Published in final edited form as:

Hear Res. 2010 May ; 263(1-2): 66–77. doi:10.1016/j.heares.2009.12.024.

Motion of the surface of the human tympanic membrane measured with stroboscopic holography

Jeffrey Tao Cheng^{1,2}, Antti A. Aarnisalo^{1,2}, Ellery Harrington^{4,5}, Maria del Socorro Hernandez-Montes^{4,5}, Cosme Furlong^{1,2,4,5}, Saamil N. Merchant^{1,2}, and John J. Rosowski^{1,2,3}

¹Eaton-Peabody Laboratory, Massachusetts Eye and Ear Infirmary, Boston, MA

²Department of Otology and Laryngology, Harvard Medical School, Boston MA

³Speech and Hearing Bioscience and Technology Program, MIT-Harvard Division of Health Sciences and Technology, Cambridge MA

⁴Center for Holographic Studies and Laser micro-mechaTronics, Worcester Polytechnic Institute, Worcester, MA

⁵Department of Mechanical Engineering, Worcester Polytechnic Institute, Worcester, MA

Abstract

Sound-induced motion of the surface of the human tympanic membrane (TM) was studied by stroboscopic holographic interferometry, which measures the amplitude and phase of the displacement at each of about 40000 points on the surface of the TM. Measurements were made with tonal stimuli of 0.5, 1, 4 and 8 kHz. The magnitude and phase of the sinusoidal displacement of the TM at each driven frequency were derived from the fundamental Fourier component of the raw displacement data computed from stroboscopic holograms of the TM recorded at eight stimulus phases. The correlation between the Fourier estimates and measured motion data was generally above 0.9 over the entire TM surface. We used three data presentations: (i) Plots of the phasic displacements along a single chord across the surface of the TM, (ii) Phasic surface maps of the displacement of the entire TM surface, and (iii) Plots of the Fourier derived amplitude and phase-angle of the surface displacement along four diameter lines that define and bisect each of the four quadrants of the TM. These displays led to some common conclusions: At 0.5 and 1 kHz, the entire TM moved roughly in-phase with some small phase delay apparent between local areas of maximal displacement in the posterior half of the TM. At 4 and 8 kHz, the motion of the TM became more complicated with multiple local displacement maxima arranged in rings around the manubrium. The displacements at most of these maxima were roughly in-phase, while some moved out-of-phase. Superposed on this in- and out-of-phase behavior were significant cyclic variations in phase with location of less than 0.2 cycles or occasionally rapid half-cycle step-like changes in phase. The high frequency displacement amplitude and phase maps discovered in this study can not be explained by any single wave motion, but are consistent with a combination of low and higher order modal motions plus some small traveling-wave-like components. The observations of the dynamics of TM surface motion

© 2009 Elsevier B.V. All rights reserved.

Contributing Author Jeffrey Tao Cheng, PhD, Eaton-Peabody Laboratory, Massachusetts Eye and Ear Infirmary, 243 Charles Street, Boston, MA 02114, USA, Phone 617 573 4128, Fax: 617 720 4408, Tao_Cheng@meei.harvard.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

from this study will help us better understand the sound-receiving function of the TM and how it couples sound to the ossicular chain and inner ear.

Keywords

Tympanic Membrane; Wave Motion; Stroboscopic Holography; Middle Ear Mechanics

1. INTRODUCTION

Sound-induced motion of the tympanic membrane (TM) has been most-often studied through measurements of umbo displacement by laser Doppler vibrometry (e.g. Goode et al., 1993; Gan, Wood and Dormer, 2004, Rosowski et al., 2008) and modeling analyses (e.g. Funnell and Laszlo, 1978, Funnell et al., 1987, Rabbitt and Holmes, 1986, Puria and Allen, 1998, Koike et al., 2001, Gan, Feng and Sun, 2004, Fay et al., 2005; Parent and Allen, 2007). Motions of the umbo and the rest of the manubrium are the input to the ossicular sound-conduction system that transfers sound energy to the inner ear. However, is not at all clear how vibrations of the entire TM surface contribute to vibration of the manubrium and ossicular sound conduction.

Previous time-averaged holographic measurements of the sound-induced motion of the TM surface have demonstrated that TM motion patterns are complicated in both their spatial and frequency dependence (e.g. Khanna and Tonndorf 1972; Tonndorf and Khanna 1972, Løkberg et al., 1979, Rosowski et al. 2009). At low frequencies (<2 kHz), a simple motion pattern is usually seen on the surface of the TM of cats and humans: The entire TM moves with one-to-three displacement maxima at different locations and with the largest motion magnitude in the posterior half of the TM. At higher stimulus frequencies, the TM motion patterns become more complicated, with multiple areas of maximal displacement magnitude, separated by node-like regions of minimal displacement magnitude. The suggestions of nodes indicate that regions of the TM move with different phase, though it should be remembered that time-averaged holography is a measure of the magnitude of the motion of each point on the TM surface, and it is insensitive to differences in phase of motion.

There are a few studies that do report phase information of TM motion driven by sound. Decraemer et al. (1989, 1999) used interferometric measurements to gather the amplitude and phase of multiple points on the surface of the TM in cat. The results show that at low frequency (<1 kHz), the entire TM vibrates in phase with the umbo and malleus, while above 5 kHz, discrete resonances are observed with different sections vibrating out of phase with the umbo in complicated spatial patterns. Goode et al. (1996) employed a scanning laser Doppler vibrometer (SLDV) to measure amplitude and phase of the displacement at multi-sites of the human TM with similar results to Decraemer et al. (1989, 1999). However, the measurement time is proportional to the density of measurement locations by the SLDV, and minutes of measurement time are needed for even moderate spatial and frequency resolution. Konrádsson et al. (1987) used computerized SLDV to record and reconstruct 3-dimensional vibration of the human TM with both amplitude and phase plots, the results are presented at two single frequencies of 578 and 3113 Hz only. Wada et al. (2002) applied sinusoidal phase modulation (SPM) to time-averaged speckle pattern interferometry to detect both the amplitude and phase of motion of the entire surface of the guinea pig TM at a moderate speed (within several seconds). The Wada et al. results describe rather complicated spatial patterns of TM displacement amplitude and phase at frequencies up to 4 kHz. However, the SPM technique is limited to small displacements that fall within the linear region of the function that relates speckle intensity and displacement amplitude.

