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High-Frequency Ultrasonic Imaging of the Anterior Segment Using an Annular Array Transducer

Ronald H. Silverman, Ph.D.^{1,2}, Jeffrey A. Ketterling, Ph.D.², and D. Jackson Coleman, M.D.¹

¹ Department of Ophthalmology, Weill Medical College of Cornell University, New York, NY

² Frederic L. Lizzi Center for Biomedical Engineering, Riverside Research Institute, New York, NY

Abstract

Objective—Very-high-frequency (>35 MHz) ultrasound (VHFU) allows imaging of anterior segment structures of the eye with a resolution of less than 40- μ m. The low focal ratio of VHFU transducers, however, results in a depth-of-field (DOF) of less than 1-mm. Our aim was to develop a high-frequency annular array transducer for ocular imaging with improved DOF, sensitivity and resolution compared to conventional transducers.

Design—Experimental Study

Participants—Cadaver eyes, *ex vivo* cow eyes, *in vivo* rabbit eyes.

Methods—A spherically curved annular array ultrasound transducer was fabricated. The array consisted of five concentric rings of equal area, had an overall aperture of 6 mm and a geometric focus of 12 mm. The nominal center frequency of all array elements was 40 MHz. An experimental system was designed in which a single array element was pulsed and echo data recorded from all elements. By sequentially pulsing each element, echo data were acquired for all 25 transmit/receive annuli combinations. The echo data were then synthetically focused and composite images produced. Transducer operation was tested by scanning a test object consisting of a series of 25- μ m diameter wires spaced at increasing range from the transducer. Imaging capabilities of the annular array were demonstrated in *ex vivo* bovine, *in vivo* rabbit and human cadaver eyes.

Main Outcome Measures—Depth of field, resolution and sensitivity.

Results—The wire scans verified the operation of the array and demonstrated a 6.0 mm DOF compared to the 1.0 mm DOF of a conventional single-element transducer of comparable frequency, aperture and focal length. B-mode images of *ex vivo* bovine, *in vivo* rabbit and cadaver eyes showed that while the single-element transducer had high sensitivity and resolution within 1–2 mm of its focus, the array with synthetic focusing maintained this quality over a 6 mm DOF.

Conclusion—An annular array for high-resolution ocular imaging has been demonstrated. This technology offers improved depth-of-field, sensitivity and lateral resolution compared to single-element fixed focus transducers currently used for VHFU imaging of the eye.

Introduction

Ultrasonic imaging allows non-invasive visualization of ocular anatomy and pathology, even in the presence of optical opacities. Factors that impact upon the overall utility of ultrasound systems include resolution, penetration, speed (frames/second), sensitivity (signal/noise) and

Address Correspondence to: Ronald H. Silverman, Ph.D., Department of Ophthalmology, Weill Medical College of Cornell University, 1300 York Avenue, Room K808, New York, NY 10021, Tel: (212) 746-6106, Fax (212) 746-8850, Email: ros2012@med.cornell.edu.

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depth-of-field (DOF). Resolution generally improves (and penetration declines) with frequency. Very-high-frequency (>35 MHz) ultrasound (VHFU) provides an axial resolution of <40- μ m, allowing exquisitely detailed depiction of anatomic structures. However, attenuation at this frequency is high, even in water, limiting clinical imaging in this frequency range to the anterior segment.

Clinical VHFU, or ultrasound biomicroscopy (UBM), systems were introduced over a decade ago^{1–3} and have been used for imaging and biometric characterization of the cornea^{4–7}, glaucoma diagnosis^{8–9}, visualization of lens implants^{10–11}, and diagnosis of tumors¹², cysts¹³, and foreign bodies¹⁴. These systems employ mechanically scanned, single-element, spherically-focused transducers. The function of the transducer is to convert an electrical pulse into an acoustic pulse and to then convert echoes from tissue structures back into voltages from which images are formed. As the F-ratio (focal-length/aperture) of the transducer decreases, lateral resolution in the focal plane improves, but DOF degrades. For a 50-MHz transducer with an aperture $a = 6$ mm and focal length $L = 12$ mm, the expected DOF is 0.85 mm (from $\text{DOF} = 7.08\lambda F^2$, where λ = wavelength and $F = L/a$).¹⁵ Outside this small region, signal amplitude and resolution fall precipitously. Experienced users of UBM systems are quite familiar with this “sweet spot”, which constrains what can be seen in any one image.

