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MULTI-SOURCE QUANTITATIVE PHOTOACOUSTIC TOMOGRAPHY WITH DETECTOR RESPONSE FUNCTION AND LIMITED-VIEW SCANNING*

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Abstract

A practical image reconstruction method for multi-source quantitative photoacoustic tomography (QPAT) is proposed in this work with the consideration of detector response function and limited-view scanning. First, the correct detector response function, i.e., spatial impulse response (SIR) and acousto-electric impulse response (EIR), is considered for the ultrasonic transducer to accurately model the acoustic measurement; second, acoustic data is only measured near optical sources with meaningful signal-to-noise ratio (SNR), i.e., the limited-view scanning, which also reduces the data acquisition time for point transducer. However, due to the incomplete limited-view data, a two-step image reconstruction method (i.e., to first reconstruct initial acoustic pressure and then reconstruct optical coefficients) no longer applies, since it is neither possible nor necessary to robustly reconstruct initial acoustic pressure with limited-view data. Therefore, here we propose a direct image reconstruction method that incorporates SIR, EIR and limited-view scanning in a coupled opto-acoustic forward model, regularizes the nonlinear QPAT data fidelity with tensor framelet sparsity, and then solves the QPAT problem with Quasi-Newton method based alternating direction method of multipliers.

Mathematics subject classification: 65N06, 65B99.
Key words: Quantitative photoacoustic tomography, Alternating direction method of multipliers, Image reconstruction.

1. Introduction

Photoacoustic tomography (PAT) (see e.g., [7, 14, 24, 27, 33]) is developed in recent years for non-invasively imaging soft biological tissues with various biomedical applications. On one hand acoustic imaging allows higher spatial resolution than optical imaging owing to the weaker acoustic scattering than optical scattering; on the other hand optical contrasts are higher and richer than acoustic contrasts. In this sense, PAT synergizes the conventional optical and acoustic imaging with the ability of imaging high and rich optical contrasts in high resolution. However, it is still unclear whether PAT can reveal optical contrasts in depth

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with high resolution, which is the goal of quantitative PAT (QPAT), e.g., the review paper [12] and the references therein.

There are two inverse problems in QPAT: acoustic inverse problem and optical inverse problem. Specifically, the acoustic inverse problem is to estimate the initial acoustic pressure from boundary acoustic measurement [35]; the optical inverse problem is to reconstruct the optical contrasts from initial acoustic pressure [12]. The simultaneous reconstruction of more than one optical coefficients is not unique with only single optical illumination or optical wavelength. Therefore QPAT with multiple optical wavelengths [10, 12, 25, 28], multi-source illuminations (MS-QPAT) (e.g., [5, 17, 19, 29, 31, 32, 37, 43], or their combination [6] have been investigated so that all optical coefficients can be uniquely reconstructed. This work focuses on MS-QPAT.

In the conventional MS-QPAT, a full-rotation boundary acoustic data needs to be acquired following each optical illumination, which may result in different level of signal-to-noise (SNR) ratio, e.g, high SNR at the boundary close to optical sources. Consequently these low-SNR data may degrade reconstructed image quality. To achieve a high SNR uniformly in the acquired data, the limited-view MS-QPAT is proposed [43], i.e., a partial-view boundary acoustic measurement following each optical illumination. In this way, high SNR can be uniformly maintained. Moreover, it can significantly reduce the scanning time proportional to scanning angles for point ultrasonic transducer. However, in addition to the SNR uniformity, for accurate QPAT reconstruction in practice, the detector response of acoustic transducer must be taken into account. Without considering detector response function, the reconstructed image quality can be degraded with distortion and reduced spatial resolution [4].

In this paper, for the practical QPAT image reconstruction, we consider MS-QPAT with limited-view scanning and detector response function. Due to limited-view scanning, the aforementioned two-step approach for QPAT fails, since the acoustic reconstruction for initial acoustic pressure is unstable [36]. On the other hand, the reconstruction of initial acoustic pressure is not the ultimate goal, and thus it is not essential as long as optical contrasts can be reconstructed. Thus, we consider the direct reconstruction of optical contrasts from the acoustic measurement based on a coupled opto-acoustic forward model with SIR and EIR.

The paper is organized as follows: The proposed practical MS-QPAT forward model and the corresponding discretization are introduced in Section 2; the numerical method for solving the proposed MS-QPAT in nonlinear least squares will be developed in Section 3; the sparsity-regularized method with simple bound constraints for QPAT is investigated in Section 4; the proposed method is validated through numerical experiments in Section 5; finally, we will conclude in Section 6.

2. Practical QPAT

2.1. Coupled Opto-Acoustic Forward Model

The photoacoustic effect is fundamental to photoacoustic imaging. When the molecules within the soft tissues are exposed to short-pulse radiation (e.g., electromagnetic energy), the initial acoustic pressure $p_0(\vec{x})$ is excited because of the thermo-elastic mechanism, then the pressure wavefield $p(\vec{x}, t)$ propagates in tissues and is detected by the transducers that locate on a measurement aperture Ω_0 on the object boundary. This process can be separately modeled, i.e., as optical model and acoustic model.

The optical propagation in the biological tissues can be accurately described by radiative transfer equation (RTE), e.g., [16, 20–22] and the references therein. Here we consider the