Comparative Analysis of Acoustic Reconstruction Methods for Chromophore and Oxygenation Quantification in Limited-View 3D Quantitative Photoacoustic Tomography

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Abstract: Three-dimensional quantitative photoacoustic tomography is challenged by uncertainties in light fluence distribution and artifacts from limited view problem. This study evaluates advanced acoustic reconstruction algorithms using model-based inversion schemes to improve chromophore and oxygenation quantification.

1. Introduction

Three-dimensional quantitative photoacoustic tomography (3D-qPAT) is an advanced imaging modality that recovers spatially resolved maps of local tissue chromophore concentrations by analyzing multispectral photoacoustic (PA) time series data. This approach provides critical insights into tissue physiology, enabling the quantification of parameters such as the concentrations of oxy- (HbO_2) and deoxyhemoglobin (HHb) and derived parameters, such as blood oxygen saturation (sO_2), which are essential for understanding tissue metabolism, vascular health, and pathological states such as hypoxia and tumor progression [1,2]. Despite its potential, achieving accurate reconstructions in 3D-qPAT is challenging due to several inherent limitations. One of the primary difficulties arises from uncertainties in the light fluence distribution within tissues, which depends nonlinearly on the chromophore concentrations and their optical properties [3]. Furthermore, finite planar detection geometries introduce reconstruction artifacts that compromise image quality and quantitative accuracy [4].

To overcome these obstacles, model-based inversion schemes have been developed, integrating Monte Carlo (MC) light transport simulations [3] and acoustic wave propagation models. These methods aim to estimate the spatial distribution of optical and acoustic properties by minimizing the difference between simulated and measured data. A key limitation of such schemes lies in the accuracy of the acoustic inversion, i.e., the accuracy of the reconstructed images of the photoacoustic time series data from limited view detection [4]. This study aims to address these limitations by systematically evaluating advanced acoustic reconstruction algorithms with an *in-silico* phantom. In particular, we investigate the role of difference acoustic reconstruction algorithms on the accuracy of the recovered HbO_2 and HHb concentration distributions and sO_2 maps, focusing on mitigating artifacts and improving quantitative accuracy in 3D-qPAT.

2. Methods

Performance evaluation was carried out using an *in-silico* model of PA signal generation and detection in a 20x20x10 mm^3 tissue volume. The tissue phantom is represented by simplified anatomical structures such as blood vessels, subcutaneous tumors, and homogeneous tissue background regions. These structures represent typical features of biological tissues, enabling an assessment of the accuracy of reconstruction methods. The absorption properties of the phantom were modeled based on HbO_2, HHb and lipids, water to simulate the optical absorption and scattering effects encountered in biological tissues. These chromophores play a crucial role in 3D-qPAT as their concentrations directly relate to tissue oxygenation and metabolic activity.

Light fluence distributions were computed using the MC method, which is suited to simulating light transport in the quasi-ballistic and diffuse regime at superficial depths of 1-2 cm. The computed fluence distributions were then multiplied with the spatially varying absorption coefficient and the Grüneisen parameter to generate the initial pressure distributions p_0, which serve as the input for simulating the photoacoustic time series signal.

An acoustic propagation model based on the k-Wave MATLAB toolbox was developed to simulate the propagation of the PA waves and their detection using a finite planar transducer array. This setup mimics the limited view

detection commonly encountered in experimental setups [4], such as those based on Fabry-Perot tomographs, where data acquisition is restricted to a subset of the full solid angle. To further approximate realistic measurement conditions, Gaussian noise was added to the simulated time series. A range of acoustic reconstruction algorithms, shown in Table 1, were applied to the simulated photoacoustic time series to reconstruct the initial pressure distributions p_0.

Table 1. Overview of acoustic reconstruction algorithms and their explanations

Methods	Abb.	Explanation of the methods
Time-Reversal	TR	Standard numerical reconstruction method of acoustic signals [1]
Iterative Time-Reversal	iTR+	Time-Reversal with iterative refinement leveraging the Neumann series to improve reconstruction accuracy [5]
Maximum *a posteriori* estimation	MAP	Bayesian inference method with prior knowledge, such as Gaussian priors or Ornstein-Uhlenbeck priors [6]
Iterative Least Squares	iLS+	Iterative minimization of the squared error between the measured and predicted acoustic signals (the least-squares cost function) [7]
Iterative Least Squares with Total Variation	TV+	Enhancement of iLS+ by enforcing spatial gradient sparsity using total variation regularization [7]
TV+ with Bregman iterations	TV+Breg	An advanced extension of TV+ incorporating Bregman iterations [7]

Following the reconstruction of the initial pressure distributions p_0, HHb and HbO_2 concentration distributions were recovered by fitting the output of the MC model to the simulated multiwavelength image dataset using an Adam-optimized inversion scheme [3]. This optimization approach leverages the strengths of gradient-based methods to efficiently solve the inverse problem of estimating millions of chromophore concentrations from high-resolution multispectral PA data. The performance of each reconstruction method was evaluated using the mean absolute error (MAE) compared to the ground truth within a defined 3D region of interest (ROI) of the recovered HHb and HbO_2 concentration distributions. The accuracy of the recovered sO_2 maps was evaluated in a similar manner. The MAE provided a quantitative measure of the deviation of the recovered values from known values, allowing an objective comparison of the different reconstruction algorithms.

3. Results

The recovered cross-sectional images of HHb and HbO_2 concentration distributions and sO_2 maps, shown in Fig. 1, revealed significant variations in performance between the reconstruction algorithms, highlighting their respective strengths and limitations.