Linear array transducers are composed of numerous independent transducer elements. A linear array can be synthetically focused electronically, unlike single element transducers which are constrained to focus at a fixed point. Linear arrays, however, are not currently commercially available at frequencies above 15 MHz because of difficulties in fabrication¹⁶ (individual transducer elements are a wavelength in dimension) and the unavailability of control electronics.¹⁷ Annular arrays, in which independent transducer elements are arranged in concentric rings, can be synthetically focused without the constraint of small element sizes and complicated electronics. Focusing is accomplished by applying appropriate time delays to the excitation pulses and the echoes received by each element (Figure 1). Although an annular array cannot be electronically steered laterally, as can a linear array, it can be as compact as a fixed-focus single-element transducer and thus fit in a typical hand-held sector scan probe housing.

Annular arrays can be fabricated with no curvature (i.e., flat)^{18–19}, with a spherical lens²⁰, or with a spherical geometry^{21–22}. While the principle of dynamic focusing is the same for all, spherically curved devices are advantageous compared to flat arrays because fewer elements are required to achieve the same improvement in DOF. Spherical curvature also leads to better lateral resolution for two transducers of similar aperture and number of elements.

This report describes a prototype 40-MHz spherically-curved annular array and testing of its performance in imaging of the anterior segment of the eye.

Materials and Methods

The spherically-curved annular array developed for these studies consisted of five concentric rings of equal area. The piezoelectric material used to send and receive ultrasound pulses was a 9- μ m thick polyvinylidene fluoride (PVDF) membrane (Ktech Corp., Albuquerque, NM) providing a nominal center frequency of 40 MHz. This was bonded to a copper-clad polyimide film (RFlex 1000L810, Rogers Corp., Chandler, AZ) upon which the array pattern was formed using standard printed circuit board techniques. The 6-mm diameter array was then pressed against a steel sphere to produce a 12-mm radius of curvature. The array was fitted into a UHF connector to provide mechanical protection and electrical shielding (Figure 2). Fabrication is described in greater detail by Ketterling (2005).²¹

We developed a LabVIEW program (National Instruments, Austin, TX) to control the components of the PC-based scanning system, including the pulser, the switching unit, receive channels, and the three orthogonal linear motion stages used for scanning.

During scanning, the transducer is mechanically translated and pulses emitted at evenly spaced positions. In a conventional system using a single-element transducer, one pulse/echo data record is acquired at each position. With an n -element annular array, however, it is necessary to acquire n^2 records per position – one for each possible send/receive pair. Hence, 25 pulse/echo records must be acquired per position with the five element array. To accomplish this, five scans were performed to form a single image: one scan for each pulsed ring, with echo data recorded from all five rings (Figure 3). Simple addition of all 25 echo sequences will produce an echo sequence equivalent to that of a focused single element transducer. However, by adding appropriate time delays to the digitized echo data from each send/receive ring pair and then summing, synthetic focusing can be achieved at any axial depth.²¹ We produced composite synthetically focused images by merging synthetically focused data over a series of 41 focal zones of increasing depth. Acquisition time for a single synthetically focused image was approximately 40 seconds.

The array was initially tested by scanning a series of 25- μ m diameter wires arranged in 1-mm intervals of increasing depth. The performance of the array was compared to that of a single-element transducer of similar center frequency, bandwidth, aperture and focal length (Panametrics PI50-2 PVDF based 40-MHz transducer; 6-mm aperture; 12-mm focal length).

The ocular imaging capabilities of the annular array were evaluated in *ex vivo* bovine, *in vivo* rabbit and cadaver eyes. Institutional Review Board (IRB)/Ethics Committee approval was obtained for the use of human tissues. Animal experimentation was performed in compliance with the Association for Research in Vision and Ophthalmology (ARVO) Resolution on the Use of Animals in Research and under a protocol approved by the Institutional Animal Care and Use Committee of the Weill Medical College of Cornell University.

