Assessing eardrum deformation by digital holography

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Abstract

A novel system measures the structure, shape, and acoustically induced changes to the membrane of the human middle ear, to help diagnose and treat hearing disorders.

Understanding the human hearing process and associated disorders depends on quantifying the geometry and properties of the outer, middle, and inner ear. The eardrum, also known as the tympanic membrane (TM), transforms sound waves from the outer ear into vibrations of the middle ear. Because of the TM's important role, and its direct visibility through the ear canal, current ear exams assess a patient's hearing by considering the health of the eardrum itself.

Measuring deformations of the TM for different acoustic stimuli can indicate the degree of a patient's hearing loss,¹ and aid diagnosis and treatment of their clinical condition. Based on this approach, current quantitative examination procedures include average acoustic estimates (admittance or reflectance), and laser Doppler vibrometry displacement measurements.² These techniques give valuable feedback on the state of the patient's hearing, but provide only average quality information about the eardrum, leaving the examiner blind to the complex patterns unfolding across the full surface of the membrane. To address this, we are developing optical methods to quantify the structure and function of the TM, using full field-of-view measurement of its shape, and acoustically induced 3D deformations.³⁻⁶

Our digital holographic system incorporates tunable wavelength lasers that enable us to assess the shape of the TM. This data, combined with deformation measurements, quantifies full 3D deformation of the TM.⁵ To further understand the mechanics of the membrane, we are concurrently developing optical coherence tomography methods⁶ to characterize the TM's multi-layer fiber-reinforced structure.

Major components of our digital holographic system include measurement, sound presentation, laser delivery, positioning, and computer and control systems (see Figure 1). The measurement and sound presentation systems are physically combined within the otoscope head module, where its stability and orientation are maintained by an autonomous positioning system (see Figure 2). The computer and control system are responsible for synchronizing the sound excitation during the displacement measurements, and controlling the laser wavelength during the shape measurements.⁵ The displacement and shape measurements of our system are based on lensless digital holographic methods that eliminate the need for imaging optics and allow focusing with no moving parts (such as lenses and their mechanisms) and after data has been recorded.⁴ A software suite provides an interface to all the system's components, synchronizing the devices.⁷ The software provides real-time digital hologram visualization, automated data acquisition, and post-processing.

The sound-induced deformation pattern of the TM is related to its structure, which contains a complex network of collagen fibers arranged in a pattern similar to that of a spider web, combining tangentially and radially oriented fibers. To describe the structure of the TM, we are developing optical coherence tomography methods to quantitatively map its 3D structure, including the fiber orientation, density, and distribution with micrometer resolution.⁶ This allows us to combine and correlate data on displacement, shape, and structure (see Figure 3) for a better understanding of the TM's function in the hearing process.

We are currently testing the digital holographic system to allow measurements *in vivo*.⁴ One challenge is to measure the TM's acoustically induced vibrations with nanometer accuracy, while isolating displacements caused by a patient's tremor of the head, breathing and heartbeat. We synchronized the acquisition timing with the patient's heartbeat, using an electrocardiographic feedback to minimize its effect on measurements. Other design challenges include complex light-tissue interactions in the enclosed space of the ear canal, and the system's dimensional constraints. Figure 4 shows *in vivo* sound-induced displacement measurements with our system.

We have demonstrated how our system can quantify the TM's shape, structure, and sound-induced 3D displacements for *in vivo* applications. The measurements allow us to assess the TM's condition, and to diagnose middle ear problems such as the bones fusing or separating, which compromise hearing. In future work, we aim to assemble the system on a smaller scale and improve acquisition speed and resolution, so that physicians might use it to improve the quality of diagnosis and treatments for ear conditions.

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Biography

Cosme Furlong is associate professor of Mechanical Engineering, working in mechanics, optical metrology, and nanoengineering, science and technology.

Ivo Dobrev is a PhD candidate in mechanical engineering, developing digital holographic medical tools for quantitative examination of the human middle ear *in vivo*.

John Rosowski is professor of otology and laryngology, and also of health sciences and technology, working in acoustics and mechanics of the external, middle, and inner ear, as well as the comparative middle and external ear structure and function.

Jeffrey Tao Cheng is instructor in otology and laryngology at Harvard Medical School, working on middle ear mechanics and tissue biomechanics through measurements and modeling.

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Figure 1. Schematic view of the holographic experimental setup. The measurement and sound presentation systems are combined within the head of the otoscope. TM: tympanic membrane, or eardrum. EKG: electrocardiogram. CCD: charge-coupled device.

Figure 2.
Overview of the entire holographic otoscope system.

Figure 3.

Representative results of our multi-domain measurements of the TM. (a) Numerical reconstruction hologram of sound-induced displacement of the TM due to sound at 5730Hz and 95 decibels sound pressure level. (b) Shape of the TM. (c) Results of optical coherence tomography measurements indicating a complex multi-layer fiber-reinforced structure with radial and circumferential collagen fibers. (d)-(f) x, y-, and z-components of the TM deformation. The outline in (d)-(f) is of the handle, or manubrium, of the malleus bone in the middle ear.

Figure 4.

Representative in vivo measurements with the digital holographic system. (a) Patient under examination. (b) Numerical reconstruction hologram with fringes due to sound excitation at 1kHz at 90dB SPL. (c) TM without sound excitation. The handle (manubrium) of the malleus is outlined, and the umbo at the end of the manubrium near the center of the TM is labeled as U.