Array Transducer Design: A Vibrant Research Theme in Medical Ultrasonics

SINCE the 1970s, when portable transducer arrays were first introduced for medical ultrasound imaging, they have undergone substantial technological developments. The development of advanced arrays is often motivated by the need to achieve high diagnostic and therapeutic efficacy and to serve new fields of application. In the past few decades, medical ultrasound array design has been an active research area with challenging technical requirements that continually seek to reduce physical size, improve sensitivity, optimize the number of array elements, realize wide bandwidth, and achieve high output power. The need to devise arrays with increased performance has concurrently stimulated advances in transducer technologies, microelectronics, and array layout design. Nowadays, representative examples can be found for both 2-D and 3-D applications such as high-intensity-focused ultrasound arrays, very-high-frequency or dual-frequency probes, kerfless arrays, 2-D sparse arrays, and probes with embedded application-specific integrated circuits. The emergence of these advanced arrays has, in turn, stimulated the development of novel, customized transmission and reception approaches, image reconstruction algorithms, and data recovery strategies to exploit or deal with the peculiarities of a specific array.

To celebrate the vibrant research activities in the above-mentioned areas, IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL has prepared a Spotlight Issue on the theme of "Recent Advances in Medical Ultrasound Array Design." This Spotlight Issue comprises a collection of two review articles and ten original research papers. It serves to highlight the latest technological advances in medical ultrasound array design and to provide a resource point for colleagues who are interested in learning about recent progress on this research theme. Four major bodies of contributions have been covered in this Spotlight Issue, as outlined in the subsections below.

A. Emerging Arrays for 3-D Ultrasound Imaging

This Spotlight Issue opens with review papers on two emerging types of array transducers for 3-D imaging applications: 1) row-column (RC) arrays and 2) 2-D sparse arrays.

In [A1], Jensen *et al.* presented recent advancements on RC arrays. The authors first provide historical information on the development of RC arrays, and it is followed by a summary of challenges in RC imaging. Several image formation techniques for RC arrays are also reviewed that serve as a resource point to newcomers to RC array research. The article concludes by providing example applications of RC array and insights into the future directions of the field.

On the other hand, in [A2], Ramalli *et al.* introduced the main factors influencing the design of sparse arrays and illustrated the main design methods. They reviewed both the experimental implementations of sparse arrays and their applications. They concluded that although some drawbacks must be solved (e.g., the limited signal-to-noise ratio), sparse arrays could represent a feasible option for the development of 3-D imaging systems at a moderate cost, and for preclinical application of novel methods.

B. Application-Specific Array Design

In some applications, the design of array transducers needs to be customized to fit special technical requirements. This Spotlight Issue has showcased three representative examples of these application-specific arrays.

In [A3], Benedict *et al.* detailed the design of a 2-D array and the driving system for powering biomedical ultrasonic implants. They assembled a 52-element, 1.8-mm pitch, 13-mm diameter array on a 0.3-mm flexible printed circuit board. Such design specifications, while meeting emission limits set forth by the Food and Drug Administration (FDA), sought to optimize the link efficiency, the intensity at the implant, and grating lobes. Also, energy transfer efficiency was maximized through time reversal and the related phase reversal approach.

In [A4], Stocker *et al*. described the design and fabrication of a 260-element phased array for use in histotripsy in the abdominal cavity. The phased array design was physically compact due to the use of arbitrary element shapes. The authors demonstrated the feasibility of their design of with arc-shaped elements, and it showed an excellent steering range for histotripsy. A modular approach, wherein each element can be tested and replaced separately, was shown to improve the overall yield of the full array.

In [A5], Pialot *et al.* showed that a 64-element, arthroscopic probe can be used for imaging the vascularization of the meniscus during surgery. Specifically, they demonstrated, through phantom experiments, that the intrinsic low sensitivity of such a miniaturized probe can be enhanced (by up to 10 dB) through a chirp-coded sequence with a compression filter robust to attenuation, even though there was a concomitant reduction in axial resolution (13% worse).

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C. Fabrication and Testing of Array Transducers

Successful development of array transducers after all requires mature protocols for probe fabrication and metrology. In this Spotlight Issue, three papers have been included to disseminate the latest knowledge and know-how on this engineering aspect of medical array design.

In [A6], Roa *et al.* addressed one critical challenge in fabricating micro-ultrasound arrays: that is, spatial constraints in making electrical connections to array elements. By using the laser ablation process, the authors have successfully patterned high-density flexible circuit cablings (with traces of 60 μm pitch and 5 μm wide) for a micro-ultrasound array with a center frequency of 43 MHz and 30 μm pitch (sublambda pitch). The array assembly showed good yield and consistent impedance across channels. These results confirmed the feasibility of prototyping micro-ultrasound arrays for endoscopic applications.

In [A7], Wei *et al*. described the design and prototyping of two sparse volumetric-imaging arrays based on the "lead zirconate titanate on printed circuit board" (PZT-on-PCB) technology. The design incorporated discrete in-probe small-signal amplifiers to improve the signal-to-noise ratio. With this design, the authors were able to achieve the required bandwidth for using the probes as a platform for sparse array imaging developments.