An advanced computer-assisted fiber-optic-based opto-electronic holographic (OEH) interferometer system developed at the Worcester Polytechnic Institute (WPI) (Furlong et al. 2009; Hernandez-Montes et al. 2009) was applied in this study. This holographic system can be operated in either time-averaged mode for rapid identification of resonant frequencies and corresponding mode shapes of TM vibrations using sound stimuli of 0.2 to over 20 kHz (Rosowski et al. 2009), or stroboscopic mode to quantify both the amplitude and phase of dynamic vibrations of the TM over the full field of view (Hernandez-Montes et al. 2009, Furlong et al. 2009).

In this study, we describe measurements of the amplitude and phase of motion of the entire human TM surface stimulated by tones of 0.5, 1, 4 and 8 kHz via stroboscopic holographic interferometry. To our knowledge this is the first time the dynamic motion of the entire TM driven by sound of 8 kHz is quantitatively described. The results describe different modal patterns of TM motion and identify regions of apparent transverse wave propagation on the TM surface.

2. METHODS

2.1 Stroboscopic Holographic Interferometry

The detailed design of the OEH interferometer used in this study can be found in Hernandez-Montes et al. (2009). The operation of the OEH in time-averaged mode was described previously by Rosowski et al. (2009). The fundamentals of stroboscopic mode are briefly described below. OEH is based on digital image recording with numerical reconstruction: Holographic interference patterns acquired by the digital camera of the OEH system are processed by computer to provide quantitative measurements of deformations of the object. Processing is based on spatial and temporal intensity distributions, $I(x, y, t)$, defined at the surface of the camera's backplane (x, y) , i.e.,

$$I(x, y, t) = I_o(x, y, t) + I_r(x, y, t) + 2\sqrt{I_o(x, y, t)I_r(x, y, t)}\cos[\Delta\phi(x, y, t) + \Delta\theta_n + \Omega(x, y, t)], \quad (1)$$

where $I_o(x, y, t)$ and $I_r(x, y, t)$ represent temporal and spatial intensities of a beam reflected from the object and a reference beam (Fig. 1) respectively, $\Delta\phi(x, y, t)$ represents the phase difference between the reflected object beam and the reference beam when two beams interact independent of stimulus, and $\Delta\theta_n$ results from the optical phase stepping of the reference beam (increasing the reference path length by either 0, $\frac{1}{4}$, $\frac{1}{2}$ or $\frac{3}{4}$ of a wave length) controlled by the optical phase shifter as shown in Fig. 1, (OEH interferometry uses a series of four phase-stepped interference images to reconstruct one hologram (Rosowski et al. 2009)). The fringe locus function $\Omega(x, y, t)$ characterizes the phase change of the reflected object beam due to stimulus-induced deformations of the object (Furlong and Pryputniewicz, 1998).

In stroboscopic holography mode, the deformation of the TM is computed based on the difference between holograms of the TM surface measured at two different time instants, where the instants are defined by the pulsing of the 'strobe switch' (an opto-acoustic modulator capable of high-frequency switching) that is phase-locked to the acoustic stimulus (Fig. 1). In this study, the sinusoidal motion of the TM driven by a tone was determined from holograms of the TM that were gathered during 'strobed' laser pulse illumination at each of eight evenly spaced stimulus phases ($\phi = 0, \pi/4, \pi/2, \dots, 7\pi/4$). Each laser pulse had duration of 10% of the period of the tonal stimulus. Let the image intensity of the four optically phase-stepped images gathered at two stimulus phases (ϕ_1 and ϕ_2) be $I_{0\phi_1}, I_{1\phi_1}, I_{2\phi_1}, I_{3\phi_1}$ and $I_{0\phi_2}, I_{1\phi_2}, I_{2\phi_2}, I_{3\phi_2}$, then the resultant modulation intensity at each camera pixel (saved as the interference hologram) between the two stimulus phases is:

$$I_M = \sqrt{(I_{0\varphi 1} - I_{2\varphi 1} + I_{0\varphi 2} - I_{2\varphi 2})^2 + (I_{1\varphi 1} - I_{3\varphi 1} + I_{1\varphi 2} - I_{3\varphi 2})^2}, \quad (2)$$

and the optical interference phase difference $\Delta\Gamma$ that describes the relative displacement of the TM (component of displacement perpendicular to the surface of the camera) between the two stimulus phases is:

$$\Delta\Gamma = \tan^{-1} \left[\frac{(I_{0\varphi 1} - I_{2\varphi 1}) \cdot (I_{1\varphi 2} - I_{3\varphi 2}) - (I_{1\varphi 1} - I_{3\varphi 1}) \cdot (I_{0\varphi 2} - I_{2\varphi 2})}{(I_{0\varphi 1} - I_{2\varphi 1}) \cdot (I_{0\varphi 2} - I_{2\varphi 2}) + (I_{1\varphi 1} - I_{3\varphi 1}) \cdot (I_{1\varphi 2} - I_{3\varphi 2})} \right]. \quad (3)$$

This optical phase difference measured over the entire TM surface is wrapped modulo $\pm\pi$ and needs to be unwrapped in order to determine phase changes that are greater or less than $\pm\pi$. Spatial phase unwrapping algorithms (Furlong and Pryputniewicz 2003; Furlong et al. 2009) are used to define the unwrapped phase at each point on the TM surface and that unwrapped phase is converted to displacement by multiplying it by the wavelength ($\lambda=0.473\mu\text{m}$) of the laser light / π . (This multiplication takes into account the double path of the object laser beam in our system, which travels from the source to the object and then is reflected back along a parallel line to the interferometer and camera (Fig. 1).)

2.2 Temporal Bone Preparation

Fresh human temporal bones without history of otologic disease were used in this study. The results from one bone (TB10, an 87 year old male) are described in this report. Similar results were observed in two other bones, a 73 year old female and a 59 year old male. The temporal bone was removed within 24 hours post mortem and stored in normal saline at 4°C prior to measurement, as approved by the Institutional Review Board of the Massachusetts Eye and Ear infirmary. The medial, posterior and inferior aspects of the petrous bone were sealed with dental cement to prevent leakage of lymphs from the inner ear. The middle-ear air space of each specimen was widely opened to enable assessment of the normality of the TM and ossicles. The round-window reflex was present, i.e. a slight inward push on the stapes produced an outward motion of the round window, consistent with the presence of inner-ear lymphs within the cochlea. The cartilaginous ear canal was resected and the bony external ear canal was drilled away until 80% to 90% of the TM surface was visible. All soft tissue in the ear canal was carefully removed while keeping the epidermal layer of the TM untouched. A hollow metal tube was glued to the edge of the TM annulus for placement of a probe microphone. To increase the amount of light reflected from the TM surface, the TM was painted with a suspension of 3% TiO₂ powder (Acros Organics, New Jersey, USA) in saline. The effect of TiO₂ powder on the motion of the TM appears small (Rosowski et al. 2009). The TM and middle-ear cavity were kept moist by frequent spraying of saline and regular immersion in saline during the measurements.

