Guest Editorial
A Glimpse Into the Cutting Edge of Interventional Ultrasound

BREAKTHROUGHS in deep learning (DL), artificial intelligence (AI), point-of-care ultrasound (POCUS), and medical robotics have set off an exciting era in interventional ultrasound. Advances in DL and AI have enabled better and faster-than-ever extraction of information from ultrasound data. POCUS is becoming increasingly popular due to its cost-effectiveness, improved image quality, and ease of use. In addition, manufacturers have moved away from analog beamforming to digital beamforming, which provides researchers with access to raw data which is usually more information-rich than beamformed B-mode images. Concurrently, medical robotics is becoming ever more established in its traditional application and is further finding new, emerging clinical applications. The Guest Editors are delighted to present 14 papers in this Spotlight Issue on Interventional Ultrasound.

A. Review of Ultrasound-Guided Interventions

The opening article by Masoumi et al. [A1] offers a comprehensive review of deep-learning algorithms in the realm of ultrasound-guided interventions. By examining the existing literature, the authors present a detailed analysis of the current trends and advancements in this field. Furthermore, they provide insightful recommendations for future research directions. The study contributes to the understanding of the recent works in deep-learning approaches for ultrasound-guided interventions, fostering further innovation in this domain.

B. Aiding Ultrasound Image Acquisition

The acquisition of high-quality ultrasound images presents a formidable challenge, even for expert sonographers. There were five submissions to address this challenge, two of them specifically for lung ultrasound due to the urgent need for low-cost and portable imaging of the lungs.

Cai et al. [A2] developed a high-precision positional and orientational localization system by incorporating an inertial measurement unit as a tracking system. The system includes simulations of the transmitter's acoustic pressure field, receiver configuration, position-dependent error, and sensor fusion. A prototype of the system was tested within the tracking volume commonly used in obstetric sonography at both slow and fast modes of ultrasound probe movement. To assess its performance, the system was compared against a commercial optical tracking device in the two speed ranges and achieved centimeter-level positional tracking accuracy.

Sai et al. [A3] presented a portable device for precise contact force in ultrasound data collection, which improves stability and reproducibility. The device includes a servo motor, gears, and a ball screw linear actuator. The force and position control system is combined with a pressure threshold to reduce chattering. The results show that the device overcomes hand and respiratory movement to improve stability and consistency, leading to more repeatability and imaging quality. The device can be handheld or integrated with a manipulator.

The same group [A4] later improved this design by making it lightweight and portable by incorporating a screw motor and Raspberry Pi as the controller, along with a user-friendly screen. Gravity compensation, error compensation, and an adaptive control algorithm ensure accurate force control. Clinical trials and extensive experiments validated its utility for various environments and prolonged examinations, reducing the reliance on clinical expertise. The device relieves stress on the sonographer's hand joints and enables rapid assessment of tissue elasticity.

Lung ultrasound (LUS) is a convenient method for diagnosing and evaluating respiratory disease. However, traditional clinical ultrasound scanning requires extensive experience. To address the shortage of medical resources, Zhang et al. [A5] proposed a robotic LUS scanning system based on visual perception and deep learning (DL). This system achieves target recognition, probe positioning, and probe movement. Using a depth camera, the system identifies LUS targets through improved DL-based target localization algorithms. Lastly, a position control strategy based on force feedback optimizes the probe's position and orientation, ensuring high-quality images and patient safety. Human LUS scanning experiments confirmed the system's accuracy. Another interesting robotic ultrasound system was proposed by Tan et al. [A6], which proposed a dual-probe system for acquiring lung ultrasound images. By optimizing the trajectory using a velocity look-ahead strategy, the system achieved more than 24% improvement in the stability of contact force and 29% increase in scanning efficiency. The robotic automatic scanning demonstrated more than 34 times better control over contact force compared to manual scanning. Notably, there was no significant

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difference in image quality between robotic scanning and manual scanning.

Trivedi et al. [A7] explored chirp-coded subharmonic imaging combined with Volterra filtering in vitro, demonstrating enhanced bubble-cloud detection and tracking. The authors show that the application of the quadratic Volterra filter significantly improves the contrast-to-tissue ratio, indicating its potential utility for histotripsy image guidance. The study shows that, for subharmonic imaging, the application of the quadratic Volterra filter improves the contrast-to-tissue ratio from 5.18 ± 1.29 to 10.90 ± 3.76 dB, relative to the application of the subharmonic matched filter.

