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● *Original Contribution*

HIGH-FREQUENCY *EX VIVO* ULTRASOUND IMAGING OF THE AUDITORY SYSTEM

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Abstract—A 50 MHz array-based imaging system was used to obtain high-resolution images of the ear and auditory system. This previously described custom built imaging system (Brown et al. 2004a, 2004b; Brown and Lockwood 2005) is capable of 50 μm axial resolution, and lateral resolution varying from 80 μm to 130 μm over a 5.12 mm scan depth. The imaging system is based on a 2 mm diameter, seven-element equal-area annular array, and a digital beamformer that uses high-speed field programmable gate arrays (FPGAs). The images produced by this system have shown far superior depth of field compared with commercially available single-element systems. *Ex vivo*, three-dimensional (3-D) images were obtained of human cadaveric tissues including the ossicles (stapes, incus, malleus) and the tympanic membrane. In addition, two-dimensional (2-D) images were obtained of an intact cochlea by imaging through the round window membrane. The basilar membrane inside the cochlea could clearly be visualized. These images demonstrate that high-frequency ultrasound imaging of the middle and inner ear can provide valuable diagnostic information using minimally invasive techniques that could potentially be implemented *in vivo*. (E-mail: J.Brown@dal.ca) © **2009 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **High-frequency, Ultrasound imaging, Transducer array, Beamformer, Annular array, Middle ear, Inner ear, Cochlea, Auditory system, Basilar membrane, Ossicles.**

INTRODUCTION

Hearing loss is one of the most common chronic conditions worldwide, affecting approximately 10% of the population, and 30% of those over 65 years old. Hearing loss typically takes one of two forms: (1) sensorineural hearing loss, which affects the inner ear (cochlea) or auditory nerve and (2) conductive hearing loss, which is a condition primarily affecting the middle ear (ossicles and tympanic membrane) or external ear canal. Mixed forms are also possible.

In the middle ear, direct visualization of pathologic tissue or fluid, and the ability to evaluate the state of the ossicles would greatly enhance the diagnosis of conductive hearing disorders and also provide a nonsurgical means of assessing the performance of middle ear implants commonly used to reconstruct the ossicular chain. In imaging the cochlea, *in vivo* visualization of the basilar membrane, the round window membrane (RWM) and stria vascularis could reveal morphologic changes associated with inner ear disorders such as Meniere's disease, sudden and subacute sensorineural hearing loss, autoimmune inner ear disease and perilymphatic fistula, and could improve the ability to diagnose and understand these poorly understood conditions. This technology may also have applications as an intraoperative guidance tool during cochlear implantation surgery (to visualize the placement of electrodes) and acoustic neuroma surgery (to visualize remaining tumor from brainstem). Current *in vivo* imaging techniques, such as MRI and CT do not have the spatial resolution to visualize micro-anatomy in the cochlea, such as the basilar membrane (Sennaroglu et al. 2002). This article describes preliminary images obtained of cadaveric ear tissues using a high-resolution ultrasound system, showing that high-frequency ultrasound has great potential as a diagnostic tool in otology.

High-frequency ultrasound (>20 MHz) is a relatively new area of ultrasonic imaging that can provide an order of magnitude better image resolution than the conventional low-frequency systems (Santosh et al. 1987; Lockwood et al. 1996). Although high-frequency