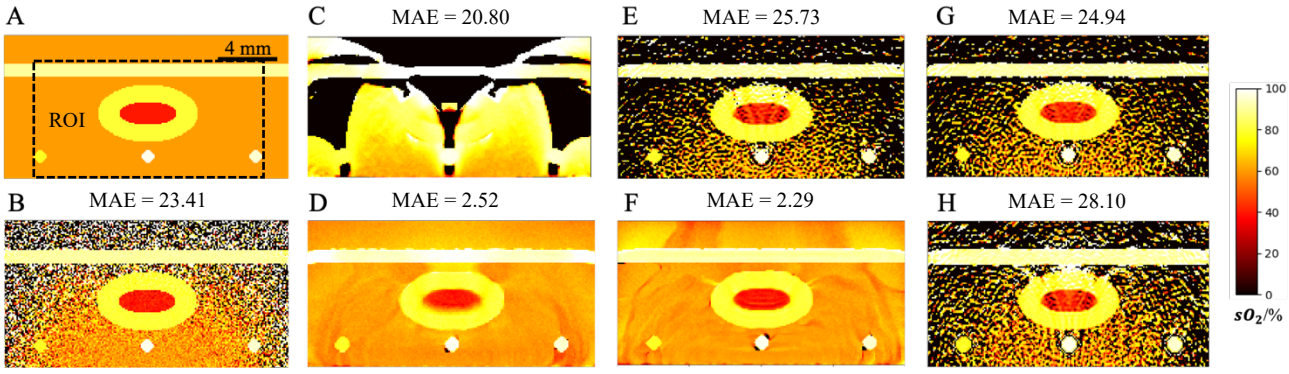

Fig. 1. Comparison between A) the cross-sectional image of the ground true sO_2 maps, and the cross-sectional images of the recovered sO_2 maps using B) the ground true p_0, or the reconstructed p_0 by methods C) TR, D) TV+, E) iTR+, F) TV+Breg, G) iLS+, H) MAP with Ornstein-Uhlenbeck priors. The mean absolute errors (MAEs) displayed above the images were computed within the 3D regions of interest (ROI).

TR reconstructions, while computationally straightforward, exhibited strong streaking artifacts as shown in Fig. 1. C, which leads to inaccurate HHb and HbO_2 concentrations and blood oxygen saturation (sO_2) values and represent a major limitation of direct back-projection approaches like TR when dealing with incomplete or noisy data. Iterative

methods such as iTR+ and iLS+ (Fig. 1. E and G) showed noticeable improvements over TR in terms of sO_2 values accuracy and overall image quality. By refining the solutions through successive iterations, these methods enhanced HHb and HbO_2 concentration accuracy, particularly within the central ROIs. However, residual streaking artifacts and noise persisted. Similarly, MAP estimation with L2OUCov+ (Ornstein-Uhlenbeck priors) exhibited these limitations, which reduced their utility for applications where precise mapping of tissue oxygenation is critical.

In comparison, Total-Variation (TV) based regularizations emerged as a robust approach for suppressing streaking artifacts and preserving image quality. TV+ (Fig. 1. D) effectively promotes sparsity in the spatial gradients of the reconstructed images, which helped to reduce noise and artifacts associated with incomplete data acquisition. This method demonstrated significant improvements in the visual quality of sO_2 maps and also provided a moderate level of accuracy in recovering HHb and HbO_2 distributions, making it a balanced choice for applications requiring both artifact reduction and reasonable chromophore quantification. TV+Breg (Fig. 1. F) further improved reconstruction accuracy. This method iteratively corrected amplitude errors in the reconstructed initial pressure distributions p_0, addressing discrepancies introduced by the limited detection aperture and noise in the time series data. TV+Breg achieved the most accurate recovery of HHb and HbO_2 distributions, resulting in the best sO_2 maps, as indicated by the lowest MAE among all methods tested within the 3D regions of interest. The method's ability to mitigate finite-aperture limitations and correct chromophore concentrations highlights its potential for applications requiring precise quantification of tissue chromophores. However, TV+Breg requires significantly more computational time for acoustic reconstruction compared to TV+. These findings show a trade-off between its superior performance in chromophore and oxygenation quantification and the computational time required for practical clinical diagnostics.

4. Conclusion

This study evaluated various acoustic reconstruction algorithms for chromophores (HHb and HbO_2) and oxygenation quantification in 3D quantitative photoacoustic tomography (3D-qPAT) under the limited view problem. TV+Breg emerged as the most accurate method for recovering HHb, HbO_2 distributions and sO_2 maps, achieving the lowest MAE values and effectively mitigating finite-aperture limitations. However, its high computational cost limits real-time clinical feasibility. For sO_2 imaging, both TV-based regularizations demonstrated superior artifact suppression, producing cleaner maps with minimal distortions. While TV+ did not match TV+Breg in HHb and HbO_2 distributions accuracy, its ability to generate high-quality sO_2 images still makes it ideal in computationally constrained scenarios. Notably, they inherently bias reconstructions toward specific structures, which can introduce inaccuracies if tissue morphology deviates from these assumed shapes. These findings suggest that a hybrid approach, combining TV+Breg's high chromophore quantification accuracy with TV+'s computational efficiency, could enhance 3D-qPAT performance. Integrating these acoustic reconstruction methods into a model-based inversion framework would improve diagnostic reliability, making 3D-qPAT more effective for clinical applications in oncology and vascular assessment.

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