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Feasibility of Rotational Scan Ultrasound Imaging by an Angled High Frequency Transducer for the Posterior Segment of the Eye

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Abstract

High frequency ultrasound over 40 MHz has been used to image the anterior segment of the eye, but it is not suitable for the posterior segment due to the frequency-dependent attenuation of ultrasound and thus the limitation of penetration depth. This paper proposes a novel scan method to image the posterior segment of the eye with an angled high frequency (beyond 40 MHz) ultrasound needle transducer. In this method, the needle transducer is inserted into the eye through a small incision hole (~1 mm in diameter) and rotated around the axial direction to form a cone-shaped imaging plane, allowing the spatial information of retinal vessels and diagnosis of their occlusion to be displayed. The feasibility of this novel technique was tested with images of a wire phantom, a polyimide tube, and an excised pig eye obtained by manually rotating a 40-MHz PMN-PT needle transducer with a beveled tip of 45°. From the results, we believe that rotational scan imaging will help expand the minimally invasive applications of high frequency ultrasound to other areas due to the capability of increased closeness of an angled needle transducer to structures of interest buried in other tissues.

I. Introduction

High frequency ultrasound (HFUS) is capable of providing improved spatial resolution over the conventional clinical frequency range, but its applications are limited due to higher attenuation and thus smaller penetration depth than its conventional counterpart. Small animal imaging is among the most popular applications of HFUS. For humans, the major applications are dermatological, ophthalmologic, endoscopic, and intravascular ultrasound (IVUS) imaging. For noninvasive HFUS imaging of human tissues, higher than 40 MHz ultrasound has been used for the surface layer of skin and the anterior segment of the eye. As a minimally invasive approach of HFUS, only IVUs and endoscopic imaging have been used since the current technology does not allow for linear or sector scanning of a single element transducer in situ in deep tissues.

Retina vein occlusion (RVO) is the second most common vascular cause of visual loss after diabetic retinopathy, affecting mainly the elderly. Among persons 43 to 84 years of age, the prevalence and 5-year incidence of central RVO (CRVO) are 0.1% and 0.2%, respectively, and both are 0.6% for branch RVO (BRVO) [1]. Since RVO leads to a significant reduction of blood flow velocity in retinal vessels, an ultrasound Doppler analyzer might be a promising tool for diagnosing RVO [2]-[4]. For accurate measurement of changes in blood flow velocity, high spatial resolution is a pivotal requirement because diameters of the retinal vessels in humans are less than 200 μm . Although HFUS can be used for diagnosis due to its high spatial resolution, more attenuation observed at higher frequencies hampers increases in operating frequency. To image the posterior segment of the human eye, for example, the viable maximum center frequency of a transducer is 20 MHz due to its distance from the cornea, approximately 25 mm. At this frequency, however, spatial resolution is insufficient, especially for diagnosis of RVO. In addition, more than 40 MHz ultrasound cannot be used to achieve higher spatial resolution in the specific application because of its higher attenuation than 20 MHz. A possible solution to effectively diagnose RVO is to insert a transducer as closely to the posterior segment of the eye as possible with a minimal incision.

A 45 MHz unfocused lead magnesium niobate-lead titanate (PMN-PT) needle transducer was fabricated and used for measuring blood flow velocity on the order of a few hundred micrometers per second from retinal vessels with diameters less than 200 μm [5]. In the measurement, however, it is hard to identify vessels generating Doppler signals without any spatial information. This is particularly true when there are intertwining vessels in the region of interest. Because the retinal vessels in the posterior segment of the eye run side by side, closely located over the choroidal vessels, spatial information for the vessels is necessary for an accurate diagnosis and evaluation of RVO.

Mechanical scanning with a single element transducer is the only approach for acquiring 40 MHz or higher frequency ultrasound images at the moment. Mechanical scanning is performed in 2 different ways: linear scanning or sector scanning. However, these methods are not suitable for minimally invasive imaging because a transducer has to move from side to side either linearly or along the arc of a sector. This requires a relatively large space to translate or wobble a single element transducer, thus possibly damaging surrounding tissues. For intraocular applications, for example, the linear movement of the transducer inside the eye may result in irreversible damage to ocular structures and thus a total loss of vision.

An alternative to conventional mechanical scan methods is to rotate a single element transducer with an angled tip to form a cone-shaped imaging plane. The rotational scanning requires relatively little space to form an image, thus allowing for the use of more than 40 MHz ultrasound to image vessels in the posterior segment of the human eye in a minimally invasive manner. In this paper, we describe this new rotational scanning method with an angled transducer. To demonstrate feasibility, we acquired images of a wire phantom, a polyimide tube, and the posterior segment of an excised pig eye.

