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Measurements of three-dimensional shape and sound-induced motion of the chinchilla tympanic membrane

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Abstract

Opto-electronic computer holographic measurements were made of the tympanic membrane (TM) in cadaveric chinchillas. Measurements with two laser wavelengths were used to compute the 3D-shape of the TM. Single laser wavelength measurements locked to eight distinct phases of a tonal stimulus were used to determine the magnitude and the relative phase of the surface displacements. These measurements were made at over 250,000 points on the TM surface. The measured motions contained spatial phase variations consistent with relatively low-order (large spatial frequency) modal motions and smaller magnitude higher-order (smaller spatial frequency) motions that appear to travel, but may also be explained by losses within the membrane. The measurement of shape and thin shell theory allowed us to separate the measured motions into those components orthogonal to the plane of the tympanic ring, and those components within the plane of the tympanic ring based on the 3D-shape. The predicted in-plane motion components are generally smaller than the out-of-plane perpendicular component of motion. Since the derivation of in-plane and out-of plane depended primarily on the membrane shape, the relative sizes of the predicted motion components did not vary with frequency.

Keywords

tympanic membrane; holography; TM shape

Introduction

The precise mechanism by which the tympanic membrane (TM) gathers and couples sound energy to the ossicular system is a continuing point of investigation by measurements (e.g. Cheng et al., 2010, in press; de La Rochefoucauld and Olson 2010; Rosowski et al. 2011) and models (Funnell and Laszlo 1977; Rabbitt and Holmes 1986; Funnell, Decraemer and

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Khanna, 1987; Blayney et al. 1997; Gan et al. 2002; Koike et al. 2002; Fay et al. 2005; Parent and Allen 2007; 2010; Goll and Dalhoff, 2011). Our understanding of this issue is clouded by several significant complications including: (1) the complex nature of the sound-induced TM displacements, (2) many of the measurements of TM motion are based on optical techniques which are only sensitive to one direction of TM motion, and (3) the conical structure of the TM complicates the relationship between unidirectional measurements of surface motion and the actual three-dimensional motions of the surface of the TM and also suggests complexities in the relationship between TM surface motions and the forces produced along the manubrium at the input to the middle-ear ossicular system.

Several optical techniques have been used to estimate the shape of the TM, as well as changes in TM shape introduced by static pressure (e.g. Moire interferometry: Decraemer et al. 1991; Dirckx and Decraemer 1992, 2001; optical coherence tomography (OCT): Chang et al. submitted; Ilgner et al. MEMRO 2012). However, the temporal resolution and sensitivity of such three-dimensional measurements are usually not sufficient to measure accurately the sound-induced motions of the TM (an exception is high-speed OCT, e.g. Chang et al. submitted). In this paper we describe a new technique for near simultaneous measurements of the shape and sound-induced motions of the TM in cadaveric chinchillas. The combination of measurements allows us to estimate the components of the TM that are in-the-plane and out-of-the-plane of the tympanic ring.

Methods

Computer Controlled Opto-Electronic Holography

Our basic technique is to capture two-dimensional holographic interference patterns in order to reconstruct holographic images of shape or motion (Hernández-Montes et al. 2009; Flores-Moreno et al. 2011). The measurement methods are based on a tunable near infrared laser beam (adjustable wavelength of 770 to 789 nm), that is split into reference and object beams within an optical head (Figure 1). One of the split beams illuminates the measurement object, and the other is a reference beam for which the light path can be shifted by 0, $\frac{1}{4}$, $\frac{1}{2}$ or $\frac{3}{4}$ of a wavelength by a mirrored piezoelectric transducer (the optical path-length shifter). The reference beam and the reflected object beam are recombined to produce an interference pattern that is imaged by a high-speed CCD camera. The camera, laser wavelength and the phase shifting of the reference beam path length are under computer control. The computer uses a 2-D FFT of the images captured at each of the four reference beam path lengths with a numerical holographic reconstruction algorithm to compute the interference pattern at the level of the object (Kolenovic et al., 2004; Flores-Moreno et al., 2011). These interference patterns are gathered with two-different wavelengths to measure shape, or with a single wavelength at different stimulus phases to determine sound-induced motions in the direction of the object illumination beam.

