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Title

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Permalink

<https://escholarship.org/uc/item/8bf0b9kh>

Journal

Progress in Biomedical Optics and Imaging, 13931

ISSN

1605-7422

ISBN

978-1-5106-9799-7

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Publication Date

2026

DOI

10.1117/12.3087819

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X-ray Induced Acoustic Corrected by Transmission Radiography

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ABSTRACT

X-ray induced acoustic computed tomography (XACT) is an emerging imaging modality capable of reconstructing three-dimensional distributions of X-ray energy deposition from a single projection. While XACT provides strong functional contrast, its image quality is often degraded by limited acoustic detection geometries, leading to reconstruction artifacts and reduced spatial accuracy. In this work, we present a dual-modality XACT imaging framework that integrates transmission X-ray imaging to improve three-dimensional reconstruction robustness. A pulsed X-ray source was used to generate acoustic signals via thermoelastic expansion, which were detected by a planar ultrasound array for volumetric XACT reconstruction. Simultaneously acquired transmission X-ray images were processed to extract structural priors that were co-registered with the XACT coordinate system and incorporated into an iterative reconstruction scheme. Experimental results demonstrate that the proposed approach substantially suppresses limited-view artifacts and improves geometric fidelity compared with conventional XACT reconstructions. This work highlights the potential of hybrid XACT–radiographic imaging to enable more accurate and reliable three-dimensional imaging, advancing XACT toward practical and image-guided interventional applications.

Keywords: Radioacoustic, X-ray, acoustic, fluoroscopy, algorithm, dual-modality Imaging

1. INTRODUCTION

For the past years, X-ray Induced Acoustic Computer Tomography (XACT) research has primarily focused on establishing the underlying physical mechanisms, improving acoustic detection sensitivity, and demonstrating high-contrast functional imaging in tissue-mimicking phantoms.^{1,2} These studies have shown that XACT is intrinsically sensitive to local X-ray energy deposition, enabling volumetric imaging from a single X-ray projection and offering a potential pathway toward rapid three-dimensional imaging.³⁻⁶

Despite these advantages, most conventional XACT implementations rely on limited acoustic detection geometries and simplified reconstruction models, leading to pronounced limited-view artifacts,⁷ geometric distortions, and degraded spatial accuracy, particularly in three-dimensional reconstructions. Previous efforts have explored advanced reconstruction strategies, such as model-based approaches,⁸⁻¹¹ to mitigate these artifacts; however, their performance typically depends on a sufficiently high signal-to-noise ratio. As a result, while XACT provides strong functional contrast, its image fidelity and anatomical interpretability remain constrained. Addressing these limitations in reconstruction robustness and spatial accuracy is critical for advancing XACT toward practical imaging applications. In this work, we introduce a dual-modality imaging approach that integrates XACT with conventional transmission X-ray imaging, enabling improved spatial accuracy by incorporating radiographic structural information.

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2. METHOD

The XACT signal is based on the generation of ultrasonic waves through the thermoelastic expansion due to the short pulsed X-ray deposition, rapid localized heating induces transient pressure rises that propagates in the form of acoustic wave as described above, and governed by the following thermoacoustic wave equations:¹²

$$\frac{\partial^2 p(\mathbf{r}, t)}{\partial t^2} - v^2 \nabla^2 p(\mathbf{r}, t) = \Gamma H(\mathbf{r}) \frac{\partial \delta(t)}{\partial t}, \quad (1)$$

where $p(\mathbf{r}, t)$ denotes the acoustic pressure at position $\mathbf{r}$ and time t , v is the speed of sound, and $\delta(t)$ is the Dirac delta function. The parameter¹³

$$\Gamma = \frac{v^2 \beta}{C_p} \quad (2)$$

is the Grüneisen parameter, where β is the volumetric thermal expansion coefficient, and C_p is the specific heat capacity at constant pressure. The term $H(\mathbf{r})$ represents the spatial distribution of deposited X-ray energy, indicating that the initial acoustic pressure source is proportional to the product of Γ and the local X-ray energy absorption.

