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Research Paper

Characterization of the nonlinear elastic behavior of chinchilla tympanic membrane using micro-fringe projection

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ABSTRACT

The mechanical properties of an intact, full tympanic membrane (TM) inside the bulla of a fresh chinchilla were measured under quasi-static pressure from −1.0 kPa to 1.0 kPa applied on the TM lateral side. Images of the fringes projected onto the TM were acquired by a digital camera connected to a surgical microscope and analyzed using a phase-shift method to reconstruct the surface topography. The relationship between the applied pressure and the resulting volume displacement was determined and analyzed using a finite element model implementing a hyperelastic 2nd-order Ogden model. Through an inverse method, the best-fit model parameters for the TM were determined to allow the simulation results to agree with the experimental data. The nonlinear stress-strain relationship for the TM of a chinchilla was determined up to an equibiaxial tensile strain of 31% experienced by the TM in the experiments. The average Young's modulus of the chinchilla TM from ten bullas was determined as approximately 19 MPa.

1. Introduction

An eardrum or tympanic membrane (TM) couples acoustic waves from ambient air in the ear canal to the middle ear; it is a key component for transmitting sound pressure to ossicular chains. The function of the TM can be affected by ambient pressure, which changes widely from a few pascal (Pa) to a few kPa. In some extreme cases, for instance, under blast in conflict zones, the overpressure can be as high as 100 kPa, which could cause damage to the TM (Ritenour et al., 2008). As TM deforms under different ambient pressures, the transmission of sound energy across the middle ear can be significantly altered (Dirckx and Decraemer, 1991; Volandri et al., 2011; Ghadarghadar et al., 2013; Thornton et al., 2013; Rosowski et al., 2014). In efforts made to understand the effect of ambient pressure on TM function for the sound transmission, the mechanical response of TMs has been investigated under various static pressures. The deformation of a TM, induced by either negative or positive pressure in the middle ear, was measured using shadow moiré technique on human temporal bones (Dirckx and Decraemer, 1991). The TM vibration under different middle-ear pressures was measured on gerbil ears (Lee and Rosowski, 2001; Rosowski and Lee, 2002), where the alterations of acoustic stiffness and impedance by static pressures were observed. The stiffening of a TM under the repetitive pressure loading from habitual sniffing was investigated on gerbil using shadow moiré (von Unge and Dricks, 2009).

In addition to experimental investigations, finite element methods (FEM) have been used to study the sound transmission in the middle ear under various static pressures. The effect of geometrical nonlinearity was reported on the movement of a cat eardrum under static pressures on TM (Ladak et al., 2006). The middle ear transfer function was also analyzed under various static pressures on a human middle ear (Wang et al., 2007). It is noted that, the fidelity of the simulation results depends, to a large extent, on the accuracy of the mechanical properties of a TM, as a function of pressure.

The mechanical properties of TMs have been measured using numerous experimental techniques. The viscoelastic properties of a human TM were measured under tension using dynamic

List of the abbreviations: A, anterior; CAD, computer-aided design; FEM, finite element method; I, inferior; IACUC, institutional animal care and use committee; IM, intramuscular; LDV, laser Doppler vibrometery; P, posterior; PVC, polyvinyl chloride; S, superior; TM, tympanic membrane; U, umbo; XYZ, x-, y- and z-axes

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mechanical analysis (Cheng et al., 2007) and acoustic pressure using laser Doppler vibrometery (LDV) (Gan et al., 2010; Zhang and Gan, 2010). A miniature split Hopkinson tension bar was used to measure the dynamic properties of human TMs under high strain rates (Luo et al., 2009a,b, 2016). Another method used was nanoindentation, it has been used to measure the mechanical properties of different quadrants of a TM. The linear viscoelastic properties of TMs were reported using nanoindentation (Huang et al., 2008). The method was also used to measure both in-plane and out-of-plane mechanical properties at different locations of a TM (Daphalapurkar et al., 2009). In all these methods, strip or cut TM specimens were used. This approach causes the collagen fibers in the radial or circumferential directions in pars tensa to shrink (O'Connor et al., 2008), and alters the physiological condition of TM, leading potentially to erroneous results. To circumvent this problem, it is necessary to employ a new method to measure the mechanical properties for the full, intact TM, which is the focus of this paper.