Measurements of Membrane Shape: Two wavelength mode

Measurements of shape were made by illuminating the TM within a cadaveric chinchilla head with the tympanic ring placed roughly orthogonal to the object beam. With the laser wavelength (λ_1) set at 779.8 nm, the camera gathered two-dimensional images of the light intensity of the interference patterns at the baseline optical path length (I_0) and with the reference path lengthened by $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4} \lambda$ (I_1 , I_2 , and I_3 respectively) by the path-length shifter. The laser wavelength was adjusted to 780.2 nm (λ_2) and images were taken at the four different reference path lengths: $I'_0, \dots, I'_3$. The optical phase difference $\phi'(x,y)$, between the two sets of images was computed:

$$\phi(x, y) = \tan^{-1} \left[\frac{(I_1 - I_3)(I'_2 - I'_4) - (I_2 - I_4)(I'_1 - I'_3)}{(I_1 - I_3)(I'_1 - I'_3) - (I_2 - I_4)(I'_2 - I'_4)} \right] \quad (\text{Eqn. 1})$$

This two-dimensional phase image was filtered and masked (Figure 2), then unwrapped and converted to variations in the depth from the tympanic ring using a synthetic wavelength of

$$\Lambda = \frac{\lambda_1 \lambda_2}{|\lambda_2 - \lambda_1|} = \frac{779.8 \times 780.2}{780.2 - 779.8} = 1.521 \text{ mm.} \quad (\text{Eqn. 2})$$

Because differences in the distance between the object and the optical head affect the path lengths of both the incident and reflected object beams, a 2π change in the wrapped phase is related to a difference in position of $\Lambda/2$, i.e.,

$$z(x, y) = \Lambda \frac{\phi'(x, y)}{4\pi}, \quad (\text{Eqn. 3})$$

where $\phi'(x, y)$ is the unwrapped masked and filtered phase.

Measurements of Sound-Induced Motion: Stroboscopic Holography

Our techniques for describing the sinusoidal motion of the TM surface at frequencies as high as 20 kHz (Cheng et al. 2010) are summarized here. The laser wavelength was fixed, and a high-speed opto-acoustic modulator (Hernández-Montes et al. 2009) placed in the output beam of the laser to strobe the laser on and off (Figure 1). The strobe was locked to selected phases of the sound stimulus cycle period with a duty cycle of 5–10% of a period. Strobe measurements were made at eight separate stimulus phases ($0, \pi/4, \pi/2, \dots, 7\pi/4$). The changes in optical phase related to the different stimulus phases at each of the 720×720 pixels were calculated using Equation 1, the phases patterns in each image were unwrapped and normalized, and the resultant phases converted to displacement using the appropriate laser wavelength (780.2 nm). The position versus stimulus phase functions gathered at each of the camera pixels were Fourier transformed and the magnitude and phase of the fundamental and second harmonic components computed. The magnitude of the second harmonic was always at least 30 dB below the fundamental, except in regions where the motion magnitude was less than the effective 5–10 nm resolution of our measurement system. In order to judge the quality of the Fourier description of the magnitude and angle of the motion at each pixel, we computed the Pearson Product Correlation Coefficient between the measured phasic variations of the motion and the sinusoidal motion reconstructed from the magnitude and angle of the Fourier determined fundamental component of the phasic motion. The square of this correlation R^2 was generally greater than 0.8 except at locations where the magnitude of the measured motions was less than 10 nm.

Specimen preparation

Measurements were made on thawed chinchilla heads that had been frozen and stored. The time after collection varied between days and months. The ears investigated were the ears contralateral to the experimental ear in single-sided physiological experiments (e.g. Chhan et al., in press). The cartilaginous external ear canal was removed and the posterior and inferior middle ear cavities were widely opened. The peripheral portions of the bony external canal were drilled away, and much, but not all, of the medial portion of the bony canal were removed. The curved pocket shape of the medial bony ear canal and its complex support

within the bones surrounding the middle ear, made it impossible to expose more than 80% of the TM to direct view (with the tympanic ring orthogonal to the illuminating light beam) without damaging the support of the tympanic membrane. An acute view angle gave access to much of the TM surface, but compromised the sensitivity of our measurements, which are only sensitive to motions in the direction of the illuminating laser beam. In removing the bony ear canal it was usually not possible to maintain the thin dermal layer of the TM that also covered the inside of the bony canal. Finally the TM was painted with a thin layer of a 60 mg/ml of zinc oxide (ZnO) in saline solution.