C. MRI-Ultrasound Registration

While MRI provides exquisite details of patient anatomy, it cannot be easily used during interventions. Ultrasound, in contrast, can be easily incorporated into surgical procedures with minimal interference. To combine the high quality of MRI and ease of use of ultrasound, two papers investigated MRI-ultrasound registration in the context of neurosurgery and prostate surgery.

Bierbrier et al. [A8] developed a technique to measure MRI-ultrasound registration errors, the first algorithm to estimate errors comprehensively in multimodal image registrations. It uses a sliding-window neural network that operates on a voxel level. For training data with known registration errors, the authors generated simulated ultrasound images from pre-operative MRI and artificially distorted them. The model was tested using artificially distorted simulated ultrasound data and real ultrasound data with manually marked landmark points, achieving a mean absolute error of approximately 0.98 ± 0.99 mm on simulated data and 2.2 ± 1.9 mm on real data.

Guo et al. [A9] proposed a new registration pipeline for the registration of 2-D ultrasound to 3-D MRI, which utilizes deep learning and operates automatically without external tracking devices. It consists of three main parts: 1) a frame-to-frame registration network that estimates the 3-D spatial position of the current frame based on previous video context, 2) a frame-to-slice correction network that adjusts the estimated frame position using 3-D ultrasound volumetric information, and 3) a similarity filtering mechanism that selects the frame with the highest image similarity to the query frame. The authors evaluated the approach on a clinical dataset of 618 subjects and tested its potential for real-time 2-D ultrasound to 3-D MR fusion. The proposed method achieved an average target navigation error of approximately 1.9 mm at a speed of 5 to 14 fps.

D. 3-D Ultrasound Elastography

Ultrasound-guided interventions heavily rely on real-time imaging. Utilizing 3-D imaging instead of conventional 2-D images allows for enhanced spatial information as it considers the entire volume of data, but it comes at the expense of longer acquisition and processing time.

Aleef et al. [A10] introduced a novel 3-D hand-operated endorectal shear wave absolute vibro-elastography (S-WAVE) system for prostate biopsy. S-WAVE enables quantitative evaluation of tissue stiffness using external multi-frequency excitation. The system incorporates an external exciter mounted directly to the transducer and allows effective frame rates of up to 250 Hz for imaging shear waves. The system's performance was assessed using eight quality assurance phantoms, while in vivo validation was conducted by intercostally scanning the livers of seven healthy volunteers. The obtained results were compared with 3-D magnetic resonance elastography (MRE) and an existing 3-D S-WAVE system employing a matrix array transducer and showed high correlations.

Hashemi et al. [A11] also proposed a SWAVE technique that employs a matrix transducer for real-time volumetric acquisition. Here, the tissue motion is estimated to solve an inverse problem based on wave equations for tissue elasticity information. The system allows a frame rate of 2000 volumes per second to acquire 100 radio frequency (RF) volumes in just 0.05 s. By employing a planewave and a compounded diverging wave, the authors estimated axial, lateral, and elevational displacements. The calculated curl of the displacements, along with local frequency estimation, was used to determine tissue elasticity in the acquired volumes. The ultrafast acquisition capability significantly expands the feasible S-WAVE excitation frequency range, reaching up to 800 Hz, enabling advanced tissue characterization.

E. Ultrasound-Guided Orthopedic Procedures

Incorporating ultrasound into orthopedic procedures has been investigated by several researchers with the main aim of decreasing intra-operative radiation exposure and providing improved guidance.

Hohlmann et al. [A12] proposed a processing system to produce complete bone models using 3-D freehand ultrasound scans. The approach involves the integration of a convolutional neural network (CNN) and a statistical shape model (SSM) to segment and extend the bone surface. The authors assessed the method on ten individuals, comparing the ultrasound-generated models to an MRI benchmark in a real-life setting. The measurements of the femur and tibia bones obtained through partial freehand 3-D scanning differed from the MRI reference by approximately 0.7–0.8 mm. Following the extrapolation process, the complete bone model exhibited an error below one millimeter for the femur and approximately 1.24 mm for the tibia.

Brößner et al. [A13] proposed a deep-learning-based bone segmentation and registration system in the context of ultrasound-guided computer-assisted scaphoid fracture fixation surgery. Successful screw placement was achieved for all ten screws, with deviations from the planned axis of 1.0 ± 0.6 and 0.7 ± 0.3 mm at the distal and proximal pole, respectively. With a complete processing time of 12 s, the method holes promise for integrating into the surgical workflow.

