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X-ray Induced Acoustic Computed Tomography (XACT) for Interventional Radiology

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ABSTRACT

We propose an innovative imaging modality, X-ray Induced Acoustic Computed Tomography (XACT), for interventional radiology applications. An XACT imaging system was developed to visualize needle insertion during interventional procedures. By integrating XACT with conventional pulse-echo ultrasound, a dual-modality imaging platform was established that takes advantage of the complementary strengths of both techniques—XACT for high-contrast localization of X-ray absorption and ultrasound for real-time soft-tissue visualization. Experimental results obtained from ex vivo tissue samples demonstrate millimeter-scale spatial resolution and dynamic two-dimensional imaging capability, highlighting the potential of XACT to improve procedural precision in image-guided interventions.

Keywords: Radioacoustic Imaging, X-ray, Ultrasound, Interventional Radiology

1. INTRODUCTION

Interventional radiology (IR) procedures require imaging techniques that support accurate needle placement.¹ Existing imaging modalities provide essential guidance but exhibit fundamental limitations. Magnetic resonance imaging offers high soft-tissue contrast but is constrained by long acquisition times and limited availability.² X-ray fluoroscopy provides real-time imaging with high temporal resolution but is intrinsically two-dimensional, limiting depth perception.³ Cone-beam computed tomography enables high-resolution volumetric imaging but relies on rotational acquisitions over several seconds, making it susceptible to motion artifacts and unsuitable for continuous real-time guidance.⁴

To address these limitations, we present X-ray Induced Acoustic Computed Tomography (XACT), a hybrid imaging modality that combines X-ray excitation with ultrasound detection.^{5,6} In XACT, short-pulsed X-ray irradiation generates acoustic waves within tissue, which are detected by ultrasound transducers and reconstructed to localize X-ray absorption in tissue. Unlike cone-beam CT, XACT does not require mechanical rotation for image formation, reducing sensitivity to motion and making it well suited for dynamic interventional imaging scenarios.^{7,8}

Previous studies have demonstrated XACT in static imaging applications, including breast imaging,⁹ bone mapping,¹⁰ and molecular contrast detection.¹¹ However, its application to dynamic interventional procedures has not been fully explored.^{12,13} Moreover, although X-ray-based imaging modalities generally provide limited soft-tissue contrast, XACT can be naturally integrated with conventional pulse-echo ultrasound within a single imaging platform, enabling complementary visualization of soft-tissue structures.

In this study, we demonstrate the feasibility of dual-modality XACT and ultrasound imaging for interventional radiology applications, including real-time needle tracking. The proposed system enables simultaneous enhanced visualization of needle trajectories using XACT and surrounding soft-tissue anatomy using ultrasound. These results highlight the potential of dual-modality XACT–ultrasound imaging as a real-time imaging platform for image-guided interventional procedures.

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2. METHOD

2.1 X-ray–Induced Acoustic Signal

The propagation of X-ray–induced acoustic waves is governed by the following thermoacoustic wave equation:^{14,15}

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

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 parameter¹⁶

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

is the Grüneisen parameter, 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. The initial acoustic pressure source is proportional to the product of the Grüneisen parameter Γ and the local X-ray energy deposition $H(\mathbf{r})$.

The analytical solution to Eq. (1) can be expressed as

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

subject to the constraint

$$|\mathbf{r} - \mathbf{r}'| = vt, \quad (4)$$

where $S(t)$ denotes a spherical surface centered at the detector location $\mathbf{r}$ with radius vt .

The reconstructed XACT image intensity reflects the initial acoustic pressure distribution induced by X-ray absorption. Because the acoustic signals originate from localized X-ray energy deposition and propagate spherically through tissue, the measured pressure signals encode spatial information that can be used to recover the underlying absorption distribution. Compared to conventional back-projection approaches, model-based reconstruction methods provide improved accuracy by explicitly accounting for acoustic propagation physics and system geometry.