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ultrasound has previously been implemented in some clinical applications, such as intravascular imaging (Pandian et al. 1990; de Korte et al. 2000), ophthalmic imaging (Cusumano et al. 1998; Hewick et al. 2004) and preclinical applications (Foster et al. 2000; Aristizabal et al. 2006), it has not been widely accepted as a diagnostic tool because commercially available systems have been conventionally based on single-element mechanically translated transducers with a limited depth-of field. In low-frequency ultrasound systems, a great improvement in depth-of-field is achieved by replacing the single-element transducer with a transducer array and an electronic beamformer. This combination allows the ultrasound energy to be electronically focused at a wide range of depths within the tissue at increased frame rates. Consequently, there has been a great deal of interest in developing array-based systems at frequencies greater than 20 MHz. Unfortunately, fabricating these high-frequency arrays and associated beamformers is complicated by the increased ultrasound frequency. In particular, to produce a well-collimated ultrasound beam, array elements with microscopic dimensions are required and the digital sampling resolution of the electronic beamformer has to be increased proportional to the frequency. Despite these challenges, there has recently been some success in developing high-frequency 30 to 50 MHz array transducers (Ritter et al. 2002; Brown et al. 2004a; Ketterling et al. 2005; Lukacs et al. 2006; Snook et al. 2006; Cannata et al. 2006; Brown et al. 2007) and beamformers (Stitt et al 2002; Brown and Lockwood 2005; Hu et al. 2006; Mehi et al. 2007; Lay and Lockwood 2007). The images described in this article were generated with a high-frequency system based on a 50 MHz, 2 mm diameter, seven-element annular array transducer and a field programmable gate array (FPGA)-based beamformer (Brown et al 2004a, 2004b; Brown and Lockwood 2005). The transducer has a kerfless array design and is based on a PZT5H substrate. The system can provide axial resolution of up to 50 μ, lateral resolution ranging between 80 and 130 μ, and a dynamic range up to 60 dB. The image depth is scanned from 3 and 8.12 mm, a range fixed by system hardware. The successful development of high-frequency array-based systems will eventually lead to more clinical utility of high-resolution ultrasound as well as new diagnostic applications such as imaging the auditory system.

Previous high-resolution imaging of the inner ear has been done using optical coherence tomography (OCT) (Wong et al. 2004; Pau et al. 2007; Sepehr et al. 2008). This technique uses low-coherence optical interferometry to achieve axial and lateral resolution of approximately 10 μm while maintaining penetration depths of a few mm in scattering tissues. In all published OCT cochlear imaging studies, light is sent in through the temporal bone. In rats (Wong et al. 2004), the temporal bone is sufficiently thin that the cochlea can be imaged by simply exposing the bone, but in larger animals such as pigs (Sepehr et al. 2008) and humans, the temporal bone is too optically dense for this technique and so must first be thinned before imaging can take place. Such thinning of the temporal bone is not suitable for *in vivo* human imaging. The technique we apply in the present report of imaging through the round window membrane might also be applicable to OCT, although to our knowledge no one has attempted such a strategy.

To date, only one group has attempted high-frequency ultrasound imaging of the cochlea. Although their preliminary results are not yet published, an article currently under review can be found on the Johns Hopkins Robotics Laboratory website. Their images were obtained by removing the dense bone surrounding the cochlea rather than through the RWM.

Fig. 1 shows some of the larger clinically relevant structures of the auditory system. Sound is received through the external ear canal and vibrations are picked up via the tympanic membrane and passed through the ossicular chain in the middle ear. The middle ear ossicles form a chain of three bones (malleus, incus, and stapes) connecting the eardrum to the cochlea. The stapes footplate sends vibrations into the cochlear fluid through the oval window at the basal end of the cochlea. A pressure wave is applied at the oval window by the stapes and pressure release is provided for the incompressible fluid at the round window membrane (RWM) across the basilar membrane. The pressure difference across the basilar membrane creates a travelling wave going from the basal to the apical ends of the cochlea. Different frequency components reach their maximum amplitude at different distances along the basilar membrane, with the lowest frequencies traveling furthest towards the apical end.

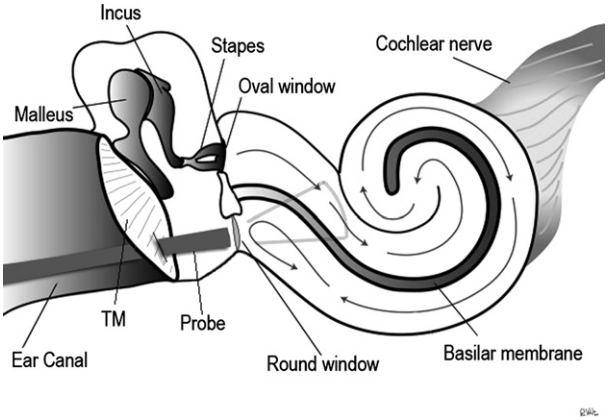

Fig. 1. Diagram illustrating the major components in the human auditory system. The tympanic membrane and ossicular chain vibrate the cochlear fluid and in turn the basilar membrane.