The temporal bone was held in a clamp and oriented as in a seated patient. The painted and widely exposed TM was placed against a sound coupler speculum integrated into the interferometer head and oriented such that the surface of the TM was perpendicular to the object beam of the laser. The reflected object beam was focused in the interferometer head where it was mixed with the reference beam (Fig. 1) to produce interference holograms. The sound source was a Tucker-Davis CF1 speaker (Tucker-Davis Technologies) that was coupled to the speculum via a short rubber tube. A calibrated Knowles EK-3103 hearing-aid microphone (Knowles Electronics, IL, USA) with probe tube was inserted into the hollow tube positioned at the edge of the TM to monitor the stimulus level at the edge of the TM surface (Fig.1).

2.3 Data Acquisition

Sound stimuli were continuous tones at four frequencies: 0.5, 1, 4 and 8 kHz, with stimulus level set between 80 and 120 dB SPL so as to produce measurable sound-induced TM displacements in the holographic images. The middle ear system has been shown to behave linearly with stimulus levels about up to 130 dB SPL (Guinan and Peake 1967; Goode et al. 1994). The voltage waveforms were generated by the computer-controlled stimulus generator (AFG 3102 Tektronix), which also generated the ‘strobe’ pulses to activate the ‘strobe switch’. The voltage produced by the Knowles microphone during sound stimulation was sampled via an A/D converter (DAQ Pad-6052E, National Instruments) and stored for later conversion to sound pressure (Fig. 1). The harmonic distortion in the sound field was estimated by comparing the 2nd harmonic component of distortion (the largest visible distortion component) to the level of the primary tonal component as measured by our probe-tube microphone during the measurements described in the report. At stimuli of 92 dB SPL at 0.5 kHz and 90 dB SPL at 1 kHz, the 2nd harmonic distortions were more than 40 dB below the primary levels. At 103 dB SPL at 4 kHz and 115 dB SPL at 8 kHz, the 2nd harmonic distortions were only 13 dB and 8 dB lower than the primary one respectively. The significance of these relatively high distortion measures is reduced by the presence of distortion within our probe microphone at these high levels. Indeed, estimates of distortion in the motion of the tympanic membrane (Table 1) are significantly lower than the distortions suggested by the microphone measurements at 4 and 8 kHz, and we will address this issue again at the end of this section.

At each measurement frequency and stimulus level, we recorded eight holograms of the TM evenly spaced in stimulus phase over one stimulus cycle (Fig. 2), and we also captured one reference hologram, a preliminary measurement at zero stimulus phase. The displacement of the TM at the eight stimulus phases are thereafter computed relative to the reference displacement. The digital camera in the current system has a frame rate of 30 frames per second, which allowed us to calculate one hologram every 0.13 s (optical-phase-stepping requires 4 frames/hologram), and it took about 1.2 s (9×0.13) to complete a measurement at each frequency and level combination. Considering the imaged TM area of 60 to 70 mm² takes up about 40,000 pixels (Rosowski et al., 2009), the current stroboscopic holographic interferometry system is much superior to other techniques such as SLDV in its combination of spatial and temporal resolution.

2.4 Data Analysis

2.4.1 Spatial Phase unwrapping—The wrapped optical-phase differences calculated from the raw phase-stepped images (Eqn.3) are unwrapped in 2-D space over the entire image region to derive sound-induced dynamic motion of the TM relative to the initial reference state. While generally robust, the spatial phase unwrapping algorithm (Furlong and Pryputniewicz 2003; Furlong et al. 2009) is sensitive to rapid spatial variations in the optical phase that sometime occur at the edges of the TM on the image, especially at locations where the real edge of the tympanic ring is hidden by a bony remnant. The algorithm also does not work well on image regions outside the TM surface where the image intensity is usually low due to reduced laser illumination. Fig. 3D shows an example of a 3D TM displacement map after unwrapping the optical phase difference between one stimulus phase and the reference phase: An ordered displacement map is seen within the TM surface area (a nearly circular area in the middle of the image), while the area outside the TM appears disordered (due to poor performance of the spatial phase unwrapping algorithm when it is challenged with highly-variable or poorly-defined optical phases).

2.4.2 Masking and Edge Normalization—In order to exclude the disordered regions of the unwrapped displacement maps, a mask is applied prior to further analysis. The mask (Figure 3E) was shaped to cover the surface of the TM and exclude the disordered regions outside of

the TM area, with the mask values set to unity within the TM surface and zero elsewhere. Masking is done through a point-by-point multiplication of the unwrapped displacement map and the mask. Figure 3A shows the unwrapped displacements along one image line (the dotted line in Fig. 3D), and Figure 3B shows the result after masking.

One should note that the unwrapped and masked displacement data of Figs. 3A, 3B and 3D all show displacements that are well above the zero x–y plane. That is because the spatial phase-unwrapping algorithm normalizes the displacement at each point of the image by the maximum inward displacement value in each image. In the data of Fig. 3, that inward maximum is a narrow spike (the dotted circle shown at the bottom of Fig. 3D) near the lower left-hand corner of the image that is within the disordered region of the unwrapped displacement map. The displacements at every point of the image are thus scaled relative to this inward maximum with the values all positive. By assuming that the inner edge of the masked TM (where the tympanic annulus is) is not moving, we reset the zero reference to the average position at the edge of the TM. The result of this edge normalization is shown in Fig. 3C, which illustrates that some parts of the TM move inward toward the middle ear (the negative displacements), while others move outward toward the ear canal (the positive displacements). Masking and edge normalization were applied to each of the eight sets of spatial phase-unwrapped displacement maps to define the surface motions of the TM relative to the reference at each of the eight stimulus-phase-locked instances in time.

2.4.3 Fourier Transform Analysis—The defined surface motions of the TM at the eight stroboscopic measurement instances were then used to construct eight frame ‘movies’ of the displacement of the TM vs. time. Fourier analysis (Matlab R2008a) of the displacement at these eight temporal instants was performed to compute the magnitude and phase of the sinusoidal displacement at each point on the TM surface (Fig. 4). Note that the laser pulse was synchronized to the stimulus voltage waveform, not to the waveform of the sound pressure or the TM displacement, therefore, the phase of the reference measurement could vary by $\pm\pi$ relative to the phase of the stimulus sound pressure. If the reference phase measurement corresponded to a temporal peak (or valley) in the sinusoidal response, all of the non-zero phase measurements would have displacements that were negative (or positive) relative to the reference position and a significant negative (or positive) DC component would be observed in the computed Fourier components. Similarly, if the reference phase measurement corresponded to a time point where the displacement of the TM was at zero, or the TM was at a neutral state, then all of the non-zero phase measurements would have displacements that were equally positive and negative, and the Fourier components would have a zero DC component.