2.2 2D Dual Modality XACT Setup

To enable dual-modality XACT/ultrasound (US) imaging, a combined X-ray–acoustic/ultrasound (XA/US) acquisition system (PhotoSound Technologies Inc., Houston, USA) was employed to perform both X-ray–induced acoustic (XA) and conventional pulse-echo US imaging (Figure. 1). Because XA signals are substantially weaker than conventional ultrasound echo signals, a dedicated preamplifier with 51 dB gain was used to amplify the XA signals to a detectable level. In contrast, conventional pulse-echo ultrasound imaging does not require additional amplification due to its inherently higher signal strength. To accommodate the distinct signal conditioning requirements of XA and US imaging without manual hardware reconfiguration, the data acquisition system incorporates an integrated transmit/receive (Tx/Rcv) switch that toggles between receive-only mode for XA acquisition and transmit/receive mode for US imaging. This design enables rapid switching between modalities, minimizes acquisition latency, and allows near-simultaneous dual-modality imaging. A clinically approved 128-element linear ultrasound probe (L12-5N40-A4, 5–12 MHz, Telemed, Milan, Italy) was integrated into the system, and ultrasound images were acquired using clinically validated EchoWave software (Telemed Ultrasound, Milan, Italy).

The synchronization scheme for dual-modality XA/US acquisition is illustrated in Figure. 1. XA acquisition was synchronized to the X-ray pulses using a custom scintillator-based trigger circuit in conjunction with a function generator (33600A, Keysight, Santa Rosa, USA). For each acquisition cycle, 100 X-ray pulses were delivered to acquire 100 XA signals, after which the Tx/Rcv switch was toggled to US mode to record a single pulse-echo ultrasound frame. To demonstrate system performance and assess suitability for biologically relevant imaging conditions, experiments were conducted using pork belly tissue as a tissue-mimicking specimen.

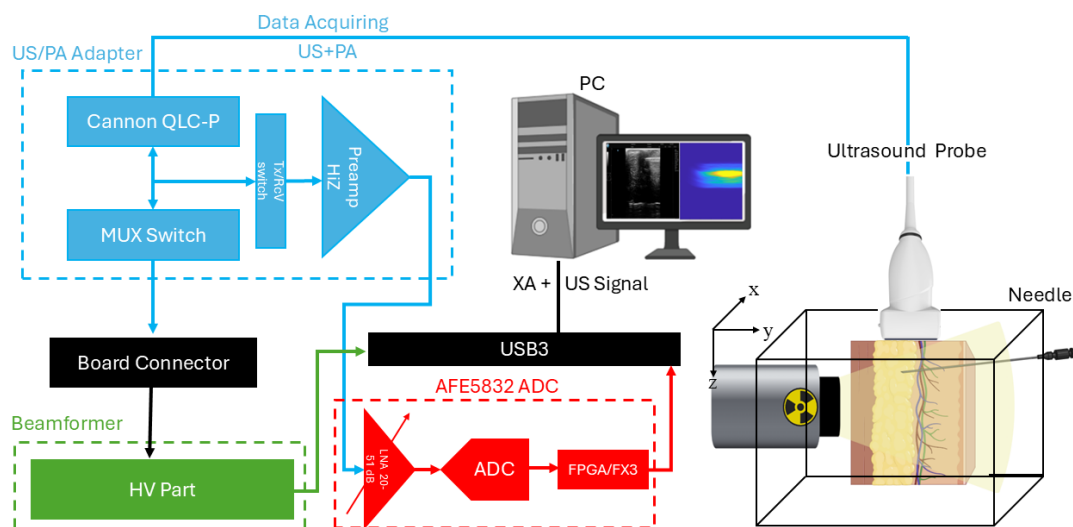


Figure 1. **Dual-modality XACT plus Ultrasound System setup:** The schematic of the dual modal system setup, a data acquisition system consist of 128 channels capable of operating in both pulse-echo and receive-only modes, with a built-in preamplifier (AFE 5832 Texas Instruments, Dallas, TX, USA)