Sound Generation and Measurement

The sinusoidal output of the stimulus generator was amplified by a unity gain power amplifier and used to drive to a dynamic speaker coupled to a reverse elliptical horn based on a Tucker-Davis Technologies (Alachua, FL) CF1 speaker. The sound stimulus left the narrow mouth of the horn, which was positioned about 8 cm away from the TM. A PCB Piezotronics (Depew, New York) pre-polarized ¼ inch microphone with a calibrated probe tube was positioned just at the edge of the TM to make measurements of sound pressure magnitude. Our techniques did not enable accurate measurement of the absolute phases of TM motion and sound pressure at the TM. However, our estimates of the relative phase of motion of different locations on the TM surface to the same stimulus are quite accurate (within 0.01 radians) as long as the motion at the TM location is larger than 10 nanometers.

Results

Shape of the TM

Figure 3 shows the shape of the TM of a chinchilla taken from a viewing angle that exposed all of the dorsal TM to view and about 1/3 of the ventral half. The z axis of the plots correspond to the lateral medial axis, with medial as positive, and the peak is the location of the spatulated umbo of the chinchilla. The outline of the umbo and the rest of the manubrium are shown in the figure. The depth of the membrane (from the umbo to the rim) is about 2.2 mm. The diameter of the membrane is about 5mm.

An alternative method for describing the TM shape is to define its surface in terms of the magnitudes of the three Cartesian components that describe the vector normal to the TM surface at each point on the surface (Figure 4). The shape data were processed by Matlab scripts that identified the plane that was tangent to the surface and the unit vector normal to the surface at each point on the TM $\mathbf{n}(x, y)$. This normal vector could then be broken into three orthogonal Cartesian components n_x , n_y , and n_z (which define the signed magnitudes of the component vectors), with the direction of the z component defined by the optical axis of the measurement system. The roughly conical shape of the TM and the similarity of the normal vector and its z component leads $n_z(x, y)$ to vary only between 0 and +1. However, $n_x(x, y)$, and $n_y(x, y)$ can be either positive or negative depending on the gradient of the surface in either x or y .

Sound-Induced Motion of the TM

Examples of the sound induced motion of the TM surface, measured along the optical axis of the laser (which corresponds to the direction of the z component of the normal vector) are illustrated in Figure 5. The motion response at all frequencies shows significant variations in the motion at different locations, and the spatial complexity of the motion response increases with increasing frequency. While the use of our techniques with human cadaveric material has yielded good matches with umbo displacement measurements made with different techniques (e.g. Rosowski et al. 2011), the absolute value of the umbo displacements we measured in this specimen were at least a factor of three smaller than the mean chinchilla

umbo displacements reported by Ruggero et al. (1990). Similar results were observed in one other chinchilla TM.

At the lowest frequency measured (414 Hz) the largest motions on the TM surface are at the dorsal (superior) edge of the TM and in the ventral (inferior) regions. There is a putative nodal line of near zero motion between these two regions. (The umbo actually straddles this zero motion line.) The phase measurements suggest the two regions are moving half a cycle out of phase with each other, where the phase changes abruptly at the location of near zero motion. The co-localization of near zero motion and a rapid phase half-cycle change is consistent with the presence of a nodal line. The correlation plot shows that the measured sinusoidal motions are well fit by the estimates of the magnitude and angle of the motion ($R^2 > 0.9$) at all locations except the nodal line, where the magnitudes of motion are too small (<10 nanometers) to be determined accurately.

With 1000 and 2500 Hz stimuli the patterns of motion become more complicated: the number of local magnitude peaks on the surface increases to at least 8, and the area of each magnitude peak is decreased in size. There is also an increase in the complexity of the phase maps with smaller areas of contiguous phase about one for each local magnitude maximum. At 1000 Hz there are multiple nodal lines of near zero magnitude associated with half-cycle phase changes. At 2500 Hz, most of the spatial variations tend to be more graded or of step sizes smaller than half-cycle.