Under stress and thermal confinement conditions, the analytical solution to Eq. (1) can be expressed as¹⁴

$$p(\mathbf{r}, t) = \frac{\Gamma}{4\pi v} \frac{\partial}{\partial t} \left(\frac{1}{vt} \int_{S(\mathbf{r}', t)} H(\mathbf{r}') dS' \right), \quad (3)$$

which relates the measured acoustic pressure to the spherical Radon transform of the X-ray energy deposition. This formulation establishes the physical basis for reconstructing the three-dimensional X-ray absorption distribution from time-resolved acoustic measurements.

2.1 Initial XACT Reconstruction

A synchronized dual-modality imaging system was developed to simultaneously acquire X-ray-induced acoustic computed tomography (XACT) signals and transmission X-ray projections. Structural information extracted from the radiographic images is incorporated as a spatial prior to guide XACT reconstruction through an iterative correction framework. Both static and dynamic phantom experiments were conducted to evaluate system performance.

The initial three-dimensional XACT volume is reconstructed from the measured acoustic signals using a time-reversal operator:

$$V^{(0)} = \mathcal{TR}(S_{\text{meas}}), \quad (4)$$

where $V^{(0)}$ denotes the initial XACT reconstruction, $\mathcal{TR}(\cdot)$ represents the time-reversal reconstruction operator, and S_{meas} is the measured acoustic signal.

2.2 Iterative X-ray-Guided Reconstruction

To suppress limited-view artifacts and enable dynamic three-dimensional imaging, an iterative reconstruction scheme incorporating an X-ray-derived spatial constraint is employed. At iteration i , the image update follows:

$$V_{\text{masked}}^{(i)} = V^{(i-1)} \odot M_{3D}, \quad (5)$$

$$S_{\text{sim}}^{(i)} = \mathcal{F}(V_{\text{masked}}^{(i)}), \quad (6)$$

$$\Delta S^{(i)} = S_{\text{meas}} - S_{\text{sim}}^{(i)}, \quad (7)$$

$$V^{(i)} = V^{(i-1)} + \mathcal{TR}(\Delta S^{(i)}), \quad (8)$$

where M_{3D} is the three-dimensional spatial constraint mask derived from the X-ray image, $\mathcal{F}(\cdot)$ denotes the forward acoustic simulation operator, $S_{\text{sim}}^{(i)}$ is the simulated acoustic signal, and $\Delta S^{(i)}$ represents the residual between measured and simulated signals. The operator $\odot$ indicates element-wise multiplication enforcing the spatial constraint.