We compared the performance of the array to that of the single-element transducer in imaging the anterior segment. The array was tested with simple addition of the individual channels (simulating a single-element transducer) and with synthetic focusing. Consecutive scans were made of each eye, decreasing the range between the transducer and the eye by 1-mm steps, allowing assessment of image quality as the geometric focus of the transducer was moved depth-wise through the anterior segment.

Results

Comparative images of 25- μ m wires obtained with the single-element transducer and the annular array in both summed and synthetic focus modes are shown in Figure 4. Note the decreased sensitivity and lateral spreading of wire targets outside the 12-mm geometric focus in images made with the single-element probe or when the array is operated without synthetic focus.

Figures 5 and 6 are scans of *ex vivo* cow eyes. In Figure 5, the eye was scanned parallel to and through the optic axis, with echo complexes acquired from the cornea and anterior lens surface. The figure compares images produced with and without synthetic focusing. Synthetic focusing allowed simultaneous high-resolution visualization of the cornea and lens, which are more than 3 mm apart (similar to a typical human anterior chamber depth). The results demonstrate the improved signal-to-noise ratio (SNR) achieved when the data are processed with the synthetic-focusing algorithm. This SNR improvement resulted from the increase in echo amplitude as the time-shifted echo data from each array transmit/receive pair were coherently summed,

while the random background noise underwent an averaging effect. The improvement in SNR became more pronounced when the strongest reflectors were situated away from the geometric focus. Figure 6 illustrates the improved DOF obtained using synthetic focusing. Here, a single-element transducer is compared to the annular array in summed and synthetic-focus modes. Both the single-element (Figure 6a) and array data with no delay corrections (Figure 6b) revealed a zone of high sensitivity and high resolution limited to the cornea (where the geometric focus was situated), while the iris and lens echoes were seen at reduced amplitude and resolution. These two images are qualitatively identical because the summed data with no delay corrections simulated a single-element transducer with a 6-mm aperture and 12-mm focal length. After synthetic focusing was applied to the array data (Figure 6c), the iris and lens were brighter and sharper and the angle more clearly seen, demonstrating improved DOF and lateral resolution.

An *in vivo* anterior-segment scan of a rabbit eye is shown in Figure 7. The summed data with no delay corrections (Figure 7a) revealed the cornea and lens, but the iris, angle, and ciliary body were poorly visualized. After synthetic focusing (Figure 7b), an improved delineation of the angle and ciliary processes was observed and the SNR was improved by 6-dB. In spite of environmental electrical noise, the *in vivo* rabbit results emphasize how an annular array is able to resolve ocular features spanning more than 5-mm of axial range.

The anterior segment of a human cadaver eye was scanned (Figures 8 and 9). Figure 8 shows an image formed from just the center element of the array ($F = 4.9$) (Figure 8a), from the full array with no delay corrections ($F=2$) (Figure 8b), and with synthetic focusing (Figure 8c). The center-element image demonstrated a larger DOF than the full array aperture, as would be expected because of the higher F-number, but at the sacrifice of resolution. The synthetically focused image (Figure 8c) again demonstrated improved image quality. Even though the geometric focus was located in front of the cornea, the deeper tissue features, such as the iris, were well defined. The effect of range on image quality is demonstrated in Figure 9. The two series of images show the appearance of the anterior segment of a cadaver eye as the range between the eye and the transducer was decreased by 1-mm increments. The top and bottom series consist of images generated without and with synthetic focus, respectively. These images demonstrate how the annular array can achieve excellent image quality as the range between the transducer and the eye is shifted over a range of 6-mm, while a fixed focus achieves high image quality only over a 1–2 mm range.

Conclusions

Current VHFU systems for evaluation of the anterior segment of the eye are constrained by their very limited DOF. This results in reduced sensitivity and degraded resolution outside a focal zone that measures under one millimeter in axial extent. In this report, we demonstrated performance of an annular array transducer operating in the same frequency range as current single-element UBM systems. We showed that this technology can provide a six-fold increase in DOF.