As frequency increases there is a continued increase in the number of local spatial maxima and regions of spatially distinct phase, with an order to the arrangement of the maxima. We no longer see clear nodal lines; however, the entire manubrium (which is firmly attached to the chinchilla TM all along its length) and the umbo generally show very small motion response. While we see an increase in regions of spatially distinct phase of motion, contiguous regions often have phase values that cluster around some mean value. For example, with 10000 Hz stimulation, the regions of the membrane in the lower-left hand quadrant of the figure tend to phase values that vary between -1 and -2 radians, while the lower right hand quadrant has regions with phases close to 1 radian. At frequencies below 10000 Hz, the phase of the umbo (the tip of the manubrium) differs from the phase of the rest of the manubrium, but these phases are similar to the phases of the adjacent TM locations. At 10000 Hz the entire manubrium (including the umbo) moves with similar phase, though this phase differs from the phase of the membrane adjacent to much of the manubrium.

Discussion

Comparison with other estimates of sound-induced motion

The spatial and frequency dependence of the magnitude of displacements in Figure 5 are consistent with time-average-holography measurements of the TM motion in chinchillas that were reported by Rosowski et al. (2009), the only other report of the motion of the entire surface of the chinchilla TM. The progression of an increasing number of spatial maxima and a decreased size of the area of each maxima as stimulus frequency increases is observed in measurements made in both live and cadaveric chinchillas reported in that study. Time-average holography cannot address the relative phases of the measured displacements without extended techniques.

There are significant similarities and differences between stroboscopic holography measurements of the motion of the TM surface in chinchilla and cadaveric human TMs (Cheng et al. 2010, Rosowski et al. 2011; Cheng et al. in press). In both preparations, we see a progression in the patterns of motion from simple to complex to ordered patterns of motion

as frequency increases, as noted by Rosowski et al. (2009). However, the frequencies where the transitions between these behaviors occur are lower in chinchillas than in humans. Related to this issue, Cheng et al. (2010; in press) demonstrate that the entire human TM moves in phase at frequencies lower than 1 kHz, while at the lowest frequency we measure in the chinchilla (414 Hz), we see half-cycle phase differences between different halves of the TM, with a nodal line nearly perpendicular to the manubrium running through the umbo (Figure 5). Similar patterns in which one half of the TM moves a half-cycle out-of-phase from the other half are not observed in humans with acoustic stimulation. It is possible that the inter-species differences in displacement pattern are a result of the difference between the circularly symmetric chinchilla TM and the relatively asymmetric human TM (Puria & Steele, 2010).

If we scale stimulus frequency by a factor of about 2.5 and compare the 1 to 2.5 kHz range in chinchilla to ~2.5 to 6.25 kHz in human, we can discern similar behaviors. At 4, 5 and 6 kHz in humans, Cheng et al. (2010; in press) describe two kinds of phase variations across the TM surface: gradual phase changes that are suggestive of either traveling surface waves or significant damping within the TM surface (Aernouts et al. MEMRO 2012), and relatively sudden half-cycle phase changes associated with local magnitude minima suggestive of nodes on the TM surface. The small number of these nodes in both humans and chinchillas is consistent with low-order modal patterns of motion (Cheng et al. 2010; in press).

At 8 to 16 kHz in humans, and 3.5 kHz and higher in chinchilla there are numerous (> 15) regions defined by oval local magnitude peaks with associated oval regions of similar phase values. There is little evidence of rapid half cycle phase shifts. Instead the phase patterns of adjacent regions generally show cyclic variations in phase of less than 0.25 cycles. This pattern has been interpreted by us (Cheng et al. 2010; Rosowski et al. 2011) to result from the combination of a large-spatial wavelength mode-like displacement, and a smaller spatial wavelength traveling-wave like component of smaller magnitude. As Aernouts et al. (submitted MEMRO 2012) point out, such patterns are also consistent with the summing of a large magnitude low-order modal motion of the membrane and a smaller magnitude higher-order modal in a membrane with losses.