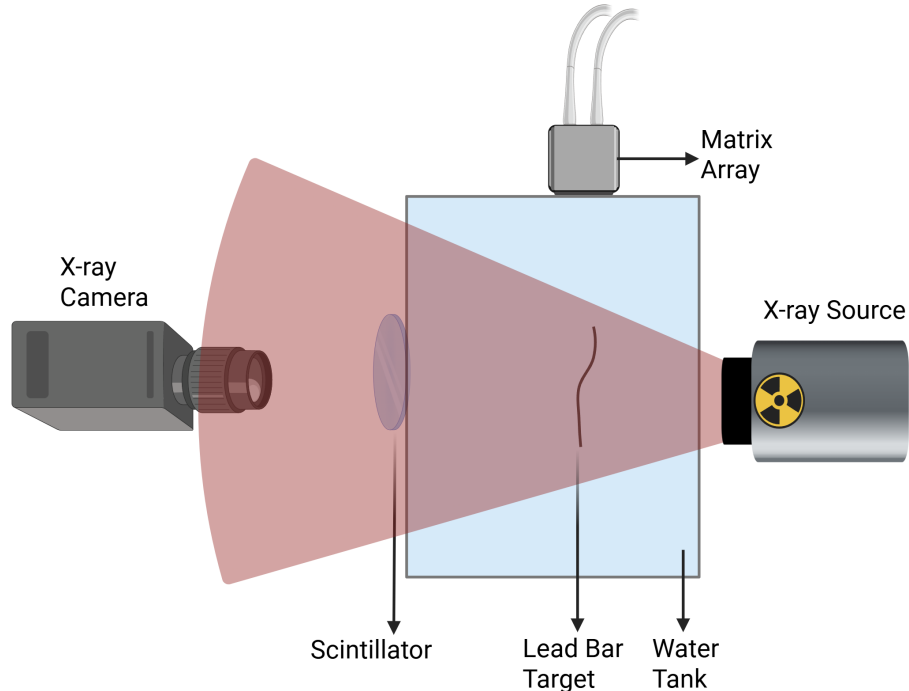


Figure 1. **Dual-Modality XACT and X-ray imaging setup:** Experimental setup for XACT imaging. The pulsed X-ray source is positioned as close as possible to one end of the water tank to minimize beam divergence. The tank wall is drilled with a small aperture and sealed with a thin membrane to reduce X-ray attenuation while maintaining water containment. The imaging target is positioned in water along the X-ray beam path and aligned above the acoustic detection array.

2.3 X-ray–Guided Reconstruction Workflow

The overall reconstruction workflow consists of the following steps:

1. **X-ray–Based Mask Generation:** A pulsed transmission X-ray image is acquired using a fast CMOS camera. Maximum-intensity projection is applied to segment the object support in the transverse (XY) plane, producing a two-dimensional binary mask.
2. **Initial XACT Reconstruction:** Acoustic signals detected by the planar ultrasound array are reconstructed into an unconstrained three-dimensional volume using a time-reversal algorithm implemented in the k-Wave toolbox.¹⁵
3. **Image Registration and Scaling:** The X-ray image is registered to the XACT coordinate system using calibration objects (lead markers) visible in both modalities. A magnification correction is applied based on geometric parameters derived from the XACT reconstruction.
4. **Three-Dimensional Mask Construction:** The registered two-dimensional X-ray mask is extruded along the axial (Z) direction to form a three-dimensional spatial constraint volume M_{3D} , which restricts the reconstruction domain.
5. **Forward Simulation and Correction:** The constrained volume is used to simulate acoustic wave propagation via the forward model. The residual between simulated and measured acoustic signals is back-projected using the time-reversal operator and added to refine the image.
6. **Iteration:** Steps 4 and 5 are repeated for a fixed number of iterations, empirically selected to balance artifact suppression and noise amplification.

2.4 Dual-modality system setup

The XACT imaging platform integrates a pulsed X-ray excitation source, a planar ultrasound receive array, and a transmission X-ray imaging chain in a dual-modality configuration, as illustrated in Fig. 1. X-ray excitation is provided by a pulsed X-ray generator (XR200, Golden Engineering Inc.), which delivers nanosecond-scale X-ray pulses with an approximate pulse width of 50 ns, a cone-beam geometry of 40° , and a maximum repetition rate of 10 Hz. The emitted X-rays, with effective energies on the order of tens of keV, induce localized thermoelastic expansion within the imaging target, generating broadband acoustic waves. For controlled operation and radiation safety, the X-ray generator is externally triggered and incorporates a programmable warning delay prior to pulse emission.

Transmission X-ray imaging is performed using an sCMOS-based detector (pco.panda 4.2, Excelitas Technologies) positioned downstream of the target along the X-ray beam axis. A scintillator layer placed in front of the camera converts incident X-ray photons into visible light, enabling high-resolution radiographic imaging with a sensor resolution of 2048×2048 pixels and a pixel pitch of $6.5 \mu\text{m}$. In addition to radiographic acquisition, the scintillator output can serve as a timing reference for system synchronization.