Wilson et al. [A14] propose a deep-learning-based self-supervised learning approach to analyze high-frequency, high-resolution micro-ultrasound data for prostate cancer detection. Through this approach, authors achieved an AUROC score of 91% in distinguishing cancer from non-cancer tissue using a dataset of 1028 biopsy cores from 391 subjects across two clinical centers.

F. Final Remarks

The Guest Editors thank all authors for their outstanding contributions. The studies showcased here have paved the way for exciting advancements, addressing key challenges and refining techniques. The Guest Editors hope this Spotlight Issue will stimulate further research, build a strong foundation for further advancements, and reinforce interventional ultrasound's position as an indispensable tool in modern healthcare.

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APPENDIX: RELATED ARTICLES

[A1] N. Masoumi, H. Rivaz, I. Hacihaliloglu, M. O. Ahmad, I. Reinertsen, and Y. Xiao, "The big bang of deep learning in ultrasound-guided surgery: A review," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 909–919, Sep. 2023, doi: 10.1109/TUFFC.2023.3255843.

[A2] Q. Cai et al., "Inertial measurement unit-assisted ultrasonic tracking system for ultrasound probe localization," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 920–929, Sep. 2023, doi: 10.1109/TUFFC.2022.3207185.

[A3] H. Sai, L. Wang, J. Zhang, C. Xia, and Z. Xu, "Portable device to assist with force control in ultrasound acquisition," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 930–943, Sep. 2023, doi: 10.1109/TUFFC.2022.3181287.

[A4] H. Sai, Z. Xu, C. Xia, L. Wang, and J. Zhang, "Lightweight force-controlled device for freehand ultrasound acquisition," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 944–960, Sep. 2023, doi: 10.1109/TUFFC.2023.3252015.

[A5] B. Zhang, H. Cong, Y. Shen, and M. Sun, "Visual perception and convolutional neural network-based robotic autonomous lung ultrasound scanning localization system," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 961–974, Sep. 2023, doi: 10.1109/TUFFC.2023.3263514.

[A6] J. Tan et al., "Fully automatic dual-probe lung ultrasound scanning robot for screening triage," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 975–988, Sep. 2023, doi: 10.1109/TUFFC.2022.3211532.

[A7] V. V. Trivedi, E. L. Wallach, K. B. Bader, and H. Shekhar, "Contrast-enhanced imaging of histotripsy bubble clouds using chirp-coded excitation and Volterra filtering," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 989–998, Sep. 2023, doi: 10.1109/TUFFC.2023.3289918.

[A8] J. Bierbrier, M. Eskandari, D. A. Di Giovanni, and D. L. Collins, "Toward estimating MRI-ultrasound registration error in image-guided neurosurgery," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 999–1015, Sep. 2023, doi: 10.1109/TUFFC.2023.3239320.

[A9] H. Guo et al., "Ultrasound frame-to-volume registration via deep learning for interventional guidance," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1016–1025, Sep. 2023, doi: 10.1109/TUFFC.2022.3229903.

[A10] T. A. Aleef et al., "3-D transducer mounted shear wave absolute vibro-elastography: Proof of concept," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1026–1038, Sep. 2023, doi: 10.1109/TUFFC.2023.3249795.

[A11] H. S. Hashemi, S. K. Mohammed, Q. Zeng, R. Z. Azar, R. N. Rohling, and S. E. Salcudean, "3-D ultrafast shear wave absolute vibro-elastography using a matrix array transducer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1039–1053, Sep. 2023, doi: 10.1109/TUFFC.2023.3280450.

[A12] B. Hohlmann, P. Brößner, L. Phlippen, T. Rohde, and K. Radermacher, "Knee bone models from ultrasound," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1054–1063, Sep. 2023, doi: 10.1109/TUFFC.2023.3286287.

[A13] P. Brößner, B. Hohlmann, K. Welle, and K. Radermacher, "Ultrasound-based registration for the computer-assisted navigated percutaneous scaphoid fixation," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1064–1072, Sep. 2023, doi: 10.1109/TUFFC.2023.3291387.

[A14] P. F. R. Wilson et al., "Self-supervised learning with limited labeled data for prostate cancer detection in high frequency ultrasound," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 9, pp. 1073–1083, Sep. 2023, doi: 10.1109/TUFFC.2023.3297840.

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