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Background
The acousto-mechanical-transformer behavior of the Tympanic Membrane (TM) is determined by its geometry (shape and thickness) and mechanical properties. The questions of “How the TM couples acoustic energy to the ossicles?” and “How TM shape and vibration affect this series of events?” have yet to be fully answered. Holographic studies of 1D vibrations of the TM have been reported by several groups; however, 3D measurements of TM motions are few. In this study, we use full-field-of-view holographic techniques to measure near simultaneously the shape and 3D sound-induced displacement of cadaveric human TMs. Combinations of shape and 3D displacement measurements are used to characterize motions tangent and normal to the TM plane.

Methods
We developed a digital holographic system capable of full-field measurements of shape and three-dimensional sound-induced motion of the TM. The spatial resolution of the measuring system is ≈1,000,000 points per the 70 mm² TM area, and the temporal resolution is determined by the 50kHz limit of the acousto-optic modulator used to strobe the phasic illumination. The method of dual-wavelength holographic contouring was used to measure the shape of the TM with a spatial sensitivity of 10-30 micrometers. The 3D motion at each location on the TM was determined within an accuracy of 10-20 nm using the method of multiple sensitivity vectors in stroboscopic holographic interferometry. A numerical rotation matrix is used to rotate the original camera-based coordinate system of the measuring system, to a local TM coordinate system enabling characterization of motion components normal to the local TM surface (out-of-plane) and tangential to the local surface (in-plane). FFT algorithms are used to quantify the magnitude and phase of the motion components.

Results
In-plane and out-of-plane sound-induced motion components of three human TM samples are quantified at frequencies between 1 and 10 kHz, a range that covers low, mid, and high auditory frequencies. Results indicate that (1) the phase of in-plane motion components are greatly affected by the dimensional shape gradients, and (2) the magnitudes of local in-plane motion components are at least 10 to 20 dB smaller than the magnitude of motions normal to the local TM surface.

Conclusions
The fact that the in-plane components are much smaller than out-of-plane components is consistent with modeling the kinematics of TM by a thin-plate, in which the direction of motion
vectors are restricted to the direction of corresponding normal vectors to the TM surface with no tangential motion.

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![Image](image-url)

**Figure 1.** Shape and 3D sound-induced motion of a human TM measured with holographic interferometry: (a) 3D shape of the TM; and (b) the in- and out-of-plane sound-induced motion components (magnitudes and phases) of the TM excited with a tone of 4.48 kHz at 91 dB SPL, normalized by the out-of-plane motion of the umbo. The motion colorbars are in logarithmic scale, and phases are in radians. The handle of the malleus, the manubrium, is outlined in all the figures.

**References**