An example of the reliability of our estimates of the Fourier components of the displacement of a single point on the TM is given in Fig. 4. We plot the raw measured displacement data (dotted line with circles) at a position near the umbo of the TM as a function of stimulus phase and the displacement vs. phase $d'(x, y, t)$ reconstructed from the computed Fourier DC component D_0 and the magnitude $|D|$ and phase angle $\angle D$ of the fundamental Fourier-derived sinusoidal displacement of the TM at the stimulus frequency (solid line):

$$d'(x, y, t) = D_0 + |D| \sin(2\pi ft + \angle D), t = 0, \frac{1}{8}T, 14T, \dots, \frac{7}{8}T \quad (4)$$

where f is the frequency of the stimulus, and $T = 1/f$ is the period of the stimulus. The correlation coefficient between the measured and reconstructed data is very high in this case (0.9942), and the mean correlation values ($\pm$ the standard deviation) over the entire TM surface were 0.9470 ± 0.1337 for 0.5 kHz, 0.9214 ± 0.1534 for 1 kHz, 0.9450 ± 0.1277 for 4 kHz and 0.9664 ± 0.0948

for 8 kHz. These high correlations between the measured waveforms and the reconstructed fundamental component of displacement of the TM also suggest the TM response is nearly linear at all four measured frequencies.

In order to further investigate whether the response of the TM varies linearly with our relatively high sound-pressure stimuli, we computed the ratios of the FFT derived 2nd, 3rd and 4th harmonic components of the maximal displacements on the TM surface to the magnitude of the FFT derived maximal TM displacements at the fundamental (stimulus) frequency. The distortion ratios are converted into dB as shown in Table 1. All the higher-ordered harmonic distortions in the maximal TM displacements are 20 to 40 dB lower than the fundamental component, and the total harmonic distortions from all measurements are around 20 dB. This result is consistent with a low-distortion level in the sound field at the TM surface during all the measurements.

3. RESULTS

To better understand the wave motion on the surface of the TM measured by the stroboscopic holography, we present our measurement results in three different ways: (1) Plots of the phasic displacements along a single chord across the surface of the TM; (2) Phasic surface maps of the displacement of the entire TM surface; and (3) Plots of the Fourier derived amplitude and phase-angle of the surface displacement along four diameter lines (one horizontal (0°), one vertical (90°), and two diagonal (45° and 135°)) that define and bisect each of the four quadrants of the TM. These presentations provide a detailed view of sound-driven TM motion.

3.1 Temporal Displacement Along One Horizontal Chord

The magnitude and phase angle of the fundamental Fourier component of the TM displacement were used to compute the displacement at each point along one horizontal chord across the TM positioned just below the umbo (the dotted line in Fig. 3D). The four panels in Fig. 5 show snapshots of the TM displacement along the chord at eight measurement phases over one stimulus cycle (0 to 7/8 cycle) for four sound stimuli: 92 dB SPL at 0.5 kHz, 90 dB SPL at 1 kHz, 103 dB SPL at 4 kHz and 115 dB SPL at 8 kHz. The location just below the umbo is marked on each panel by a thick solid line, and the x-axis shows the approximate distance along the chord relative to the center of the umbo (anterior = negative; posterior = positive).

At 0.5 kHz (Fig. 5A) and 1 kHz (Fig. 5B), the displacements of the TM with time along the chord demonstrate that the largest motion is in the posterior half of the TM. Furthermore, the eight temporally-related lines are regularly arranged and generally do not cross each other which suggests all the points along the chord move in phase. At 0.5 kHz (Fig. 5A) the largest outward motions at each location occur at a stimulus phase between 1/4 and 3/8 cycle. At 1 kHz (Fig. 5B) the largest outward motions at each position generally occur at a stimulus phase between 3/4 and 7/8 cycle, though just posterior to the umbo ($x \sim +1.3$ mm) there is a small region where the largest outward motions occur at phases between 0 and 1/8 cycle. (The colored lines of different line type across the bottom of each panel code the stimulus phase associated with the largest outward motion at each location. When the maximal outward motion occurs at two different phases, two lines are shown.) At both frequencies, it is clear that the peak-to-peak displacement near the umbo location is much less than the peak-to-peak displacement in the posterior half of the TM (shown by vertical arrow lines).

At 4 kHz (Fig. 5C) and 8 kHz (Fig. 5D), the displacement patterns are more complex with multiple local maxima and minima along the chord that reach their peak at different stimulus phases. At 4 kHz, we observe four positions where the amplitude of the sinusoidal motion reaches a local maximum (P1, P2, P3 and P4): each of these positions reaches its maximum outward motion at a stimulus phase between 0 (black solid line) and 1/8 cycle (red solid line).

We also see two locations (indicated by arrows) where the displacement is near zero at all measurement phases and the angle changes by a half cycle on either side. Such behavior is consistent with the presence of a 'node' or modal minimum. A third feature of the data in Fig. 5C is that there are broad ranges of locations that move with approximately the same phase, e.g. from -0.7 to 0.4 mm and from $+1.7$ to $+4.6$ mm the maximal outward motion occurs at a stimulus phase of 0 (solid black). A fourth feature is that there are regions where the phase at maximum outward motion shifts gradually with locations: e.g. shifting from $5/8$ cycle (red dashes) at -3.7 mm through $1/8$ cycle (red solid) at -2.4 mm and from $1/2$ cycle (black dashes) at -1.8 mm to 0 cycle (black solid) at -0.6 mm. A fifth feature is that at 4 kHz the magnitude of the displacement just under the umbo is within a factor of two of the largest motions visible along the chord.

At 8 kHz the pattern of motion with time is more complicated but shows many of the features visible in the 4 kHz data, with eight positions with identifiable local magnitude peaks (P1–P8). The most anterior peak (P1) and the five posterior peaks, P4–8 achieve their maximum outward displacements at a stimulus phase within $0 \pm 1/4$ cycle (green dashed line to black, red and orange solid lines). The timing of the maxima at peak P2 occurs a half cycle later, while the timing of the maximum at peak P3 occurs nearly a half cycle later than that at P2 and within a $1/4$ cycle of the other peaks. Consistent with the locations of rapid near half-cycle phase changes are three 'nodal' regions of minimal motion at -2.0 , -2.9 and -3.4 mm. There are also regions along the chord where we see more gradual changes in the phase of the maxima, and the motion magnitude just below the umbo is similar to that seen in the regions with the largest magnitudes of motion.