II. Rotational Scanning Method

During retinal surgery, surgical instruments are usually inserted into the eye through a small scleral incision hole approximately 1 mm in diameter. If a single element needle transducer is less than 1 mm in diameter, Doppler signals from the retinal vessels can be obtained with the needle transducer inserted into the eye through the hole. For retinal vessel imaging, it is possible to form an image by rotating the needle transducer if its tip is beveled to a certain angle ϕ . When the angled needle transducer is inserted through the hole and rotated around the axial direction, a 3-dimensional (3-D) cone-shaped imaging plane can be obtained as shown in Fig. 1(a). To display the scan, the cone-shaped surface is unfolded onto a 2-D plane. If the needle

transducer is fully or partially rotated, an image displaying on a monitor will be a polar or sector image after unfolding the cone-shaped imaging surface. Fig. 1 illustrates an example explaining how to convert a 3-D cone-shaped imaging surface into a sector scan.

When a φ -angled needle transducer is partially rotated by an angle of θ , part of a cone is formed as shown in Fig. 1(a). At an axial distance of z_0 , the base radius and the slant height of the cone, respectively, become $z_0 \cdot \tan(\pi/2 - \varphi)$ and $z_0/\cos(\pi/2 - \varphi)$, where the angle of $\pi/2 - \varphi$ represents a half of the opening angle (or aperture) of the cone. If the surface of this partial cone is unfolded, it becomes a sector shape with a central angle of ξ and a radius of $z_0/\cos(\pi/2 - \varphi)$ as shown in Fig. 1(b). The central angle can be calculated by using the fact that the partial circumference of a cone defined by a rotation angle θ is equal to an arc of a sector shape:

$$2\pi z_0 \tan\left(\frac{\pi}{2} - \varphi\right) \cdot \frac{\theta}{2\pi} = 2\pi \frac{z_0}{\cos\left(\frac{\pi}{2} - \varphi\right)} \cdot \frac{\xi}{2\pi}. \quad (1)$$

Arranging (1) with respect to ξ yields

$$\xi = \theta \cdot \cos \varphi. \quad (2)$$

Therefore, an angle between 2 scan lines becomes

$$\frac{\theta}{N-1} \cdot \cos \varphi, \quad (3)$$

where N is the total number of scan lines forming a sector image as shown in Fig. 1(b). As a result of using this transformation, it is possible to use a conventional scan converter to display the data acquired in the 3-D space in the conventional sector format.

III. Experimental results

An experimental study was undertaken to determine whether it would be possible to image blood vessels and structures of the posterior segment of the eye by using the rotational scanning method. Images of a polyimide tube (Medsorce Technologies, Trenton, CA) and the posterior segment of an excised pig eye were acquired. The imaging was performed through a data acquisition protocol mimicking rotation of a 40 MHz unfocused PMN-PT needle transducer with a 45° angled tip (see [5], [6] for details). The needle transducer had a rectangular aperture of 0.4 mm by 0.56 mm and a 52% fractional bandwidth.

In the protocol, the needle transducer is held at a fixed position while an object is placed on a rotational stage as shown in Fig. 2. For one scan line, the needle transducer is excited by a commercial high voltage pulse generator (5900PR, Panametrics, Inc., Waltham, MA), and echo signals are acquired with an oscilloscope (LC534, LeCroy, Chestnut Ridge, NY) after being amplified by a 35 dB preamplifier (AU-1466-BLC, MITEQ, Hauppauge, NY) and band-pass filtered (BIF-40, Mini-circuits, Brooklyn, NY). Once echo samples from a scan line are obtained, the rotational stage is manually turned at a 0.5° increment and then the acquisition process is repeated for the next scan line. This protocol enabled us to acquire echo samples from scan lines to form a B-mode image without the need of actually building a rotational motor and its control system, thus allowing examination of the feasibility of rotational scanning.

To validate the data acquisition protocol, an image of a 20- μm -diameter tungsten wire as shown in Fig. 3(b) was obtained (california Fine Wire co., Grover Beach, CA) with the protocol, and its spatial resolution was compared with that of a point target image, shown in Fig. 3(a), generated with the Field II simulation program [7]. For the wire phantom image, the rotational stage was manually turned from 0 to 70° in 0.5° increments and 141 scan lines were obtained. In the simulation, a needle transducer with the same configuration as the one used in the experiment was modeled, and it was rotated by 70° to obtain 141 scan lines. Envelope calculations with both sets of echo samples from the experiment and the simulation were performed and the envelope information was logarithmically compressed with a dynamic range of 72 dB before scan conversion. The -6 dB axial and lateral beam widths of the wire phantom image were 81.9 μm and 393.0 μm , respectively. These values are comparable to the simulation results, i.e., the -6 dB axial and lateral beam widths of 65.6 μm and 384.8 μm if the diameter of the tungsten wire, 20 μm , is taken into account.

