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Research paper

Response of the human tympanic membrane to transient acoustic and mechanical stimuli: Preliminary results

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A B S T R A C T

The response of the tympanic membrane (TM) to transient environmental sounds and the contributions of different parts of the TM to middle-ear sound transmission were investigated by measuring the TM response to global transients (acoustic clicks) and to local transients (mechanical impulses) applied to the umbo and various locations on the TM. A lightly-fixed human temporal bone was prepared by removing the ear canal, inner ear, and stapes, leaving the incus, malleus, and TM intact. Motion of nearly the entire TM was measured by a digital holography system with a high speed camera at a rate of 42 000 frames per second, giving a temporal resolution of <24 μs for the duration of the TM response. The entire TM responded nearly instantaneously to acoustic transient stimuli, though the peak displacement and decay time constant varied with location. With local mechanical transients, the TM responded first locally at the site of stimulation, and the response spread approximately symmetrically and circumferentially around the umbo and manubrium. Acoustic and mechanical transients provide distinct and complementary stimuli for the study of TM response. Spatial variations in decay and rate of spread of response imply local variations in TM stiffness, mass, and damping.

1. Introduction

Though most characterizations of tympanic membrane (TM) response to sound have used steady-state tonal stimuli, most environmental sounds are transient in nature. Studies of TM motion in response to steady-state stimuli include, among others, Tonndorf and Khanna (1972), Khanna and Tonndorf (1972), Decraemer et al. (1989), and Cheng et al. (2010, 2013). In animals, an early holographic study (Dancer et al., 1975) examined guinea pig TM motion amplitude in response to acoustic transients, and de La Rochefoucauld et al. (2010) examined the gerbil middle ear response to clicks. Dobrev (2014) and Dobrev et al. (2014a) have demonstrated techniques to measure TM transient responses, but the complex response of the entire human TM to transients has not yet been studied in any detail.

As in most mammals, the human TM is attached to the tympanic ring along its edge and to the malleus manubrium at more central locations. Unlike in other mammals, the human TM is attached firmly to the manubrium at only two points: the umbo (extreme end of the manubrium) and the lateral process near the TM rim (e.g., Gea et al., 2010; De Greef et al., 2014). Between these two firm attachment locations is a thin epithelial fold, the plica mallearis, that attaches the TM to the manubrium (De Greef et al., 2016).

There is an ongoing debate about how different parts of the TM contribute to sound transmission to the middle ear with low- or high-frequency stimuli. For example, some have argued that the motion of the TM distant from the umbo contributes little to motion of the umbo (and the coupled ossicular chain and cochlea) at high frequencies (Tonndorf and Khanna, 1970, 1972; Shaw, 1977, 1982; Shaw and Stinson, 1981), while others suggest that the radial fibers within the TM help couple distant TM motions to the TM at all frequencies (O'Connor et al., 2008). The debate includes questions of how the response characteristics and mechanical properties of the TM may vary over its surface; for instance, the TM thickness and presumably its mass varies among regions (Van der

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Jeught et al., 2013), and different parts of the TM may have different natural frequencies (Fay et al., 2006).

Transients provide a means to investigate these ideas by determining how different parts of the TM contribute to middle-ear input. Sound stimuli activate the entire TM nearly identically and simultaneously (Ravicz et al., 2014), and motion of the umbo in response to acoustic transients ("clicks") represents a summing of the contributions of the entire surface of the TM to umbo motion, where the contribution of different TM locations to the total umbo motion may vary with location and frequency. In contrast, mechanical transients ("pokes") that directly stimulate only a discrete small region of the TM allow the assessment of how individual small regions contribute to the motion of the umbo. Transient stimulation also provides a rich data set for modeling, including the determination of best frequencies and damping along the membrane surface. Since transients contain many frequencies, TM responses to transients are amenable to modal analysis.

In this paper we investigate the response of the TM in a human cadaveric temporal bone to global transient stimuli (acoustic clicks) and to local transient stimuli (mechanical impulses) applied to several different locations on the TM. We present TM transient responses measured using a newly-developed high-speed holographic system capable of measuring TM motion over most of its surface with a temporal resolution of less than 24 μs (Dobrev et al., 2014a). We use this technique to acquire preliminary results with both clicks and pokes in the same bone to examine three questions: (1) How do TM responses to global and local transient excitation differ? (2) Do the mechanical properties of the TM differ among locations and, if so, how? (3) Do different parts of the TM contribute differently to umbo motion?