3.2 Temporal Displacement over the Entire TM

Figure 6, Figure 7 and Figure 8 show perspective plots of the instantaneous displacement (normalized by sound pressure) of the entire TM at eight measurement stimulus phases for stimulus frequencies of 0.5, 4 and 8 kHz. The color bar on the right side represents the normalized displacement value in $\mu\text{m}/\text{Pa}$. The orientation of the TM and the location of the umbo are shown in the first image at the 0 cycle of the stimulus.

At 0.5 kHz (Fig. 6), the entire TM is seen to move roughly in phase from Fig. 6(a) to 6(h). Two regions of maximal displacement develop with time in the posterior half of the TM: Region P1 is slightly superior and more anterior to region P2. The motions at these locations are at their maxima between $1/4$ and $3/8$ cycle of the stimulus, though P2 reaches the maximum somewhat later than P1. The maximal normalized displacement amplitude at 0.5 kHz is about $0.1 \mu\text{m}/\text{Pa}$ at both P1 and P2.

At 4 kHz (Fig. 7) we can identify about ten separate regions of maximum displacement on the TM surface. These regions reach their maximal positive displacement at stimulus phases between $7/8$ and 0 cycles and reach their most-negative values a half cycle later. There are also places that reach their maximal positive displacements at other phases. Panel 7e shows a single region that reaches its maximal positive displacement at stimulus phases a half cycle later than the phases where maxima occurred in Fig 7a. Again, we also see signs of slow spatial phase gradients: The peak on the left in panel 7c appears to travel more or less towards the center in panels 7d and 7e. The peak on the right in panel 7c also seems to result from a slow shift of one of the posterior peaks in panels 7a and 7b. These phase gradients of the peaks suggest some wave traveling phenomena on the TM surface. The maximum normalized displacement amplitude at 4 kHz is only about $0.01 \mu\text{m}/\text{Pa}$, much smaller than that at 0.5 kHz. Such a decrease in normalized displacement with increasing frequency is consistent with many other measurements of TM motion (Goode et al., 1993,1994). Similar motions of the TM at 8 kHz are shown in Fig. 8, with the entire surface of the TM being separated into multiple peaks and valleys in displacement. The maximum normalized displacement amplitude at 8 kHz is about

$6 \times 10^{-3} \mu\text{m}/\text{Pa}$. Short animations of the data in Fig. 5, Fig. 6, Fig. 7 and Fig. 8 are available for viewing at: [https://myfiles.meei.harvard.edu/users/rosowsj/www/Index Page.htm](https://myfiles.meei.harvard.edu/users/rosowsj/www/Index%20Page.htm).

3.3 Displacement Amplitude and Phase along Radial Lines on the TM Surface

The magnitude and phase of the sinusoidal displacement of the TM at 0.5, 1, 4 and 8 kHz are plotted in Fig. 9 along four diameters (0° , 45° , 90° and 135°), all going through the umbo, that separate and bisect the four quadrants of the TM surface. The x-axis shows the approximate distance away from the umbo (at 0 mm) along the four diameters. The inset cartoon in the bottom panel of Fig. 9A shows the four diameters as dotted lines. The four panels on the top show displacement magnitude and the four panels on the bottom show displacement phase. Note phases are only determined for regions with displacement amplitudes larger than $0.014 \mu\text{m}$, which we estimate as the noise floor of this measurement set.

At 0.5 kHz (Fig. 9A), the displacement amplitude along the 0° and 45° lines show peaks in the posterior-superior quadrant of the TM. The 90° and 135° lines, which do not pass through the peak regions on the posterior side of the TM (Fig 6), show smaller displacement magnitudes. The displacement phase is nearly identical along all four diameters with some small differences along the 0° and 45° diameters in the more posterior positions. Such small variations are consistent with the small phase difference between the two peaks visible in Fig 6.

At 1 kHz (Fig. 9B), we see displacement amplitude and phase patterns similar to those at 0.5 kHz. One difference is the presence of near half-cycle phase shifts near the edges of the TM. These phase shifts occur in regions where the motion of the TM is small and may be affected by measurement noise.

At 4 kHz (Fig. 9C), we see multiple spatial maxima and minima in the displacement magnitude across all four diameters, consistent with the large number of spatial maxima we identified in Figure 7. We also see significant variations in the displacement phase with location. Those phase variations in space take several forms, including: (a) slow back and forth variations in phase of less than ± 0.2 cycles around some mean phase value (as occurs along the 0° line), (b) rapid step-like half-cycle changes in phase that occur in the 45° , 90° and 135° lines in the anterior and superior quadrants of the TM (these steps usually occur at locations where the magnitude of motion is at a minimum, which is consistent with the presence of displacement 'nodes'), and (c) consistent slower phase changes with position over short distances (e.g. along 45° , 90° and 135° lines between 1 and 3 mm), that sometimes coincide with the rapid half-cycle phase changes described above (e.g. along 45° , 90° and 135° lines between -4 and -1 mm). The patterns of displacement amplitude and phase along the four diameters with the 8 kHz stimulus (Fig. 9D) are qualitatively similar to those at 4 kHz.

4. DISCUSSION

Our measurements of sound-induced motions of the human TM at four stimulus frequencies show a progression of motion patterns with frequency. With stimuli of 0.5 and 1.0 kHz, the posterior parts of the TM move more than other regions, but the entire surface of the TM is moving approximately in the same phase. At 4 and 8 kHz, our data illustrate large spatial variations in the motion along the TM surface with multiple local motion maxima that move either nearly in phase with each other, nearly out-of-phase with each other, or follow phase gradients in space. We also report the presence of a few 'nodal' TM locations where the displacement magnitude is near zero while the phase varies by nearly a half cycle on either side, although such nodal behavior is not dominant in our data.