A simple model relating shape and motion

Three dimensional motions can be recovered by measurements of optical phase with displacements, U , and optical phase, ϕ , related by the fringe-locus function

$$\phi = \mathbf{K} \cdot \mathbf{U}, \quad (\text{Eqn. 4})$$

where $\mathbf{K} = \mathbf{K}_2 - \mathbf{K}_1$ is the sensitivity vector characterizing the illumination-observation geometry of the optical setup and $\mathbf{U} = \mathbf{P}' - \mathbf{P}$ are vectors representing induced motions, as shown in Figure 6. The expanded form of Equation 4

$$\phi = (K_x, K_y, K_z) \cdot (U_x, U_y, U_z) \quad (\text{Eqn. 5})$$

indicates that in order to recover the three components of motion, (U_x, U_y, U_z) that introduce measurable optical phase changes at point (x, y, z) on an object, it is necessary to (1) determine the object's shape, which together with the knowledge of the points of illumination and observation, $\mathbf{P}_1, \mathbf{P}_2$, respectively, define the sensitivity vector (K_x, K_y, K_z) and (2) recover corresponding optical phase, ϕ , by multiple measurements requiring at least three independent sensitivity vectors (Stetson, 1975; Vest, 1979; Pryputniewicz, 1986).

Our optical configurations (Hernández -Montes et al. 2009; Flores-Moreno et al. 2011; Lu 2012) have been designed to define parallel illumination-observation conditions that lead to a simplified fringe-locus function

$$\phi = \frac{2\pi}{\lambda} (0, 0, K_z) \cdot (U_x, U_y, U_z), \quad \text{Eqn. 6}$$

where λ is the laser wavelength and $(0, 0, K_z) = (0, 0, 2)$ is the sensitivity vector defining parallel illumination-observation conditions. Similar to Equation 3, Equation 6 describes measurements along a single axis with the recovered motions of the TM corresponding to the components of the deformation vectors that are parallel to the measuring optical axis. A method that we are investigating to recover the three components of the deformation vector in an absolute coordinate system consists of using multiple sensitivity vectors with Equation 5. The method requires making measurements along multiple directions of observation. Though promising for shape measurements, further investigations are underway in order to minimize temporal decorrelation of displacements that occur when sensitivity vectors are changed.

Our recently developed approach to recover three dimensional motions of acoustically excited TM by the use of a single optical instrument and a single sensitivity vector consists of simultaneously applying Equations 3 and 6 together with well-accepted structural mechanics theories and assumptions. From the structural point of view, the TM can be considered as a thin shell because the maximum value of the ratio of its thickness and any other of its dimensions is < 0.05 (Timoshenko, 1959; Saada, 1974). In addition, the acoustically induced deformations of interest with magnitudes $< 1 \mu\text{m}$ are substantially smaller than the $10\text{--}30 \mu\text{m}$ of the thickness of the chinchilla TM (Decraemer and Funnell 2008), as has been demonstrated in other species by earlier work (Khanna and Tonndorf, 1972; Rosowski et al., 2009; Cheng et al., 2010, in press). Therefore, by considering thin shell theory (Figure 6), and assuming negligible TM thickness changes introduced by acoustic excitation, we have developed and computationally validated, with $< 3\%$ uncertainty, the hypothesis that the major components of acoustically induced deformations occur parallel to the local surface normals of the middle thickness layer of the TM (Lu, 2012). Such a judgment is consistent with Kirchhoff's thin shell theory with small displacements (Love 1888), and with estimates of the very small sound-induced TM thickness change (Chang et al. in preparation).

Estimation of the normal component of TM motion

With our hypothesis that the major components of acoustically induced deformations occur parallel to the local surface normals of the TM and measurements with an optical setup characterized by Equation 6, it is possible to recover the normal components of TM motion, $\mathbf{U}$, in a Cartesian coordinate system defined by the corresponding sensitivity vector, Figure 7. Specifically, single axis measurements, U_z , together with the knowledge of surface normals, $\mathbf{n} = (n_x, n_y, n_z)$, enable estimation of the two additional corresponding orthogonal components of motion, U_x and U_y with

$$U_x = n_x \frac{U_z}{n_z}, U_y = n_y \frac{U_z}{n_z}, \quad (\text{Eqn. 7})$$

and the resultant normal TM motion, $\mathbf{U}$, with

$$\mathbf{U} = |\mathbf{U}| \cdot (n_x, n_y, n_z), \text{ and } |\mathbf{U}| = \sqrt{U_x^2 + U_y^2 + U_z^2} \quad (\text{Eqn. 8})$$

