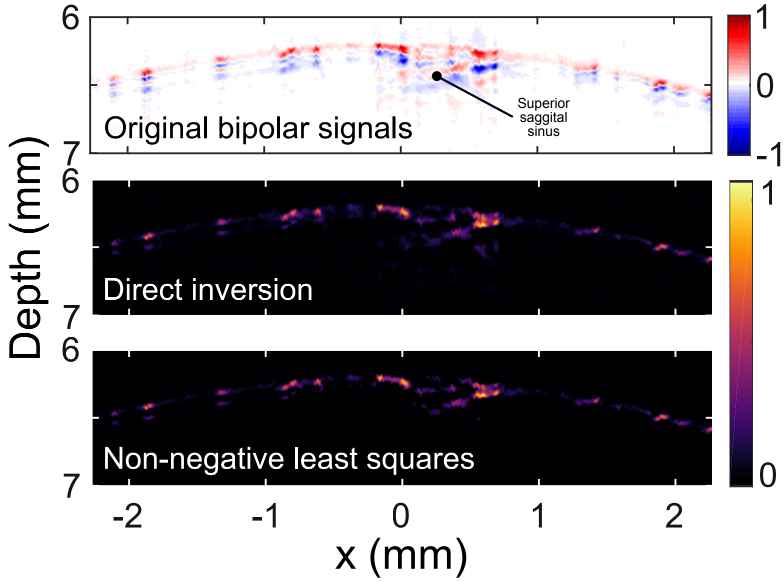

Figure 3. Coronal cross section of a transcranial mouse brain OR-OAM scan acquired *in-vivo*. The original signals show considerable reverberations induced by the skull (colorbar, optoacoustic signal amplitude (a.u.)). Using a simple free-field model including the transducers geometry, bandwidth, and optical beam width, two images can be reconstructed using different inversion procedures (colorbar, normalized image).

the free-field model for direct inversion, it produces a better result when non-negative least squares inversion is employed. In addition, the depth-shift produced when the ultrasound wave is transmitted through the skull (higher speed of sound than tissue) can only be corrected using the plate model. Neither the free-field model or the dictionary learning approach[17] can correct for the depth-shift.

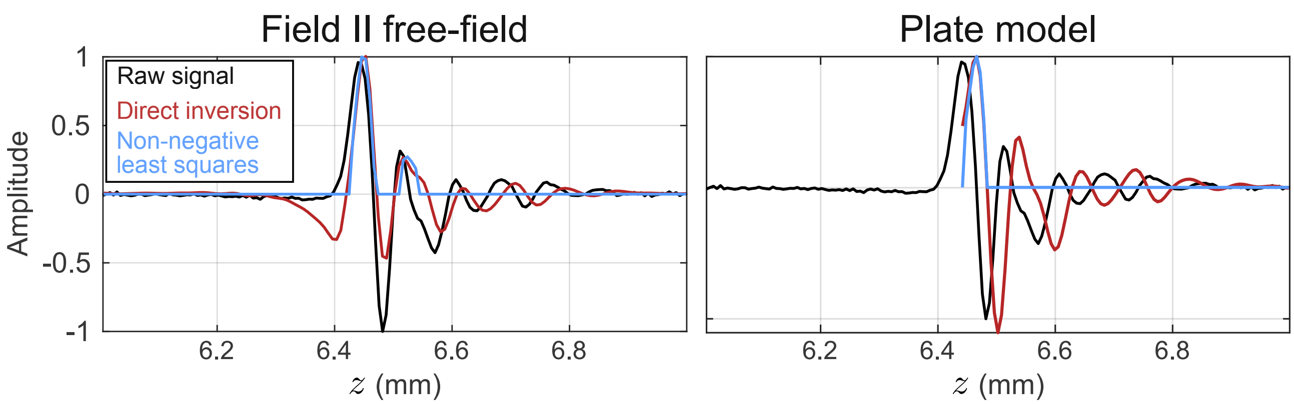

Figure 4. Comparison between free-field and plate model matrix for direct and non-negative least squares inversion.

4. CONCLUSIONS

We show a model-based reconstruction strategy to increase the quality of OR-OAM images. The axial resolution can be considerably increased and the hurdle of dealing with bipolar signals reasonably solved. Even in the complicated case of transcranial OR-OAM, our methodology shows promising results. Further work is necessary in order to find adequate regularization parameters to refine our results. Also improvements to the plate model and the selection of the skull's elastic and geometrical parameters are needed to properly handle the transcranial problem.

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