

TIME AVERAGE HOLOGRAPHY STUDY OF HUMAN TYMPANIC MEMBRANE WITH ALTERED MIDDLE EAR OSSICULAR CHAIN

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Computer-assisted time average holographic interferometry was used to study the vibration of the human tympanic membrane (TM) in cadaveric temporal bones before and after alterations of the ossicular chain. Simultaneous laser Doppler vibrometer measurements of stapes velocity were performed to estimate the conductive hearing loss caused by ossicular alterations. The quantified TM motion described from holographic images was correlated with stapes velocity to define relations between TM motion and stapes velocity in various ossicular disorders. The results suggest that motions of the TM are relatively uncoupled from stapes motion at frequencies above 1000 Hz.

1 Introduction

The tympanic membrane (TM) is the first middle-ear structure involved in the transduction of air-borne sound to sound pressure in the cochlear fluid. Alterations of the middle ear by trauma or disease (such as TM perforation and ossicular disorders) reduce the efficiency of sound coupling between the TM and inner ear and result in various degrees of conductive hearing loss [1, 2]. While the clinical diagnosis of conductive hearing loss can be made from audiometry, it is not always easy to differentiate various causes of the conductive hearing loss especially in patients with intact TMs. Nakajima et al. [2] used temporal bone studies to quantify the relationship between umbo and stapes velocity in three cases of artificial ossicular chain fixation (malleus, incus and stapes fixations); the results indicated that the relative reduction of stapes and umbo velocity depended on the locations of the ossicular fixation. However, those results are limited by the measurement of a single point on the TM surface (umbo) and how such fixations affect the vibration of the entire TM is not known. In this study, we used time average holography interferometry (TAHI) [3] to investigate the effects of ossicular manipulations on the motions of the TM and the stapes over a range of 0.1 to 25 kHz. The results improve our understanding of the function of the TM and may help in the diagnosis of various ossicular disorders and plans for treatment.

2 Method

2.1 Time Average Holographic Interferometry (TAHI)

Computer-assisted TAHI uses a digital camera synched with an optical phase shifter to capture two-dimensional interference images while stepping the optical phase of one of the interfering beams in cyclic steps of 90° [4]. Digital manipulation of four consecutive phase-stepped interference patterns yields one time average hologram for every 4 camera frames, where frame rates of 40 fps allow the calculation of a new hologram every 0.1 s. This rapid computation rate reduces the effects of very low-frequency motion noise in the system and allows observation of TM motion at video rates.

The TAHI image describes the magnitude of motion of a surface via a gray-scaled surface map in which the intensity of the image at any point $I(p)$ is proportional to the square of the 0th order Bessel function J_0 of the displacement amplitude $z(p)$ [5]:

$$I(p) \propto J_0^2(4\pi z(p)/\lambda) \quad (1)$$

where λ is the wavelength of the laser, and the wave number is $k=2\pi/\lambda$.

The mapping between the image intensity and the displacement magnitude couples the smallest displacement of the surface with the highest intensity, or the brightest area of the image. As the displacement magnitude at a local area increases, the image intensity at that location goes through a series of relative maxima and minima, which appear as a series of lighter areas bordered by dark fringes. Each fringe defines an iso-displacement contour whose magnitude corresponds to a zero of Eq. (1).

2.2 Temporal Bone Preparation

A fresh human temporal bone without history of otologic disease was prepared. The bony external auditory canal (EAC) was drilled away, down to the level of the tympanic ring in order to expose 80 to 90% of the TM surface. All soft tissues near the lateral surface of the membrane in the canal were carefully removed while keeping the epidermal layer of the TM untouched. The stapes was accessed by widely opening the mastoid and removing the segment of the facial nerve between the petrous bone and the posterior rim of the TM. The roof of the middle-ear air space was opened to access the head of the malleus and body of the incus. Mucosal folds covering the inside of the middle ear cavity and the ossicles were gently stripped away to improve later ossicular fixations. A hollow metal needle tube was glued to the edge of the TM annulus for placement of a probe microphone. The TM and middle ear cavity were kept moist by frequent spraying of saline and regular immersion in saline.

2.3 Holographic Interferometry Measurement

The temporal bone was positioned at the opening of the sound coupler (Fig. 1) within the interferometer head such that the tympanic ring was perpendicular to the object beam of the laser, with easy access to the stapes via the facial recess and the head of the malleus

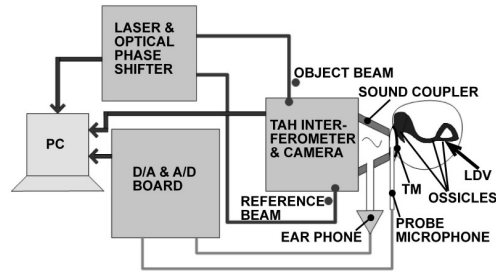


Figure 1. Experimental Setup.

and incus. An earphone piped to the coupler provided the stimulus to the TM, and a probe microphone positioned at the edge of the TM monitored the stimulus level.

