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Dynamic properties of human round window membrane in auditory frequencies running head: Dynamic properties of round window membrane

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ABSTRACT

Round window is one of the two openings into cochlea from the middle ear. Mechanical properties of round window membrane (RWM) affect cochlear fluid motion and play an important role in the transmission of sound into cochlea. However, no measurement of mechanical properties of RWM has been reported because of the complication of its location and small size. This paper reports the first investigation on dynamic properties of human RWM using acoustic stimulation and laser Doppler vibrometry measurement. The experiments on RWM specimens were subsequently simulated in finite element (FE) model and an inverse-problem solving method was used to determine the complex modulus in frequency-domain and the relaxation modulus in time-domain. The results show that the average storage modulus of human RWM changes from 2.32 to 3.83 MPa and the average loss modulus from 0.085 to 0.925 MPa over frequencies of 200–8000 Hz. The effects of specimen geometry and experimental condition on complex modulus measurements were discussed through FE modeling analysis. Dynamic properties of RWM reported in this paper provide important data for the study of middle ear and cochlear mechanics.

1. Introduction

Round window is one of the two openings into the cochlea from the middle ear. The round window membrane (RWM) vibrates with an opposite phase to acoustic vibrations entering the cochlea through the stapes at the oval window, another opening of the cochlea to the middle ear. RWM serves as a barrier between the middle ear cavity and cochlea and plays an important role in middle ear and cochlear mechanics [1–3]. Mechanical properties of RWM affect cochlear fluid motion and thus the movement of the basilar membrane.

RWM consists of three layers from the middle ear to cochlear side: the outer epithelium, core of connective tissue layer and inner epithelium [4,5]. The core of connective tissue contains collagen fibers, fibroblast and other elastic fibers and provides the main structural support for RWM. Adult human RWM is usually thicker at the edge than at the center, and its average thickness is about 70 μm [4,5].

Middle ear diseases such as otitis media usually induce the changes of RWM in thickness and permeability and induce possible sensorineural hearing loss [6–8]. Recently, it has been reported that the vibration transducer of middle ear implantable hearing device has been attached on the RWM to stimulate cochlear fluid for restoring hearing level [9–11]. Beltrame et al. [12] coupled the floating mass transducer (Soundbridge, MED-EL, Austria) onto the RWM and assessed its function for patients with mixed hearing loss associated with otitis media or otosclerosis. Koka et al. [13] measured the cochlear microphonic and mechanical (stapes velocity) response in chinchillas, which were induced by normal acoustic stimulation and round window stimulation with an active middle ear prosthesis. Arnold et al. [14] tested the effectiveness of different coupling methods with the floating mass transducer on RWM in a human cadaver head and discussed the factor to improve the vibration transfer. The studies on RWM using implantable transducers indicate that the attachment method and RWM mechanical properties directly affect the efficiency of vibration stimulation into the cochlea.

To better understand the role of RWM in normal, diseased, and implanted ears, the finite element (FE) models of the human ear, including the middle ear cavity, RWM, and cochlea, in addition to the ossicles and tympanic membrane, have been reported by Bohke and Arnold [15], Gan et al. [16], and Zhang and Gan [17]. However, the mechanical properties of RWM were assumed in these FE models because there were no mechanical properties of RWM available in the literature. Bohnke and Arnold used 9.8 MPa as Young's modulus of RWM, Gan et al. used 0.35 MPa, and Zhang and Gan used 0.7 MPa for RWM. Noticeable differences of the RWM elastic modulus were observed among these studies. The accurate measurement on the mechanical properties of RWM is needed to improve the FE modeling analysis of the human ear. As human RWM works under

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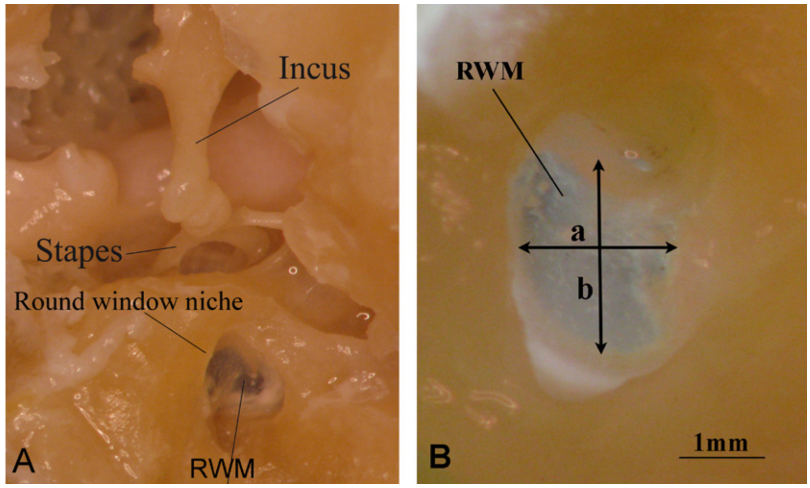

Fig. 1. (A) The RWM specimen with the incus and stapes harvested from a human temporal bone. This picture shows the relative location of the RWM to the incus, stapes and round window niche. (B) Enlarged RWM specimen image with 1 mm reference bas. (a) Short axis of RWM and (b) long axis of RWM.

auditory frequency range, the dynamic properties or complex modulus in the frequency domain has more value than the static elastic modulus.