A limitation of the annular array as currently configured is acquisition speed. In the current system, five passes (one for each ring) are needed to acquire a single image. Furthermore, data transfer and the post-processing to form images add additional time constraints. These limitations are largely a result of the prototype nature of the current device. High-speed switching or dedicated pulsers for each element would allow each of the five annuli to be excited sequentially at each scan position so that only a single pass would be required to form an image. High-speed data transfer and storage would also reduce overhead. The use of digital signal microprocessors could significantly reduce the time needed to form synthetically-focused images as compared to that required when performing these operations in software,

as is done in the current configuration. Using presently available technology, speeds of 5–10 frames/second are obtainable.

The improved resolution and sensitivity offered by annular array technology will provide significant practical advantages in diagnostic imaging of anterior segment anatomy and pathology. Furthermore, this technology can be readily extended to lower frequencies, such as 20–25 MHz, that would allow improved assessment of vitreoretinal pathologies.

In summary, we have demonstrated a prototype 40-MHz array transducer for imaging of the anterior segment that achieves improved depth-of-field, sensitivity and lateral resolution.

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Figure 1.

Schematic illustrating operation of a curved annular array. The figure shows a three-element array in cross-section and *en face* (insert, upper left). Left: When all the array elements are excited simultaneously, the wavefronts from each element will converge at the geometric focus. Right: Here, the outermost ring is excited first and the central ring last, resulting in convergence of wavefronts at a synthetic focal point closer than the geometric focus.

Figure 2.
Photograph of prototype annular array and flex circuit containing the electronic fan-out.

Figure 3.

During scanning, the crosspoint switch directs excitation pulses to only one of the five transducer elements at a time (bold arrow) while echo data are collected from all five channels. To acquire all 25 possible send/receive pairs needed to form an image, the transducer is scanned five times, once for each excited element.

Figure 4.

B-mode images of a series of wire targets at increasing ranges about the geometric focus with (a) a focused single-element transducer, (b) the array without synthetic focusing and (c) the array with synthetic focus processing. Where synthetic focusing is not used, the array functions as the equivalent of a conventional single-element transducer. Note the improved lateral resolution obtained outside the geometric focus when synthetic focusing is used. Also note the improvement in dynamic range (reduced noise) in the array compared to the single-element transducer.

Figure 5.

Central cornea and anterior lens surface of an *ex vivo* bovine eye scanned with the annular array with (a) no delay corrections and (b) synthetic focusing (41 focal zones, 180 $\mu\text{m}/\text{zone}$). The interfaces seen in the image include (from left to right) the epithelial surface, Bowman's membrane, the posterior corneal surface, and the anterior lens surface. The position of the geometric focus at 12 mm is indicated by white triangles. The signal-to-noise ratios (SNR's) were (a) 26 dB and (b) 34 dB. Note the much improved depiction of the anterior cornea (near field) and lens surface (far field) with synthetic focus.

Figure 6.

Anterior segment images of an *ex vivo* bovine eye showing data from a) a focused single-element transducer, b) the array with no delay corrections and c) the array with synthetic focusing (41 focal zones, 120 $\mu\text{m}/\text{zone}$). Note the improved depiction of the iris and lens surface (L) with synthetic focus. The signal-to-noise ratios were (a) 41 dB, (b) 45 dB and (c) 51 dB. The white triangles indicate the geometric focus.

Figure 7.

In vivo anterior segment scan of a rabbit with (a) no delay corrections and (b) synthetic focusing (41 focal zones, 177 $\mu\text{m}/\text{zone}$). The signal-to-noise ratios were (a) 35 dB and (b) 41 dB. The white triangles indicate the geometric focus.

Figure 8.

Images of the anterior segment of a cadaver eye showing data from (a) the center array element, (b) the full array with no delay corrections and, (c) the full array with synthetic focusing (41 focal zones, $177\ \mu\text{m}/\text{zone}$). The signal-to-noise ratios were (a) 43 dB, (b) 43 dB, and (c) 51 dB. The white triangles indicate the position of the geometric focus.

Figure 9.

Series of anterior segment images of a cadaver eye with the geometric focus (white triangles) progressively incremented by 1-mm axial steps. The top row (a) shows the summed data with no synthetic focusing. The bottom row (b) shows the data after synthetic focusing (41 focal zones, 177 mm/zone). Note how image quality is maintained as the range between the transducer and the eye changes when synthetic focusing is used.