The complex spatial displacement patterns of the TM that we observed at 4 and 8 kHz are not consistent with any previous simple models describing TM motion. The presence of multiple

amplitude maxima and half-cycle phase steps with locations on the TM surface are suggestive of modal displacements of the TM (Tonndorf and Khanna 1970; Fletcher 1992; Rosowski et al. 2009). However, modal displacement patterns should show nodes (minima in displacement magnitude associated with half-cycle phase shifts) between adjacent displacement maxima, while we observe only a few of nodes and often see adjacent displacement maxima move in phase. The slow progressive changes in phase with locations that we see with higher-frequency stimulation in Fig. 5, Fig. 7, Fig. 8 and Fig. 9 are most consistent with traveling waves moving along the TM surface, as suggested by Puria and Allen (1998) and Parent and Allen (2007, 2009), though our measurements are dominated by peaks that are mostly stationary in phase. Indeed, a conceptual model that seems to explain significant features of the behavior of the TM that we observed is that the TM is responding to the uniform stimulus on its surface with a combination of stationary modes of motion plus some smaller traveling-wave like components.

This combination of modal and traveling-wave like patterns at high frequency is consistent with the motion of the gerbil TM as described by de La Rochefoucauld and Olson (MEMRO 2009). These authors measured the displacement amplitude and phase along a line from the center of the umbo to the edge of the TM at varied frequencies (Fig. 2 and Fig. 3 in de La Rochefoucauld and Olson, MEMRO 2009), they suggested the TM motion could be approximated as the combination of a wave-like motion and a back-and-forth piston-like motion, where the piston-like motion accounts for sound transmission, while the wave-like motion is related to the resonance of the drum-like TM which is transmitted to the manubrium producing fine structures of manubrium motion. Our data with multiple displacement amplitude peaks that generally move in- or out-of-phase (Fig. 7 and Fig. 8) with some smaller spatially varying phase components (Fig. 9) agrees with their suggestion of a combination of multiple wave motions on the TM surface, though the precise wave types and wave numbers are not yet clear and need further investigation.

The existence of traveling waves on the TM has been predicted by a time domain wave model of the human TM proposed by Parent and Allen (MEMRO 2009). Their hypothesis is that waves traveling on the TM contribute to the middle ear delays that have been observed experimentally (Olson 1998; Puria and Allen 1998; Overstreet and Ruggero 2002; Ravicz et al. 2008). Our study does show some traveling wave like components on the TM surface while the TM is driven by sound, but it also shows a strong modal pattern of TM motion. The latter pattern is more consistent with uniform stimulation of the TM surface. Further study is required to tease out these complex behaviors of the TM, and determine how wave travel on the TM surface contributes to the transfer of sound energy to the ossicles and whether such behavior explains the observed middle-ear delays.

Stroboscopic holography allows us to quantify the displacement amplitude and phase over the entire surface of the TM at over 40000 measurement points within a 70 mm² area. This full-surface measurement with large point density provides a complete view of TM motion and allows a quantitative description of multiple displacement peaks over the TM surface and how these peaks move around on the TM surface. In this study, we report TM motion measured by stroboscopic holography at four frequencies (0.5, 1, 4 and 8 kHz). The limitation in frequency is primarily related to the large amount of time needed to determine how to analyze and display the holographic data. As we further develop our analysis techniques, more closely-spaced-frequency measurements can be evaluated in order to estimate group-delay on the TM surface and the frequency-dependent wave velocity and potential delay caused by wave propagation on the TM surface. Nevertheless, the four-frequency data set of the present study provides substantial new insights into the complex motion of the TM.

5. CONCLUSION AND FUTURE WORK

In this study, we used stroboscopic holographic interferometry to measure the vibration of the human TM stimulated by tones of 0.5, 1, 4 and 8 kHz. This technique can quantify both displacement amplitude and phase of the surface motion of the TM over a wide frequency range, allowing a more complete view of the dynamics of TM motion. Our results suggest that at 0.5 and 1 kHz the entire surface of the TM moves generally in phase with the largest motions occurring in the posterior half of the TM. At 4 and 8 kHz the TM vibrates with multiple (4 to 10) local maxima distributed over the surface. Many of these maxima occur at the same phase of stimulation, while some occur at opposite phase, and others show signs of graded phase with position. These patterns are consistent with a combination of low-order modal motions and waves-traveling on the TM surface. Future work will refine our understanding of these wave-like phenomena (e.g. modal displacements in a lossy membrane have many features in common with traveling waves (Fletcher 1992, Page 78–79)), and also investigate how these complex motion patterns of the TM are related to sound coupling and transmission to the middle ear.

List of Abbreviations

OEH	Opto-electronic holograph
SLDV	Scanning laser Doppler vibrometer
SPM	Sinusoidal phase modulation
THD	Total harmonic distortion
TM	tympanic membrane
WPI	Worcester Polytechnic Institute

Acknowledgments

The authors thank Diane Jones at the Eaton-Peabody Laboratory (EPL) of the Massachusetts Eye and Ear Infirmary (MEEI) for her help in the acquisition of temporal bones for this work. Mr. Nesim Hulli from the Center for Holographic Studies and Laser micro-mechaTronics (CHSLT) and Department of Mechanical Engineering at the Worcester Polytechnic Institute (WPI) has provided much technical assistance with the Holographic Interferometry system. We value discussions with Michael Ravicz and Dr. Heidi Nakajima of our results. Mr. Christopher Scarpino an engineer at the EPL has assisted in the fabrication of the holography and sound-delivery system and was instrumental to the marriage of the expertise at the WPI and MEEI. This work was supported by NRSA fellowship 1F32DC009949-01 and R01-DC008642 from NIDCD and a donation from L. Mittal.

REFERENCES

- Decraemer WF, Khanna SM, Funnell WR. Interferometric measurement of the amplitude and phase of tympanic membrane vibrations in cat. *Hear Res* 1989;38(1–2):1–17. [PubMed: 2708151]
- Decraemer WF, Khanna SM, Funnell WR. Vibration at a fine grid of points on the cat tympanic membrane measured with a heterodyne interferometer. *EOS/SPIE Int Sym*, Munchen. 1999
- de La Rochefoucauld O, Olson E. A sum of simple and complex motions on the eardrum and manubrium in gerbil. *Hearing Research MEMRO*. 2009
- Fay J, Puria S, Decraemer WF, Steele C. Three approaches for estimating the elastic modulus of the tympanic membrane. *J Biomech* 2005;38:1807–1815. [PubMed: 16023467]
- Fletcher, NH. *Acoustic Systems in Biology*. New York: Oxford Univ. Press; 1992.
- Funnell WR, Laszlo CA. Modeling of the cat eardrum as a thin shell using the finite-element method. *J Acoust. Soc. Am* 1978;63:1461–1467. [PubMed: 690327]
- Funnell WR, Decraemer WF, Khanna SM. On the damped frequency response of a finite-element model of the cat eardrum. *J Acoust. Soc. Am* 1987;81:1851–1859. [PubMed: 3611506]