Tones of frequencies of 0.2 to 25 kHz and levels between 75 and 130 dB SPL were used as stimuli. The sound pressures varied with frequency to cover the range between minimal (the first signs of TM motion) and near maximal (large motions of the entire TM surface) TM excitation (usually a range of 20 dB in 2 dB steps). To increase the light reflected from the near transparent TM, the TM surface was painted with a solution of TiO₂ powder. This painting has a small effect on middle-ear motion.

2.4 Laser Doppler Vibrometry (LDV) Measurement of stapes motion

The laser beam from the LDV was focused on the posterior crus of the stapes via the open facial recess with an angle of 45 to 60 degree relative to the plane of the stapes footplate. Simultaneous measurements of the stapes velocity and ear canal sound pressure were measured in response to a series of stepped tones (0.2 to 25 kHz).

2.5 Ossicular Chain Fixation

The ossicular fixations mimic conductive pathologies produced by middle ear disease [2]. We first fixed the malleus head to the epitympanic wall with dental cement. After TAHI and LDV measurements, the cement was removed to return the ossicular chain to the baseline condition and TAHI and LDV measurements were repeated. Finally the stapes was fixed and both TAHI and LDV measurements were repeated.

2.6 Analysis of TAHI Images for TM Sensitivity to Sound

The average intensity of TAHI images was used to quantify TM motion. The outline of the TM was identified first on TAHI images. The intensity was then averaged over the TM surface and normalized by the average intensity of the TM without stimulation. According to Eq. (1), when the displacement increases, the image intensity decreases due to an increase in gray level on the TM, such that the normalized intensity approaches 100% (the no stimulus value) at the lowest stimulus level. We select the 80% level of normalized image intensity as a threshold and compare the sound levels needed to achieve this threshold at different frequencies and various ossicular states.

3 Results and Discussion

Figure 2 illustrates TAHI images produced at six frequencies (increasing from the top to bottom) and four different bone conditions: column (A) the control case, (B) malleus head fixation, (C) malleus head freed and (D) stapes fixation. The manubrium is outlined in the bottom panel of each column. At frequencies of 1 kHz and lower, there are a few areas of maximal displacement defined by several concentric dark fringes on the TM surface. These “simple” patterns are consistent with previous results from Tonndorf and Khanna [3, 6]. At frequencies between 1 and 8 kHz, the patterns become “complex” with multiple inter-digitating local maxima. When the frequency is higher than 10 kHz, we see “ordered” patterns with many displacement maxima arranged like “pearls” on “strings”. The strings are arranged roughly in concentric circles around the manubrium, and the pearls are arranged radially on the strings. The distance between the strings and the size of the pearls decreases as frequency increases. Such “ordered” patterns are suggestive of regular two-dimensional standing waves, a phenomenon that has not been observed

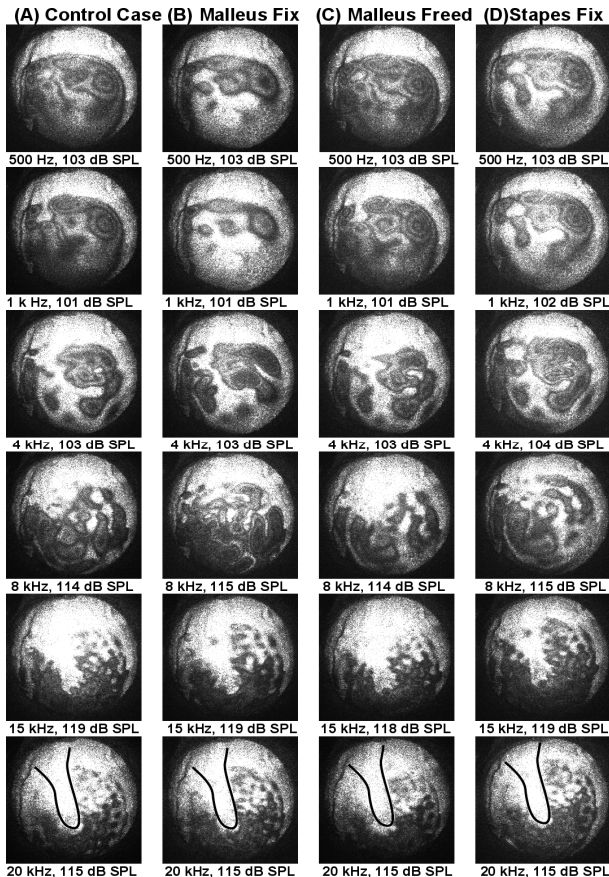


Figure 2. TAHI Images of Human TM before and after Ossicular Fixations.