2. Methods

2.1. Preparation of specimens

A de-identified human temporal bone was collected by the Massachusetts Eye and Ear Infirmary and fixed for three weeks according to the method of Thiel (2002; Stieger et al., 2012).[2] The specimen was prepared by removing as much of the ear canal as possible, the inner ear, and the stapes to provide visual access to as much of the TM as possible. The TM, tympanic ring, and the malleus, incus, and their supporting ligaments were maintained (Fig. 1b, c). After preparation, the specimen was taken to the Center for Holographic Studies and Laser micro-mechaTronics at the Worcester Polytechnic Institute for holographic measurements. The lateral surface of the TM was painted with a zinc oxide (ZnO) solution to increase the reflectivity of the TM surface (Rosowski et al., 2009; Cheng et al., 2013). We have shown that neither the Thiel fixation nor the paint have a substantial effect on TM motion (Guignard et al., 2014; Cheng et al., 2013).

2.2. Stimuli and acoustic responses

Acoustic impulses ("clicks") generated by a 50-μs square voltage pulse through a power amplifier (2100; NAD Electronics, Pickering, ON, Canada) were delivered to the lateral side of the TM by a loudspeaker (SB29RDC-C-4; SB Acoustics, Denmark) located about 12 cm laterally to the TM, at approximately 30° off axis. The click had a peak sound pressure of 10 Pa as measured by a microphone (ER-7; Etymotic Research, Elk Grove Village, IL, USA) positioned at the posterior TM rim (Fig. 1b). Examples of the voltage pulse and resulting click waveform near the lateral TM surface are shown in Fig. 2a. Note that the (rarefaction) click waveform measured near the TM begins approximately 441 μs after the voltage pulse, due to the propagation time from the speaker to the TM. Irregularities in the click waveform after 500 μs are likely due to reflections off nearby structures. Because the middle ear was open, sound could reach the medial TM surface also, but the acoustic baffle action of the preparation and its mounting and the additional sound propagation distance to the medial TM reduced the significance of medial sound pressures on early TM responses.

Mechanical displacement impulses ("pokes") in response to the same 50-μs square voltage pulse were delivered by a small actuator comprising a piezoelectric stack (PI P-882.51,Karlsruhe, Germany; 3 × 2 × 18 mm long) with a thin extension rod made of stainless steel hypodermic tubing (22 ga: 0.7 mm outer diameter (o.d.) × 0.4 mm inner diameter (i.d.) × 10 mm long) anchored in a 3 × 2 × 0.8 mm thick aluminum plate glued to the end of the piezoelectric stack to produce a contact area 0.7 mm in diameter. Pokes were delivered to the medial side of the TM at the umbo or at three other locations (Fig. 1c, d). The mechanical stiffness of the piezoelectric stimulator is very high, so the displacement amplitude of the poke stimulus was effectively the same among poke locations. The acoustic response to the poke was recorded by the microphone as described above. An example of the poke waveform is also shown in Fig. 2a. Spectra of these stimuli are shown in Fig. 2b. The spectral rolloff of the voltage stimulus at 20 kHz is consistent with the 50-μs voltage pulse width.

2.3. Measurement of TM motion

Motion of nearly the entire TM surface was measured by a high-speed digital holography system (Fig. 1a), which includes a continuous-wave (CW) 532 nm laser (SLIM-532, 50 mW; Oxxius, O'Fallon, MO, USA), variable ratio beam splitter, an optical phase shifter, a high-speed camera (SA5 1000 k; Photron, San Diego, CA, USA), and beam combining and imaging optics (Razavi et al., 2015a).

Digital holograms were recorded by splitting the laser into two beams, object and reference, by the use of a variable ratio beam splitter; see Fig. 1a. A reference/object beam power ratio of about two was used. The reference beam illuminated the camera detector, whereas the object beam was directed and expanded to illuminate the specimen. The irradiance that reflected off the specimen was captured by a telecentric lens and combined with the reference beam. The interference pattern of the two beams was digitized by the camera. Displacements of the TM toward the camera are described as in the positive direction.

High-speed acquisition was achieved by a novel high-speed $2 + N$ frame acquisition method (Razavi et al., 2015a) based on a hybrid spatio-temporal local correlation (LC) phase sampling approach (Dobrev et al., 2014a,b,c), that allows quantification of the TM transient deformations by utilizing two reference frames and N consecutive deformed frames recorded before and throughout the evolution of the event of interest. The high-speed camera capabilities allow for frame rates from 7000 frames per second (fps) at full resolution (i.e., 10^6 pixels) to 10^6 fps at reduced resolutions (i.e. 1000 pixels). For measurements of the TM transient motion presented in this paper, a trade-off was made by setting the camera at 384 × 384 pixels and at 42 000 fps to achieve both (a) adequate spatial resolution (~22 μm per pixel) to resolve the complex deformation patterns of the TM and (b) adequate temporal resolution (<24 μs for 25 ms after the stimulus) to resolve the full hearing range bandwidth.

The amount of the TM we could measure was constrained by the field of view of the camera, which was limited by how completely

[2] The specimen was the left ear from a 71-year-old male and was frozen for approximately 2 years before being thawed and fixed.