In this paper, we report a novel experimental setup to measure dynamic properties of human RWM using acoustic driving and laser Doppler vibrometer (LDV). LDV is commonly used to measure vibrations of the tympanic membrane (TM) and stapes footplate and determine the transfer function of the middle ear [18,19]. However, LDV has not been directly used to measure mechanical properties of the ear tissue until the recent study on human TM by Zhang and Gan [20]. They employed the mechanical testing system and LDV to measure vibration of the TM sample in response to acoustic pressure over the frequency range of 200–8000 Hz. Dynamic properties of the TM were finally determined through the FE model with acoustic-structure coupled analysis. Following the similar approach, we investigated the dynamic properties of human RWM and report the results here. The generalized standard linear viscoelastic solid model was used for RWM, and the dynamic properties of RWM were derived by the inverse-problem solving method. The complex modulus over the auditory frequency range provides new knowledge and needed data for the field of middle ear and cochlea mechanics.

2. Methods

2.1. RWM specimen preparation

Eight RWM samples from fresh human cadaver temporal bones (three left and five right) obtained through the Willed Body Program at the University of Oklahoma Health Sciences Center were used for this study. All donors had no history of ear diseases associated with the RWM and the average age of the donors was 70 (ranging from 59 to 82, 5 males and 3 females). To maintain soft tissue compliance and hydration within five days before the experiment, the bones were immersed in a 0.9% saline solution mixed with providine (i.e., 15% amount of providine in saline solution) at 5 °C until use. The temporal bone was cut into a block (2 cm × 2 cm × 2 cm) containing the middle ear cavity and cochlea. The middle ear cavity was then opened and the TM with malleus attached was carefully removed under microscope (Olympus SZX12). Incus and stapes remained intact in the specimen block, and the round window niche was identified as well as the RWM (Fig. 1A). The cochlea was then removed and RWM was exposed from both the middle ear and cochlear sides. The specimen was examined under microscope to verify that the RWM was not damaged during the preparation. Subsequently, we place microbeads (30 μm in diameter, Mo-Sci Corp, Rolla, MO) onto the center of the cochlear side of RWM as the laser reflecting target. The mass of each bead is about 3.96×10^{-5} mg. Such a small mass should not affect the measurement. Fig. 1B shows a RWM specimen image obtained by a CCD camera in this study. The RWM was in an elliptical shape with the short axis (a) and long axis (b). Table 1 lists the dimensions of (a) and (b) measured from each specimen using the image analysis tools (Adobe Photoshop 7.0) with the average long axis of 2.08 mm and short axis of 1.81 mm.

2.2. Experimental setup

A laser Doppler vibrometer (HLV-1000, Polytech PI, Tustin, CA) was used to measure the vibration of the RWM induced by acoustic driving, a technique recently developed in our lab to determine dynamic properties of the human TM [20]. Fig. 2 is the schematic diagram of the experimental setup. Briefly, the RWM specimen with the bony wall was fixed in a micro-manupulator and placed on a vibration isolation table. 80 dB SPL pure tones across the frequency range of 200–8000 Hz were delivered to the middle ear side of the RWM by a sound delivery tube (inner diameter 1 mm) connected to the speaker. The sound signals were generated by the dynamic signal analyzer (DSA, HP 35670A, CA) and amplified by the power amplifier (B & K 2718, Norcross, GA). The distance between the tube end and the surface of RWM was set at 1 mm. A probe microphone (ER-7C, Etymotic Research, IL) attached to the sound delivery tube

Table 1
The dimensions, resonance frequency f_n and vibration amplification ratio R of RWM specimens.

RWM specimen	RWM-1	RWM-2	RWM-3	RWM-4	RWM-5	RWM-6	RWM-7	RWM-8	Mean ± S.D
Short axis a (mm)	1.92	1.78	1.88	1.68	1.74	1.82	1.86	1.76	1.81 ± 0.08
Long axis b (mm)	2.18	2.06	2.08	1.88	2.00	2.06	2.12	1.98	2.05 ± 0.09
f_n (Hz)	1500	1665	1888	2132	1892	1886	1687	1896	1818 ± 193
R	4.08	2.98	3.51	5.66	3.81	2.88	3.18	3.37	3.68 ± 0.89