Acoustic signal detection is achieved using a planar ultrasound matrix array consisting of 16×16 elements (256 elements total; Doppler Co. Ltd.) with a nominal center frequency of approximately 1 MHz. The array is positioned orthogonally (90°) to the X-ray beam direction to capture X-ray-induced acoustic (XA) waves without obstructing X-ray transmission. The received acoustic signals are digitized using a 256-channel analog-to-digital conversion system (ADC; PhotoSound Technologies Inc.) at a sampling rate of 40 MHz.

Acoustic coupling and target placement are implemented using a water-filled enclosure that provides acoustic impedance matching between the imaging target and the ultrasound array while maintaining an unobstructed transmission path between the X-ray source and the radiographic detector. During data acquisition, each X-ray pulse simultaneously generates a transmission radiograph and a corresponding set of XA waveforms recorded across all array elements, enabling three-dimensional XACT reconstruction using time-reversal or back-projection-based algorithms. To improve signal-to-noise ratio, multiple X-ray pulses may be averaged for XACT reconstruction, whereas single-pulse acquisition is typically sufficient for transmission radiography. Current system performance is limited by the repetition rate and thermal duty cycle of the X-ray source, motivating future optimization toward higher-speed excitation and real-time imaging.

3. VALIDATION RESULTS

Figure 2 illustrates the reconstruction workflow of the proposed XACT+ X-ray imaging framework. Panel (a) shows the transmission X-ray image acquired simultaneously with acoustic data, providing a high-contrast projection of the target geometry. This image serves as a structurally accurate reference and is intrinsically co-registered with the XACT acquisition due to the shared excitation geometry.

An initial three-dimensional XACT reconstruction is obtained using a time-reversal algorithm, as shown in Fig. 2(b). Owing to the limited acoustic detection aperture and incomplete angular coverage, the unconstrained reconstruction exhibits pronounced limited-view artifacts, background clutter, and geometric distortion, which degrade spatial fidelity.

To mitigate these effects, the X-ray image is segmented and transformed into a refined spatial constraint mask, shown in Fig. 2(c). This mask is registered to the XACT coordinate system and extruded along the depth direction to form a three-dimensional prior that defines the feasible region of acoustic source distribution. The spatial constraint suppresses out-of-object artifacts and stabilizes the ill-posed inverse problem.

Finally, an iterative forward-backward reconstruction is performed, incorporating the X-ray-derived constraint at each iteration. As illustrated in Fig. 2(d), this guided reconstruction significantly reduces background artifacts, corrects geometric distortion, and improves spatial accuracy of the recovered XACT volume. The resulting image demonstrates enhanced structural consistency with the X-ray projection while preserving the functional contrast provided by XACT.