In [A8], Maffett *et al.* performed a metrology investigation to evaluate the feasibility of using a density-tapered spiral array transducer for high-volume-rate 3-D imaging. The spiral array was fabricated using a capacitive micromachined ultrasound transducer (CMUT) design approach. The results showed that the spiral array could consistently deliver unfocused transmissions with a spatial-peak, pulse-average intensity of 0.3 W/cm^2 (within the FDA limit), and its received pulse echoes could be beamformed to produce B-mode images with good spatial resolution.

D. New Imaging Schemes for Ultrasound Arrays

As array transducers are actively being developed, novel schemes and algorithms have emerged to make adept use of these arrays to achieve robust imaging performance. This Spotlight Issue has included four articles on different aspects of this research topic.

In [A9], Sobhani *et al.* introduced a new coherent compounding scheme for ultrafast coded synthetic aperture imaging using a new type of RC arrays with bias-switchable functionalities. This new method produced high-quality images that were not susceptible to tissue motion. It was deemed to yield a good tradeoff between system complexity, field of view, and frame rate.

In [A10], Lafci *et al.* aimed at aiding the development of optimized hardware and image acquisition strategies for reflection ultrasound computed tomography (RUCT). The authors experimentally showed that a reduced number of large elements allowed the preservation of imaging performance at the central part of the image. On the other hand, a sparse distribution of small elements was found resulting in a more uniform performance across the field of view with reduced contrast.

In [A11], Xiao *et al.* investigated the possibility of reconstructing missing channel data when only half of the array elements may be used concurrently due to constraints in system electronics. The solution was based on deep learning in the form of a convolutional encoder–decoder neural network. The authors showed with *in-vivo* data that, when using the proposed deep learning framework, degradation of the resulting B-mode image quality was limited (below 3 dB) even if only every other array channel was used for pulse-echo data sampling.

In [A12], Soozande *et al*. reported an imaging sequence for a dedicated 3-D intracardiac probe that can yield high volumetric rates of 1000 volumetric frames per second. This imaging sequence was intended for use in mapping the electromechanical wave propagation pattern in the heart. The authors showed via extensive simulations that high volumetric frame rates and good image quality could be simultaneously achieved when using micro-beamforming, which was needed to reduce cable count in the catheter shaft.

E. Final Remarks

The Guest Editors would like to take this opportunity to thank all contributing authors for their excellent work. The Guest Editors hope this Spotlight Issue can serve to prompt further engineering innovations and applications of medical ultrasound array transducers. Realization of these advances will be crucial for the continued growth of ultrasound imaging in clinical diagnostics.

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APPENDIX: RELATED ARTICLES

[A1] J. A. Jensen *et al.*, "Anatomic and functional imaging using row–column arrays," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3191391.

[A2] A. Ramalli, E. Boni, E. Roux, H. Liebgott, and P. Tortoli, "Design, implementation, and medical applications of 2-D ultrasound sparse arrays," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3162419.

[A3] B. C. Benedict, M. M. Ghanbari, and R. Muller, "Phased array beamforming methods for powering biomedical ultrasonic implants," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3197705.

[A4] G. E. Stocker *et al.*, "A modular, kerf-minimizing approach for therapeutic ultrasound phased array construction," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3178291.

[A5] B. Pialot, A. Bernard, H. Liebgott, and F. Varray, "Sensitivity enhancement using chirp transmission for an ultrasound arthroscopic probe," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3160880.

[A6] C.-F. Roa *et al.*, "Fine pitch flexible printed circuit board patterning for miniaturized endoscopic microultrasound arrays," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3189338.

[A7] L. Wei *et al.*, "Sparse 2-D PZT-on-PCB arrays with density tapering," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3204118.

[A8] R. Maffett *et al.*, "Unfocused field analysis of a density-tapered spiral array for high-volume-rate 3-D ultrasound imaging," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3188245.

[A9] M. R. Sobhani, M. Ghavami, A. K. Ilkhechi, J. Brown, and R. Zemp, "Ultrafast orthogonal row–column electronic scanning (uFORCES) with bias-switchable top-orthogonal-to-bottom electrode 2-D arrays," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3189345.

[A10] B. Lafci, J. Robin, X. L. Deán-Ben, and D. Razansky, "Expediting image acquisition in reflection ultrasound computed tomography," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3172713.

[A11] D. Xiao, W. M. K. Pitman, B. Y. S. Yiu, A. J. Y. Chee, and A. C. H. Yu, "Minimizing image quality loss after channel count reduction for plane wave ultrasound via deep learning inference," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3192854.

[A12] M. Soozande *et al.*, "Imaging scheme for 3-D high-frame-rate intracardiac echography: A simulation study," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 10, Oct. 2022, doi: 10.1109/TUFFC.2022.3186487.

Alessandro Ramalli (Senior Member, IEEE) was born in Prato, Italy, in 1983. He received the master's degree in electronics engineering from the University of Florence, Florence, Italy, in 2008, and the joint Ph.D. degree in electronics system engineering and in automation, systems, and images from the University of Florence and the University of Lyon, Lyon, France, in 2012.

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