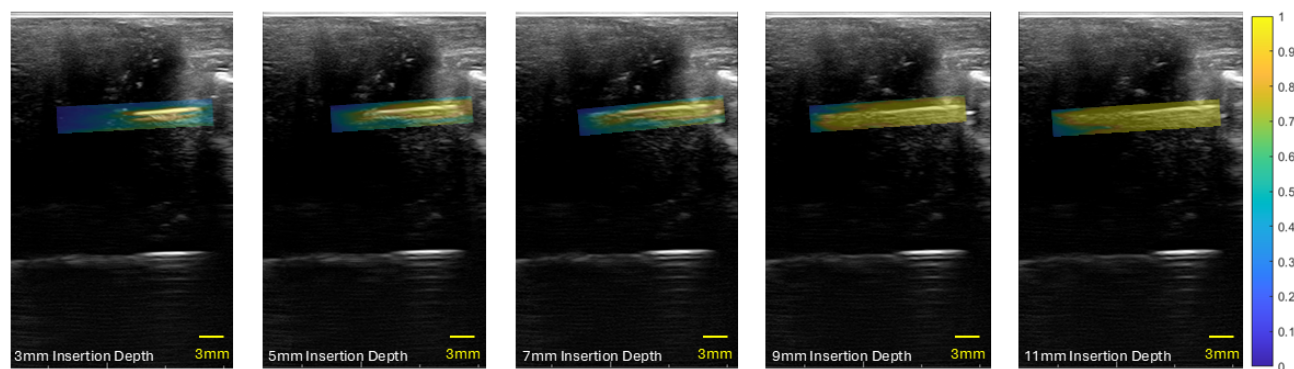


Figure 2. **Representative selective frames of the 2D ultrasound images overlaid with the XACT image:** The XACT images (shown in parula) overlay on top of grayscale Ultrasound. The ultrasound image captured using professional software (EchoWave II, Teleded ultrasound, Milan, Italy) with the L12-5L40N-4 array, provides anatomical details of tissue layers (fat, muscle), while XACT enhances needle contrast dynamically (100 averages, 4 seconds per frame)

3. VALIDATION RESULTS

To validate the feasibility of XACT for interventional procedures, needle insertion experiments were performed on real biological tissue. A pork belly sample was selected to closely mimic human tissue composition, as it contains representative layers of skin, subcutaneous fat, and muscle.

The configuration of the experimental system is illustrated in Figure 1, showing the relative geometry of the ultrasound probe, the X-ray beam, and the tissue sample. A 14-gauge therapeutic needle was inserted through the skin layer into the tissue, as shown in Figure 1. To mitigate strong acoustic reflections caused by impedance mismatch at the water–air interface, the hollow interior of the needle was filled with water prior to insertion.

Precise needle advancement was controlled using a linear motor stage, with incremental insertion depths of 3 mm, 5 mm, 7 mm, 9 mm, and 11 mm. The ultrasound probe was positioned on top of the pork belly sample with a thin layer of ultrasound gel to ensure effective acoustic coupling, while the X-ray beam was delivered from the side, perpendicular to the needle insertion axis. After each insertion step, 100 X-ray pulses were delivered and recorded by the data acquisition (DAQ) system, followed by conventional ultrasound image acquisition. XACT images were reconstructed by averaging more than 100 pulses per frame to improve signal-to-noise ratio. A spatial resolution analysis was conducted by measuring the full width at half maximum (FWHM) of the line spread function (LSF) extracted from the XACT image.

Representative dual-modality XACT/ultrasound images acquired during the needle insertion experiment are shown in Figure 2. The progressive advancement of the needle tip at depths of 3 mm, 5 mm, 7 mm, 9 mm, and 11 mm is clearly visualized using XACT, confirming its effectiveness for real-time needle tracking in heterogeneous tissue environments.

4. CONCLUSION

This study presents the first demonstration of dynamic, dual-modality XACT/ultrasound imaging for interventional radiology applications, including needle placement guidance. By integrating XACT with conventional ultrasound, the proposed dual-modality approach leverages the complementary strengths of both modalities, offering a promising imaging platform to enhance procedural safety and accuracy during image-guided interventions.

Despite these advances, several limitations remain. In particular, the current X-ray source is constrained by a low repetition rate, a small focal spot, and the absence of active cooling, necessitating mandatory cooling intervals to prevent tube damage. These factors limit achievable imaging speed and represent key barriers to clinical translation. Addressing these challenges will require system-level optimizations, including the development of high-performance, actively cooled X-ray sources, improvements in acquisition speed and spatial resolution, and the integration of advanced real-time dual-modality visualization tools. Moreover, the current dual-modality system is limited to 128 channels, which restricts probe selection and field of view (FOV). Consequently, the development of an advanced 1024-channel platform is strongly motivated.