- Furlong C, Pryputniewicz RS. Hybrid computational and experimental approach for the study and optimization of mechanical components. *Opt. Eng* 1998;37(5):1448–1455.
- Furlong C, Pryputniewicz RS. Optoelectronic characterization of shape and deformation of MEMS accelerometers in used in transportation applications. *Opt. Eng* 2003;42:1223–1231.
- Furlong C, Rosowski JJ, Hulli N, Ravicz ME. Preliminary analyses of tympanic-membrane motion from holographic measurements. *Strain* 2009;45:301–309. [PubMed: 20209120]
- Gan RZ, Wood MW, Dormer KJ. Human middle ear transfer function measured by double laser interferometry system. *Otol Neurotol* 2004 Jul;25(4):423–435. 2004. [PubMed: 15241216]
- Gan RZ, Feng B, Sun QL. Three-dimensional finite element modeling of human ear for sound transmission. *Ann. Biom. Eng* 2004;32(6):847–859.
- Goode RL, Ball G, Nishihara S. Measurement of umbo vibration in human subjects-methods and possible clinical applications. *Am J Otol* 1993;14:247–251. [PubMed: 8372921]
- Goode RL, Ball G, Nishihara S, Nakamura K. Laser Doppler Vibrometer (LDV) – a new clinical tool for the otologist. *Am J Otol* 1996;17(6):813–822. [PubMed: 8915406]
- Goode RL, Killion M, Nakamura K, Nishihara S. New knowledge about the function of the human middle ear: Development of an improved analog model. *Am J Otol* 1994;15:145–154. [PubMed: 8172293]
- Guinan JJ Jr, Peake WT. Middle-ear characteristics of anesthetized cats. *J Acoust. Soc. Am* 1967;41:1237–1261. [PubMed: 6074788]
- Hernandez-Montes, Mds; Furlong, C.; Rosowski, JJ.; Hulli, N.; Harrington, E.; Cheng, JT.; Ravicz, ME.; Santoyo, FM. Optoelectronic holographic otoscope for measurement of nano-displacements in tympanic membrane. *J. Biomed. Optics* 2009;14(3):034023.
- Khanna SM, Tonndorf J. Tympanic membrane vibrations in cats studied by time-averaged holography. *J. Acoust. Soc. Am* 1972;51(6):1904–1920. [PubMed: 5045250]
- Koike T, Wada H, Kobayashi T. Modeling of the human middle ear using the finite-element method. *J Acoust. Soc. Am* 2001;111(3):1306–1317. [PubMed: 11931308]
- Konrúðsson KS, Ivarsson A, Bank G. Computerized laser Doppler interferometric scanning of the vibrating tympanic membrane. *Scand Audiol* 1987;16:159–166. [PubMed: 3324293]
- Løkberg OJ, Hogmoen K, Holje OM. Vibration measurement on the human tympanic membrane in vivo. *Appl. Optics* 1979;18:763–765.
- Olson ES. Observing middle and inner ear mechanics with novel intracochlear pressure sensors. *J. Acoust. Soc. Am* 1998;103:3445–3463. [PubMed: 9637031]
- Overstreet EH III, Ruggero MA. Development of wide-band middle-ear transmission in the Mongolian gerbil. *J. Acoust. Soc. Am* 2002;111:261–270. [PubMed: 11831800]
- Parent P, Allen JB. Wave model of the cat tympanic membrane. *J. Acous. Soc. Am* 2007;122(2):918–931.
- Parent P, Allen JB. Time-domain “wave” model of the human tympanic membrane. 2009 doi:10.1016/j.heares.2009.12.015.
- Puria S, Allen JB. Measurements and model of the cat middle ear: Evidence of tympanic membrane acoustic delay. *J. Acoust. Soc. Am* 1998;104:3463–3481. [PubMed: 9857506]
- Rabbitt RD, Holmes MH. A fibrous dynamic continuum model of the tympanic membrane. *J Acoust Soc Am* 1986;80(6):1716–1728. [PubMed: 3794078]
- Ravicz ME, Cooper NP, Rosowski JJ. Gerbil middle-ear sound transmission from 100 Hz to 60 kHz. *J. Acoust. Soc. Am* 2008;124:363–380. [PubMed: 18646983]
- Rosowski JJ, Nakajima HH, Merchant SN. Clinical utility of laser-Doppler vibrometer measurements in live normal and pathologic human ears. *Ear Hear* 2008;29(1):3–19. [PubMed: 18091103]
- Rosowski JJ, Cheng JT, Ravicz ME, Hulli N, Hernandez-Montes Mds, Harrington E, Furlong C. Computer-assisted time-averaged holograms of the motion of the surface of the mammalian tympanic membrane with sound stimuli of 0.4 to 25 kHz. *Hear Res* 2009;253:83–96. [PubMed: 19328841]
- Tonndorf J, Khanna SM. The role of the tympanic membrane in middle ear transmission. *Ann. Otol* 1970;79:743–753.
- Tonndorf J, Khanna SM. Tympanic membrane vibrations in human cadaver ears studied by time averaged holography. *J. Acoust. Soc. Am* 1972;52(4):1221–1233. [PubMed: 4638037]

Wada H, Ando M, Takeuchi M, Sugawara H, Koike T. Vibration measurement of the tympanic membrane of guinea pig temporal bones using time averaged speckle pattern interferometry. *J. Acoust. Soc. Am* 2002;111(5):2189–2199. [PubMed: 12051438]

Figure 1.

Experimental setup and schematic of Opto-electronic Holographic (OEH) Interferometry system. The sinusoid acoustic stimuli are generated by a computer-controlled stimulus generator that drives an earphone. The sound pressure near the TM surface is monitored by a probe-microphone and recorded in the computer via an analog-to-digital (A/D) converter. In stroboscopic holographic measurement mode, the laser beam (473 nm wavelength) is controlled by the 'strobe switch' (an opto-acoustic modulator capable of high-frequency switching) which generates a series of stimulus-phase-locked strobed laser pulses with a duration of 10% of the tonal stimulus cycle. The laser pulses are split into a reference beam and an object beam with a beam splitter. The reference beam is subjected to an optical phase shift that changes the optical path length by 0, 1/4, 1/2 or 3/4 of the optical wavelength, and the object beam is sent to illuminate the specimen through a mirror and collimator. The reflected object beam interferes with the reference beam producing interferograms that are recorded by the digital camera of the OEH system. The time varying displacement of the TM is measured by the computer as a series of stroboscopic holograms at different time instants and processed by computer to provide quantitative measurements of the deformations of the TM between two different time instants. (This figure is an expanded version of Fig 1. of Rosowski et al. (2009)).

