Ultrasound Transducers for Biomedical Imaging and Therapy

Ultrasound has been one of the most widely adopted and rapidly developing diagnosis and therapy modalities because of its nondestructive and nonion radiative nature since the first published medical ultrasound paper in 1942.\(^1\) Ultrasound transducers, as key components in ultrasound instruments, have been developed from single element transducers to two-dimensional (2D) arrays with thousands of elements [1]\(^2\) toward the goal of real-time imaging with desired resolution and imaging depth or sufficient acoustic energy for spatially and temporally controlled therapies. Generally, in the field of medical imaging, high-resolution, super-resolution or super-harmonic imaging, etc., demand high frequency, broadband, or multifrequency transducers [2–6] in the form of single element or arrays. Arrays with a relatively large number of elements are usually preferred in real-time three-dimensional (3D) imaging including ultrafast imaging [1].\(^3\)

In focused ultrasound, arrays with a large number of elements for imaging guided therapy with precise spatial control are desirable [7,8]. In recent years, in addition to imaging and focused ultrasound therapy (or high intensity focused ultrasound), pulsed ultrasound or low intensity ultrasound for particle manipulation and therapy including neural stimulation has received tremendous research attention [9–13]. The power intensity of pulsed ultrasound is usually higher than that of imaging ultrasound, but much lower than that of focused ultrasound or HIFU. As new medical ultrasound applications are booming, challenges for ultrasound transducers must be taken well by the community.

High Frequency Transducers

One of the challenges is to develop high frequency transducers for high-resolution imaging [2,14]. Different piezoelectric thin films have been investigated for high frequency transducers, though the poor electromechanical coupling properties are not preferred broad bandwidth transducers [6]. Piezoelectric composite micromachined ultrasound transducers (PC-MUT) were first reported in 2006 suggesting promising sensitivity and bandwidth for intravascular ultrasound imaging [6,15]. Focused lithium niobate transducers were also successfully developed for high frequency imaging applications [16]. High frequency linear arrays (up to 75 MHz) have been successfully developed for small animal imaging.\(^3\) More recently, particle manipulations using high frequency-focused transducers were demonstrated because of the high radiation force and fine acoustic beam of high frequency ultrasound [10]. High frequency composite array transducers and 2D arrays are being studied, and they will be critical to high-resolution real-time 2D and 3D imaging [6].

Multi-Frequency Transducers

Because of the limited bandwidth of transducers, multifrequency transducers are necessary for advanced imaging and therapies. For example, in superharmonic imaging, low frequency (\(f_0\)) ultrasound waves are transmitted to excite microbubbles for nonlinear responses, and the high order of harmonics (e.g., \(3f_0 \geq 7f_0\)) are received with a high frequency transducer, and hence, a dual frequency transducer is required [17]. The superharmonic imaging technique (also known as acoustic angiography) is capable of high-resolution imaging of vascular structure that is associated with inflammation and angiogenesis [18,19]. Dual frequency transducers are also desired for multimode imaging including conventional B-mode, subharmonic, and harmonic imaging [4], which is believed to be critical in obtaining images with less near-field and side lobe artifact, better signal-to-noise ratio, high agent-to-tissue ratios, etc. [20]. In the case of imaging with both high resolutions at the near field and a relative deep field, a multifrequency transducer configuration is also adopted since the low frequency transducer can be used for imaging at depth, while the high frequency one can be used for high resolution imaging.

In addition to imaging, ultrasound therapy can benefit from multifrequency transducers. Recent works on multifrequency tissue ablation found that temperature rise rate and saturated temperature due to bioheating could be higher by using multifrequency ultrasound rather than the conventional single frequency one, which is likely attributed to the enhanced cavitation in tissue ablation using multifrequency ultrasound [21,22]. Similarly, thrombolysis using dual frequency ultrasound showed enhanced lytic rate over the conventional single frequency ultrasound [23]. Further, the use of ultrasound for various droplet atomization and disintegration for various lung therapy and drug delivery has attracted intensive research in recent years [24].

Despite the demand from imaging and therapy applications, multifrequency ultrasound transducers are generally not commercially available. It is believed that more efforts on development of multifrequency transducers and arrays are needed to address these challenges.