Future work will also include in vivo studies to further evaluate the feasibility and clinical utility of dual-modality XACT/ultrasound imaging in complex interventional procedures, where existing imaging techniques may be insufficient.

In conclusion, dual-modality XACT/ultrasound imaging demonstrates strong potential as a reliable adjunct for clinical interventional radiology, providing enhanced procedural accuracy and complementary information to existing imaging technologies.

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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.

REFERENCES

- [1] De Jong, T. L., Van De Berg, N., Tas, L., Moelker, A., Dankelman, J., and Van Den Dobbelsteen, J., “Needle placement errors: Do we need steerable needles in interventional radiology?,” *Medical Devices: Evidence and Research* **11**, 259–265 (Aug. 2018).
- [2] Obuchowicz, R., Piórkowski, A., Urbanik, A., and Strzelecki, M., “Influence of Acquisition Time on MR Image Quality Estimated with Nonparametric Measures Based on Texture Features,” *BioMed Research International* **2019**, 1–10 (Nov. 2019).
- [3] Lopez, P. D., “Fluoroscopy history, evolution, and technological advancements: A narrative review,” *Journal of Medical Imaging and Radiation Sciences* **55**, 347–353 (June 2024).
- [4] Withers, P. J., Bouman, C., Carmignato, S., Cnudde, V., Grimaldi, D., Hagen, C. K., Maire, E., Manley, M., Du Plessis, A., and Stock, S. R., “X-ray computed tomography,” *Nature Reviews Methods Primers* **1**, 18 (Feb. 2021).
- [5] Yan, Y. and Xiang, S. L., “X-ray-induced acoustic computed tomography and its applications in biomedicine,” *Journal of Biomedical Optics* **29** (Dec. 2023).
- [6] Xu, Y. and Xiang, S. L., “Radiacoustic imaging,” *Nature Reviews Physics* **7**, 660–670 (Sept. 2025).
- [7] Xiang, L., Han, B., Carpenter, C., Pratz, G., Kuang, Y., and Xing, L., “X-ray acoustic computed tomography with pulsed x-ray beam from a medical linear accelerator,” *Medical Physics* **40**, 010701 (Jan. 2013).
- [8] Xiang, L., Tang, S., Ahmad, M., and Xing, L., “High Resolution X-ray-Induced Acoustic Tomography,” *Scientific Reports* **6**, 26118 (May 2016).
- [9] Tang, S., Yang, K., Chen, Y., and Xiang, L., “X-ray-induced acoustic computed tomography for 3D breast imaging: A simulation study,” *Medical Physics* **45**, 1662–1672 (Apr. 2018).
- [10] Robertson, E., Samant, P., Wang, S., Tran, T., Ji, X., and Xiang, L., “X-Ray-Induced Acoustic Computed Tomography (XACT): Initial Experiment on Bone Sample,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **68**, 1073–1080 (Apr. 2021).
- [11] Choi, S., Park, S., Pyo, A., Kim, D.-Y., Min, J.-J., Lee, C., and Kim, C., “In situ x-ray-induced acoustic computed tomography with a contrast agent: A proof of concept,” *Optics Letters* **47**, 90 (Jan. 2022).
- [12] Wang, S., Ivanov, V., Pandey, P. K., and Xiang, L., “X-ray-induced acoustic computed tomography (XACT) imaging with single-shot nanosecond x-ray,” *Applied Physics Letters* **119**, 183702 (Nov. 2021).
- [13] Wang, S., Pandey, P. K., Lee, G., Van Bergen, R. J. P., Sun, L., Xu, Y., and Xiang, L., “X-ray-induced acoustic computed tomography: 3D X-ray absorption imaging from a single view,” *Science Advances* **10**, eads1584 (Dec. 2024).
- [14] Wang, L. V. and Yao, J., “A practical guide to photoacoustic tomography in the life sciences,” *Nature Methods* **13**, 627–638 (Aug. 2016).
- [15] Yao, J. and Wang, L. V., “Photoacoustic tomography: Fundamentals, advances and prospects,” *Contrast Media & Molecular Imaging* **6**, 332–345 (Sept. 2011).
- [16] Yao, D.-K., Zhang, C., Maslov, K., and Wang, L. V., “Photoacoustic measurement of the Grüneisen parameter of tissue,” *Journal of Biomedical Optics* **19**, 17007 (Jan. 2014).