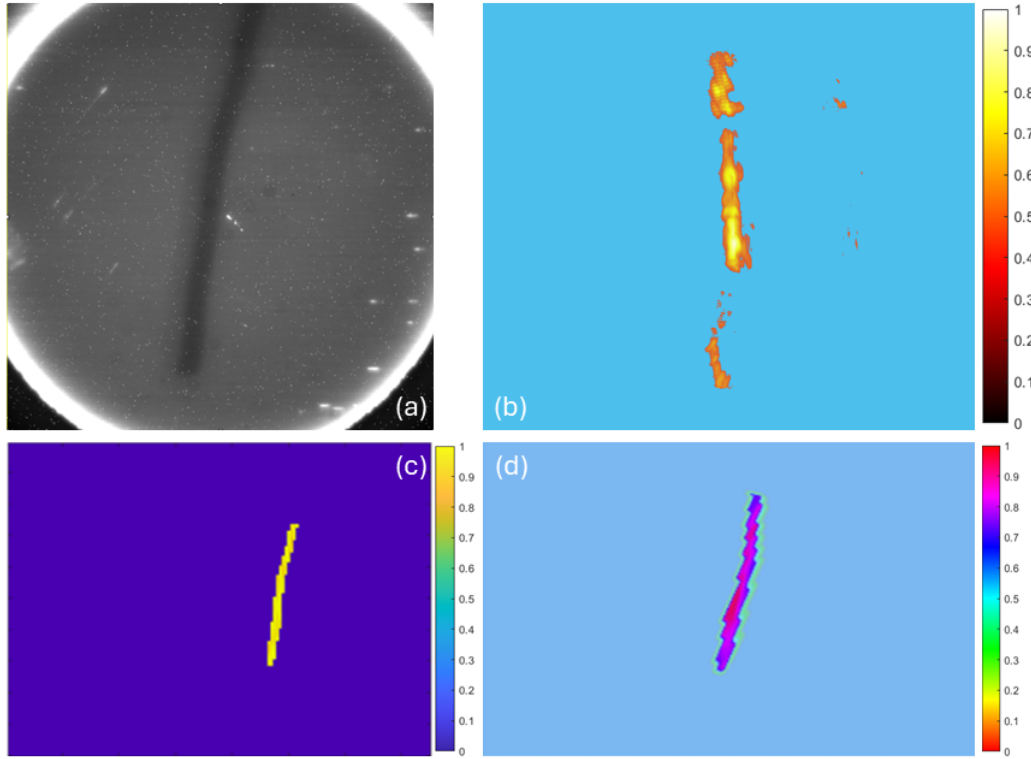


Figure 2. **XACT+ X-ray workflow results:** (a) Original X-ray images obtained from the X-ray camera (20 pulses averages) (b) Initial unconstrained XACT reconstruction obtained using time-reversal, exhibiting limited-view artifacts and geometric distortion. (c) A refined spatial constraint is applied by enforcing the registered mask, effectively suppressing out-of-object artifacts. (d) 3D visualization of the final reconstructed XACT volume after iterative forward-backward correction, where the X-ray-derived spatial constraint guides artifact suppression and improves spatial fidelity.

4. DISCUSSION AND CONCLUSION

4.1 Discussion

The results demonstrate that incorporating transmission X-ray-derived spatial constraints substantially improves the robustness and spatial fidelity of XACT reconstruction under limited-view conditions. Conventional time-reversal-based XACT reconstructions are highly sensitive to incomplete angular coverage, leading to elongated structures, background artifacts, and geometric distortion, as observed in the unconstrained reconstruction. These effects arise from the ill-posed nature of the inverse problem and the lack of sufficient acoustic aperture information.

By utilizing the high-contrast structural information provided by the co-registered X-ray projection, the proposed XACT+ framework effectively constrains the feasible solution space. The X-ray-derived mask suppresses out-of-object artifacts and enforces geometric consistency during iterative forward-backward reconstruction, resulting in improved shape recovery and reduced background clutter. Importantly, this approach preserves the functional sensitivity of XACT while compensating for its inherent limitations in spatial sampling.

Despite these improvements, several limitations remain. The current reconstruction accuracy is influenced by the quality of X-ray segmentation and registration, and the achievable temporal resolution is constrained by the low repetition rate and limited irradiation area of the present X-ray source. Future work will focus on optimizing X-ray source performance, improving dynamic imaging capability, and extending the framework to more complex geometries and in vivo scenarios.

4.2 Conclusion

In this work, we present a dual-modality XACT+ X-ray imaging framework that integrates transmission radiography with X-ray-induced acoustic computed tomography to address fundamental limitations of standalone

XACT By incorporating X-ray-derived spatial constraints into an iterative reconstruction scheme, the proposed method significantly suppresses limited-view artifacts and improves geometric accuracy in three-dimensional XACT imaging. This hybrid approach combines the functional contrast of XACT with the structural fidelity of X-ray imaging, offering a promising pathway toward accurate, robust, and potentially real-time volumetric imaging for image-guided interventional applications.

5. ACKNOWLEDGEMENT

This work was supported by the National Institutes of Health (R37CA240806, U01CA288351, R50CA283816). The authors would like to acknowledge the support from UCI Chao Family Comprehensive Cancer Center (No. P30CA062203).

6. CONFLICT OF INTEREST

Dr.Liangzhong Xiang has financial interest in SoundDose, Inc., which, however, did not support this work. The remaining authors declare no conflict of interests.

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