Two-Dimensional Transducer Arrays

Real-time 3D imaging can be obtained using 2D transducer arrays, and has been successfully used in fetal, cardiac, transrectal, and intra-vascular applications [1,25]. The large number of elements is important to achieve the 3D imaging; however, the fabrication cost of 2D arrays has been a concern. Alternative 2D array techniques include capacitive-micromachined ultrasound transducers (CMUT) and piezoelectric-micromachined ultrasound transducers (PMUT) [26,27]. PMUTs and CMUTs take advantage of semiconductor fabrication processes and the integrated circuits.
which can lead to significantly reduced 2D array cost. However, further development of CMUT and PMUT is necessary prior to their clinical deployment because of their poor sensitivity and other issues. More recently, micromachined arrays using bulk piezoelectric wafers were successfully demonstrated, with reasonable imaging results [6]. Another alternative approach was reported by developing row-column 2D arrays, so that the high number of interconnects and electronic channels can be avoided (or from $N \times N$ to $2N$; $N$ is the element number along elevation or azimuth direction) [28]. In a row-column 2D array, the array elements can be addressed by their row index in transmitting and by their column index in receiving, or vice versa. Imaging results using row-column 2D arrays were proved to be comparable with those obtained using conventional 2D arrays. Both CMUT arrays and conventional piezoelectric arrays were studied in the form of row-column configurations.

On the other hand, low cost transducer arrays are increasingly in demand by the portable ultrasound devices, which can be a smart phone-based ultrasound imaging device (e.g., butterfly⁴) or a fingerprint device in a smart phone [29] or part of a wearable health care system. These portable ultrasound devices poise to the bright future of micromachined transducer arrays. It is likely that the ultrasound community will conduct more research on 2D array design, fabrication, and the associated imaging algorithm development within the next decade or so.

**Photoacoustic Transducers**

Photoacoustic (PA) imaging has been successfully developed and applied in small animal imaging [30]. PA offers greater specificity than conventional ultrasound imaging with the ability to detect hemoglobin, lipids, water, and other light-absorbing chromophores, but with greater penetration depth than other optical imaging modalities [31]. PA can also be used to visualize anatomical microvasculature, and provide functional information in the form of blood oxygenation, blood flow, and temperature. Broadband transducers are required in PA imaging since the laser pulse induced acoustic waves are known with a broad bandwidth and relatively high frequency (>10 MHz). More recently, photoacoustic effect-based laser ultrasound transducer was reported with impressive high pressure amplitude and bandwidth [32]. The so-called laser ultrasound utilizes a layer of light absorptive material and a layer of thermal elastic material to efficiently convert optical energy into acoustic pulses, which can be effective in triggered drug release and other therapies [33]. The on-going fiber laser ultrasound transducer development may open up new minimal invasive and intracavitary ultrasound therapies.

Other emerging ultrasound transducer research and development efforts can also be found to address the increasing biomedical challenges. Deep brain stimulation using ultrasound can be attractive because of its noninvasive feature, and a relatively large array capable of wave propagation control through the human skull is required [11,12]. High power intensity ultrasound transducers with miniature aperture are required for the promising histotripsy study [34]. Catheter transducers for side-viewing and forward-viewing imaging and therapy may offer unprecedented opportunity for minimal invasive diagnosis and treatment [35–37]. Transducers with embedded sensors are important for automated ultrasound imaging, in combination with artificial intelligence (AI) [38,39]. Bone, lung, and other tissue/organs that were regarded as ultrasound nonapplicable are now receiving serious investigations on ultrasound diagnosis and therapy [40–43].

In addition to the above-mentioned biomedical application needs, new transducer materials and structure designs can certainly motivate the ultrasound transducer innovations [44,45].

Ultrasound is one of the main areas inspired by all disciplines including engineering, science, and medicine for translational research. A collaborative team from these disciplines usually conducts this type of multidisciplinary research, toward innovative ultrasound transducers for effective clinical applications. Translation of insights from an idea for a clinical need, which could start from the hospital to preliminary investigation by scientists to determine its feasibility then to engineers to produce a device or a protocol to respond to the demand, is a powerful collaborative scheme of research. The outcome of such an investigation will be taken back to the hospital to be tested by the clinicians for performance and validation. Thus, the development by multidisciplinary researchers into diagnostic or therapeutic devices or procedures is undoubtedly a fruitful area of research. The ASME Journal of Engineering and Science in Medical Diagnostics and Therapy recognizes the importance of translational research and acknowledges that such research is best carried out through collaborative approaches based on applied and basic sciences. One of the goals of this journal is to provide a platform in an area such as biomedical ultrasound that is open, efficient, and responsive to the needs of individuals or teams of investigators involved in medical translational fields of research. The journal aims at encouraging participation of researchers from engineering, science, and the medical profession by making the articles published in this journal readable to members from these communities. Engineering knowledge and perspectives are essential in solving healthcare challenges. The journal strives for moving research areas such as ultrasound from bench to bedside by integrating ideas from any of the disciplines with clinical needs and by maximizing the exposure of knowledge from this area of translational research to the most relevant readers.

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**References**