Estimation of the x and y components of TM motion

We have used Equations 7 to estimate the x and y components of the TM motion (U_X and U_Y) from measurements of the motion in z (U_Z) and the shape in the same chinchilla TM (Figure 8). The right-hand pair of columns (C & D) in Figure 8 illustrate great similarity between the magnitudes of the measured U_Z and the computed motion normal to the surface (the resultant, U). Such similarity is expected in these measurements because of the near alignment of the direction normal to the TM surface and the z -axis that is demonstrated by the z -component of the normal vector, n_z , having a value of 0.75 to 1 over most of the TM surface (Figure 4D). Furthermore, since n_z is always positive (Figure 4), the temporal phase of the motion measured along the z -axis is the same as the phase of motion in the direction normal to the TM surface.

Columns A, B and D of Figure 8, on the other hand, suggest large differences between the magnitude and phase of the resultant normal displacement (U) and its x - and y -components (U_X and U_Y): The x and y displacement components are of significantly smaller magnitude and there are regions of the TM surface where the predicted U_X and U_Y are negative relative to U . (This negativity implies U and the component with a negative values are a half-cycle out of phase.) U_X and U_Y are negative at locations where the x - or y -component of the unit normal vector are negative, while the differences in magnitude occur because the magnitudes of the x - or y -component of the unit normal vector generally fall between 0 and 0.5

Because the z measurement axis is roughly orthogonal to the tympanic ring, the x - and y -components computed in Equation 7 describe motions in the plane of the tympanic ring, where the magnitude and phase of such ‘in-plane’ motions is directly related to that of the measured z -component and the components of the normal unit vector computed from the shape of the TM (Figure 3). The significance of the in-plane motion components is unknown. It is worthwhile noting that, according to our thin-shell assumption and the small size of the measured displacements relative to membrane dimensions, the motion of the TM is well approximated by motion along the direction normal to the TM surface, and we assume no additional motion components in the plane tangential to each TM location.

The predicted motions in the plane of the tympanic ring (columns A & B of Figure 8) are computed by the product of the measured z -component of the displacement, U_Z , and the ratio of the positive or negative real number defined by the x - or y -component of the normal unit vector to the positive real number defined by the z -component of the normal unit vector (Equation 7). Therefore, the thin-shell assumption predicts the motions that occur in the plane of the tympanic ring are either in-phase or half a cycle out of phase with the motions of the normal vector. This contrasts with oral reports (Jackson et al., presented at MEMR0 2012 and ARO 2012) that 3-D laser Doppler measurements of TM motion in humans show in-plane motion components with phases different from that of the out-of-plane motions and magnitudes comparable to the out-of-plane motions. The cause of these discrepancy is unknown, but could be related to limitations of the thin shell assumptions we apply in this report, or to difficulties in the 3-D laser determination of motions within the plane of a surface whose orientation to the laser varies in space.

Summary

We describe a new optical method for near simultaneous measurements of the 3D-shape and 1D motion measurements of the tympanic membrane based on opto-electronic computer assisted holography. These methods have been applied to the study of the sound-induced motions of the chinchilla TM. The coupling of these two methodologies with the hypothesis that the TM acts primarily as a thin shell in which the primary motion component is normal to the surface of the membrane allows us to estimate the three-dimensional motion of over 250000 points on the TM surface. By this theory, the relative phases of the in-plane and out-of-plane motion depend on the gradient of the TM surface, and the in-plane motions can never be larger in magnitude than the motion normal to the TM surface. However, the computed in-plane motions can be larger than the motion estimated from a single measurement direction in which the measurement vector is not normal to the TM surface. The sound-induced motion of the chinchilla TM has several features in common with those observed in humans (Cheng et al. 2010, in press); however, these features occur in lower frequency ranges in chinchilla.

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Summary: A new method for simultaneously measuring the shape and sound-induced motion of the tympanic membrane is utilized to estimate the 3D motion on the membrane surface.