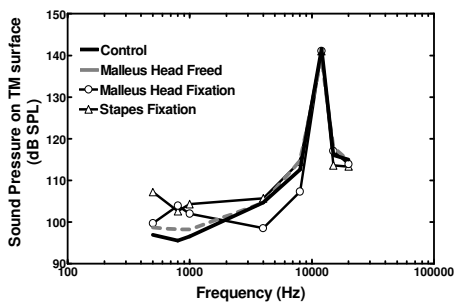


Figure 3. TM Sensitivity to Sound.

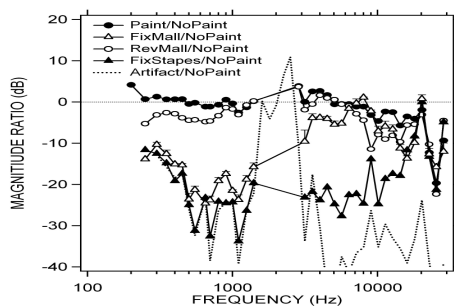


Figure 4. Stapes Velocity from LDV.

before. Figure 2 also illustrates the effects of ossicular manipulations on TM vibration. Column A (the control case) differs significantly from column B (malleus fixed) at $f < 4$ kHz but not at higher frequencies. Much of these differences are explainable by attenuations of the entire TM motion. Column C (malleus freed) is similar to Column A. Column D (stapes fixed) shows patterns intermediate between A and B at $f < 4$ kHz and small differences at higher frequencies.

Figure 3 shows computed 80% image intensity thresholds. In the control case (the thick dark line without symbols), the threshold sound pressures are lower at low frequencies, consistent with a higher sensitivity of TM motion at low frequencies [7]. Above 1 kHz, the thresholds generally increase, peak around 12 kHz, and then decrease till 20 kHz. This maximum at 12 kHz needs further investigation. After malleus head fixation (the solid line with open circles), the thresholds are increased at low frequencies compared to the control case, which is consistent with published data describing a decrease in umbo movement after malleus-head fixation [2]. However, the increased sensitivity of TM motion between 3 and 8 kHz after malleus fixation is not consistent with published umbo motion data [2]. After the malleus is freed (the gray dashed line), the thresholds return to near the control case. After stapes fixation (the solid line with triangles), the thresholds at $f < 4$ kHz are increased, consistent with a decrease in TM motion [2], while above 4 kHz, the thresholds are equal to the control case. The stapes fixation produced larger changes in TM motion than malleus fixation, which is contrary to previous umbo motion measurements [2].

Changes in stapes velocity produced by the same ossicular manipulations and the effect of painting the TM are illustrated in Fig. 4. The illustrated velocities are all relative to the velocity measured in the NoPaint condition. Painting the TM (filled circles) produced little change in stapes motion (differences of +2 to -5 dB at $f < 20$ kHz). Malleus fixation (open triangles) produced 20 dB or larger decreases in stapes motion at $f < 1$ kHz and little change at $f > 4$ kHz. Malleus freed (the open circles) returns the stapes velocity to near the initial case. Stapes fixation (the filled triangles) produced a reduction in stapes motion of at least 20 dB except at the highest and lowest frequencies. These changes are similar to those observed by Nakajima et al. [2], and are significantly larger

in magnitude than the differences in 80% thresholds in Fig. 3. Also illustrated in Figure 4 is the relative velocity of the petrous bone. This estimate of motion artifact in our system places lower bounds to discriminate the differences of motion. The artifact is generally 20 to 35 dB smaller than the stapes motion, except in a band between 1 and 3 kHz where the artifact dominates the measured motions. We excluded data in this band from our analysis. The cause of this artifact peak may be related to motion between the LDV laser mounted on an operating microscope and the bone coupled to the TAHI system.

4 Conclusion

The vibrations of the human TM stimulated by pure tones over 0.2 to 25 kHz were studied through TAHI and grouped into three patterns: simple, complex and ordered. The TM motions at various conditions were compared with stapes velocity. The results show the ossicular manipulations had effects on stapes motion that were visible at higher frequencies than the effects observed on TM motion. This is particularly true in stapes fixation, which reduced stapes velocity by at least 20 dB at frequencies less than 10 kHz, but had little effect on TM motion at frequencies of 4 kHz or higher.

Acknowledgments

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