Polyimide tube imaging was performed to demonstrate how a blood vessel running along the lateral direction appears on a rotational scan image. The tube has inner and outer diameters of 810 μm and 886 μm , respectively, and its thickness is 76 μm . For longitudinal imaging, the tube was inserted into a deionized water-filled container on the rotational stage as shown in Fig. 2. The position of the tube was adjusted so that its longitudinal direction could be perpendicular to the direction of ultrasound propagation along the middle of 181 scan lines, which were obtained by manually rotating the stage from 0 to 90° in 0.5° increments. As seen in Fig. 4, the tube was shown on the image as arc-shaped lines, instead of the straight lines that would appear when conventional sector scanning was performed. This is an inherent characteristic of a rotational scan image. In the image, bright arc lines correspond to the portion of the tube on or near the cone-shaped imaging plane. The level of brightness is the highest at the spot where the tube is within the imaging plane and decreases as the distance between the tube and the imaging plane increases. Since the unfocused transducer was used in the experiment, the beam width was broad in all directions. In particular, broad elevation beam thickness would cause fired ultrasound to be reflected from a portion of the tube off the imaging plane. This is the reason why weak echo signals were collected and thus dim arc lines were shown in the outer area of the image.

Fig. 5 shows an image of the posterior segment of an excised pig eye obtained by rotational scan imaging. For this experiment, the lens of the pig eye was removed so as to facilitate manually rotating the stage, using the same experimental parameters as the previous ones. In Fig. 5, the retina and the detached retina from the sclera are shown, although the image quality is not good enough due to the use of an unfocused transducer and manual rotation. The image quality may be significantly improved if a focused-angled needle transducer and a motorized rotational control system are available. With these experimental results, however, we can reach a conclusion that rotational scanning is potentially capable of providing spatial information on the posterior segment of the eye, including vessels.

IV. Discussion and Conclusion

High frequency ultrasound beyond 40 MHz has been used for imaging the surface layer of skin and the anterior segment of the eye due to its shallow penetration depth. This shallow imaging depth is the main bottleneck to using ultrasound in this frequency range for imaging of deeplying tissues. To overcome this limitation, a minimally invasive imaging approach can be used. Linear or phased arrays operating at more than 40 MHz might be an ideal method if arrays of a very small size aperture and housing can be developed. Without such arrays, only a single element or an annular array transducer operating at higher than 40 MHz are viable methods. However, these devices require conventional mechanical scanning to form an image, which is not suitable for minimally invasive imaging, because that there is no space in tissues for either

linear or sector scanning. The experimental results have shown that rotational scanning with an angled needle transducer would overcome the drawback of conventional mechanical scanning. Also of significant merit is the lesser susceptibility of rotational scanning to the penetration depth problem of HFUS, because the scanning takes place very close to the region of interest. This means that the operating frequency of a transducer can be further increased if necessary. These merits of rotational scanning may further expand the applications of HFUS imaging.

Imaging of RVO is one suitable application for rotational scanning in which it is crucial to image the position and size of small vessels in the posterior segment of the eye with a high spatial resolution to allow Doppler measurements to be made. Even though HFUS rotational scan imaging can provide such information, it may not be practical as a diagnostic tool due to the requirement of incision, especially if other imaging modalities such as optical coherence tomography and fluorescein angiography are available. However, the rotational scan imaging would offer the benefit of imaging the occlusion site and monitoring the recovery of blood flow during and/or after surgery through the same incision hole required for the surgical procedure. In addition, it might be easily implemented in an IVUS system in which it would be applicable to mucosal tissues such as mouth and cervix that are not currently accessible to high frequency ultrasound.

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Fig. 1.

Diagram explaining how to convert a 3-D cone-shaped imaging plane (a) into a sector one (b). When a ϕ -angled needle transducer is partially rotated by an angle of θ , part of a cone is formed (a). The angle of $\pi/2 - \varphi$ represents half of the opening angle (or aperture) of the cone. If the surface of this partial cone is unfolded, it becomes a sector shape with a central angle of ζ and a radius of $z_0/\cos(\pi/2 - \varphi)$ (b).

Fig. 2.

Experimental arrangement to collect echo signals from scan lines on a cone-shaped imaging plane formed by manually turning a rotational stage in 0.5° increments for each scan line.

Fig. 3. Images of a point target generated with the Field II simulation program (a) and 20-μm-diameter tungsten wire obtained with the data acquisition protocol used for experiments (b). For both images, logarithmic compression with a 72 dB dynamic range was performed.

Fig. 4. Longitudinal-section image of polyimide tube with 810 μm inner and 886 μm outer diameters. Over a rotational angle of 90° , 181 scan lines were acquired, and logarithmic compression with a 60 dB dynamic range was performed.

Fig. 5. Rotationally scanned image of the posterior segment of an excised pig eye. Over a rotational angle of 90° , 181 scan lines were acquired, and logarithmic compression with a 60 dB dynamic range was performed.