- A new method for simultaneously measuring the shape and sound-induced motion of the tympanic membrane is utilized to estimate the 3D motion on the membrane surface.
- The method reveals motion of the chinchilla TM surface similar to those reported in humans.
- The computed in-plane TM motions are of significantly smaller magnitude than the out-of-plane motions.
- The assumptions used in deriving 3D motion lead to all motion components being either in phase or a half-cycle out-of-phase.

Figure 1. The tunable laser, strobe switch, optical path length shifter, CCD camera, stimulus and timing generator, earphone, microphone and the measurement control computer. The dashed lines are analog and digital stimulus and sensing lines.

Figure 2.

Masked and filtered wrapped phase image, $\phi(x,y)$, computed from a two-laser shape measurement. The gray scale of each pixel is coded with a value between $\pm\pi$. The three fringe lines (the transitions between black and white that are labeled with white numbers) suggest the total phase change between the outer rim and the apex of the cone (marked by a '+') is just over 6π , and equivalent to a rim to a cone height of $(6\pi/4\pi)*1.521$ or 2.28 mm (Eqn. 3).

Figure 3.

A reconstruction of the shape of a chinchilla TM. The z axis corresponds to the lateral-medial direction with medial as positive that was defined by the longitudinal axis of the illuminating and reflected laser beam. The x direction corresponds roughly to the rostral (anterior) - caudal (posterior) axis with rostral positive. The y direction corresponds roughly to the dorsal (superior) - ventral (inferior) direction with ventral positive. The black outline shows the connection of the TM to the manubrium of the malleus. The umbo of the manubrium is at the apex of the TM cone, which is colored deep red. The ventral (inferior) edge of the TM is hidden from view by a significant remnant of the boney ear canal. The inset in the upper left corner shows a 2-dimensional view of the TM looking along the x -axis.

Figure 4.

A lateral surface view of the three Cartesian components of the unit vector normal to the TM surface. A). A schematic illustrating the normal vector $\mathbf{n}$ at a point on the TM surface, and its decomposition into three Cartesian vectors with signed magnitudes of n_x , n_y , and n_z and corresponding unit vectors based on a z axis defined by the direction of the illuminating and reflected laser light. The α , β and γ describe the angles between the normal vector and the Cartesian vectors. B & C). Color rendering of $n_x(x,y)$ and $n_y(x,y)$. Note that x and y components of the normal vector are negative for positions where the gradient of the TM surface in x and y is negative. The outline of the manubrium is included in the figure for orientation. D). A color rendering of $n_z(x,y)$. Due to the conical shape of the TM and the similarity of $n_z(x,y)$ to the normal vector, $n_z(x,y)$ is always positive. The components of the normal unit vector are unitless.

Figure 5.

Color renderings of the fundamental Fourier magnitude and angle of the sound-induced motion of the TM surface along the z axis made at 5 combinations of stimulus frequency and level. The leftmost data column contains the computed magnitudes of motion. The center column contains the computed angles. The rightmost column shows the square of the correlation coefficient between the measured time waveform at each point and the waveform predicted by the Fourier magnitude and angle. Each figure in the data table shows the location of the manubrium, with the umbo at its central tip. The magnitude color bars are coded in micrometers. The phase colorbars are in radians. The correlation colorbar show variations in R^2 between 0 and 1.

Figure 6.

Illumination-observation geometry of an interferometric optical setup: (a) overall geometry; and (b) detail showing motions, U , at a single point on the object. Points of illumination and observation are P_1 , P_2 , and vectors of illumination and observation are K_1 , K_2 . Geometry relates motions with sample shape as well as with optical phase measurements via Equation 4.

Figure 7.

The relationship between the displacement normal to the TM surface U and the signed magnitudes of the three Cartesian components that describe the normal displacement U_X , U_Y , and U_Z .

Figure 8.

The components of the normal displacement U . (A & B) The x and y components of the normal displacement calculated as describe above. The color bar in between (which scale both positive and negative values in μm) applies to both columns. Because U_X and U_Y are the product of the normal displacement magnitude and the x and y components of the normal unit vector, the scales include both negative and positive values. (C & D) The magnitude of the z component of the normal displacement U_Z and the computed normal displacement U . The color bars in between these two columns only scale positive values.