Figure 2.

Stroboscopic holograms of the TM recorded at eight stimulus phases ($0, \pi/4, \pi/2 \dots 7\pi/4$), in which the motion of the TM relative to the reference hologram (the reference is not shown but is a repeated measurement at a stimulus phase of 0) is recorded as spatial variations of the image intensity (Eqn 2). The near-circular window on each image is the edge of the round-shaped speculum which bounds the view of the TM. The manubrium is outlined on each image, while the umbo and the posterior (P) and superior (S) orientations of the bone are marked in the last image taken at stimulus phase of $7\pi/4$.

Figure 3.

Results of masking and edge normalization on raw displacement data of the TM at the stimulus frequency of 8 kHz and the stimulus phase of $3\pi/4$. (A) The unwrapped displacement data along one line on the image. (B) As in A, but after application of the Mask. (C) As in B, but after normalization by the mean value at the edge. (D) A surface view of the displacement data reconstructed after phase-unwrapping of the raw displacement data. The orientation of the TM is identified by the outline of the manubrium (thick solid black line) on the TM surface, with the dotted line showing the line used in plots A through C. The narrow inward spike used to define the zero displacement position is marked by a dotted circle at the bottom. (E) The mask used to exclude regions outside the surface of the TM, with a value of 1 within the edge of the TM and 0 outside the edge.

Figure 4.

The displacement at one point near the umbo on the TM surface changing with stimulus phase computed from raw stroboscopic holographic data (dotted line with circle) and reconstructed from the Fourier analysis (solid line). The correlation between the raw displacement data and the Fourier reconstruction is very high (0.9942).

Figure 5.

The displacement along one horizontal chord across the TM. The chord is positioned just below the umbo. The displacements are illustrated at eight stimulus phases for four sound stimuli: 92 dB SPL at 0.5 kHz, 90 dB SPL at 1 kHz, 103 dB SPL at 4 kHz and 115 dB SPL at 8 kHz. The x-axes show the approximate distance along the chord from a point just below the umbo (anterior = negative; posterior = positive). The location just below the umbo is marked on each panel by a thick solid line. The colored lines of different line type across the bottom of each panel code the stimulus phase associated with the largest outward motion at each location. When the maximal outward motion occurs at two different phases, two lines are shown. (A) At 0.5 kHz, the displacements of the TM along the chord at varied phases are of the largest magnitude in the posterior half of the TM and all of the points along the chord move with roughly the same phase. (B) At 1 kHz, the TM moves similarly as in 0.5 kHz, with the largest motion in the posterior site and all of the points along the chord moving with roughly the same phase. (C) At 4 kHz, the displacement pattern is more complex with multiple local maxima along the chord occurring at different stimulus phases. (D) At 8 kHz, the pattern of motion with time is more complicated with eight identifiable magnitude peaks.

Figure 6.

Perspective (3D) plots of the instantaneous displacement (normalized by sound pressure) of the entire TM surface at eight stimulus phases for a stimulus frequency of 0.5 kHz. The color bars on the right side represent the normalized displacement value in $\mu\text{m}/\text{Pa}$. The orientation of the TM and the location of the umbo are shown in the first image at the stimulus phase 0. The entire TM is moving roughly in phase from (a) to (h), with two local peaks developing with time and marked by P1 and P2. The two peaks reach their maxima between 1/4 and 3/8 cycle of stimulus phase, with P2 somewhat later than P1.

Figure 7.

Perspective plots of the instantaneous displacement (normalized by sound pressure) of the entire TM surface at eight instant stimulus phases for stimulus frequency of 4 kHz. The color bars on the right side represent the normalized displacement value in $\mu\text{m}/\text{Pa}$. The orientation of the TM and the location of the umbo are shown in the first image at the stimulus phase 0. About ten separate peaks are identified on the TM surface as shown in panel (a). Motion within some of the peaks occurs with different phases (panels c, d and e) and some peaks appear to move to different locations (panels d and e).

Figure 8. Perspective plots of the instantaneous displacement (normalized by sound pressure) of the entire TM surface at eight instant stimulus phases for stimulus frequency of 8 kHz. The color bars on the right side represent the normalized displacement value in $\mu\text{m}/\text{Pa}$. The orientation of the TM and the location of the umbo are shown in the first image at the stimulus phase 0.

Figure 9.

Fourier derived displacement magnitude and phase of the TM along four diameters at 0°, 45°, 90° and 135° on the TM surface for the stimulus of 0.5 (Fig. 9A), 1 (Fig. 9B), 4 (Fig. 9C) and 8 (Figure 9D) kHz. The top panel of each figure shows the magnitude of the displacement in micrometers, the bottom panel of each figure shows the displacement phase in cycles. The cartoon in the bottom panel of Fig. 9A shows the orientation of the TM and the four diameters, which are illustrated by dotted lines that run through the umbo. The x-axis shows the approximate distance away from the umbo (at 0 mm) along the diameters. (A) At 0.5 kHz, the displacement magnitude along 0° and 45° diameters shows peaks in the posterior-superior quadrant of the TM, and smaller displacement magnitudes along the 90° and 135° diameters. The displacement phase is nearly identical along all four diameters. (B) At 1 kHz, the displacement amplitude and phase along four diameters are similar to those in Fig. 8A. The near half-cycle phase shifts near the edges of the TM are probably due to measurement noise. (C) At 4 kHz, the displacement amplitude shows multiple spatial maxima and minima along all four diameters, with significant phase variations along different diameters at different locations on the TM surface. (D) At 8 kHz, similar complex displacement patterns are seen along the four diameters on the TM surface, the displacement amplitude shows multiple spatial maxima and minima, while the displacement phase shows variations along the diameters at different locations.

Table 1
FFT Harmonic Distortion (HD) of Displacement

The ratios (in dB) of the computed harmonic distortions in TM displacement to the magnitude of displacement at the fundamental (stimulus) frequency. The listed measurements are from the locations of maximal displacement on the membrane surface at each frequency.

FFT Harmonic Distortion (HD) of Displacement	500 Hz	1000 Hz	4000 Hz	8000 Hz
Fundamental	—	—	—	—
2 nd HD	−31 dB	−38 dB	−31 dB	−43 dB
3 rd HD	−28 dB	−25 dB	−23 dB	−32 dB
4 th HD	−37 dB	−42 dB	−30 dB	−29 dB
THD	−22 dB	−22 dB	−18 dB	−24 dB

THD: Total Harmonic Distortion, the ratio of the sum of all harmonic components to the fundamental one.