Full-field measurement methods have been used in the last several years to measure the mechanical responses of a TM. Using LDV and stroboscopic holography, deformations of a human TM were measured with acoustic loading, and viscoelastic properties were determined through a hybrid method allowing FEM simulated umbo displacement to agree with the experimental measurement (De Greef et al., 2014a,b). Another full-field method to probe mechanical properties was developed to measure the TM elastic properties (Aernouts et al., 2010; Buytaert and Drickx, 2009) using geometric moiré and indentation loading. The geometric moiré was used to determine the surface topography while the indentation was applied; the mechanical response of the TM was simulated by FEM to determine the elastic properties and the viscoelastic properties under low frequencies (Aernouts and Drickx, 2012a,b; Aernouts et al, 2012) using an inverse problem solving scheme. The Young's modulus was measured as approximately 20 MPa by nano/micro-indentation (Aernouts et al., 2010, Aernouts and Drickx, 2012a,b; Hesabgar et al., 2010; Soons et al., 2010; Salamati et al., 2012). Both methods measure TM properties under indentation loading, which is applied on a small local region; that is a loading situation that is different from the condition under normal hearing or under blast, in which air pressure is applied on the entire TM. In addition, for the latter method, the contact nature and the localization of force applied on a small region could impose challenges to maintain the indenter positioning under increasing load. There is also a potential issue on convergence in the analysis considering a contact mechanics problem. An alternative computer-based method was developed; in which case, the pressure was used instead of indentation (Ghadarghadar et al., 2013). In that method, the Young's modulus of TM was estimated by minimizing the difference in displacements over the entire TM calculated from model with that measured from experiment. The replacement of indentation loading with pressure loading simplified the experimental setup. Ghadarghadar et al. (2013) showed a rather good agreement between the computational displacement and experimental results on the pars tensa of the TM, but not on the pars flaccida (a small portion of the dataset). They also pointed out that the material property of pars flaccida can be significantly different from pars tensa. It is noted that, the nonlinearity of the mechanical behavior of TM under different pressures has not been considered.

In this paper, we provide a non-contact, full-field optical method on the measurement of mechanical properties of an intact TM under quasi-static pressure. An inverse method combining experimental and numerical investigation is used to determine the mechanical properties of a chinchilla TM. The TM inside a bulla is pressurized while its topography is determined by a full-field micro-fringe projection technique. Volumetric displacement is then calculated from the topography. FEM with a nonlinear material model is applied to model the topography of TM under pressure, to provide the simulated relationship between pressure and volume displacement that is consistent with experiment. The nonlinear mechanical properties of TM under different quasi-static pressures are thus determined.

2. Method

2.1. Micro-fringe projection technique

A micro-fringe projection technique was used to determine the deformed surface topography of the TM under a prescribed static pressure. In micro-fringe projection, a grating is projected onto an object and the image of the projected fringe on the surface of the object is acquired by a digital camera. Another image of fringe projected onto a reference plane under the same setup is also acquired. The object image is subsequently digitally superimposed with the reference image to generate interferometry (Ortiz and Patterson, 2003, 2005). Virtual shifting is conducted by utilizing five phase-shifted images of the original image to calculate the phase difference between reference plane and the object from the interferometry map (Ortiz and Patterson, 2005).

The inverse tangent function outputs phase angle within the interval $[-\pi, \pi]$ with 2π discontinuity at the end of the period. In order to determine the surface profile from the direct output, phase angle has to be unwrapped. A quality bins algorithm is used to unwrap the phase map for surface profile reconstruction (Ghiglia and Pritt, 1998; Ortiz, 2004). In the case where the projection is telecentric, the out-of-plane position Z is determined from the phase angle difference $\Delta\Phi$ for any point on the object surface:

$$Z = \frac{ph}{d}\frac{\Delta\Phi}{2\pi} \quad (1)$$

where h is the distance between the camera and the object, and d is the distance between the camera and the light source, as shown schematically in Fig. 1(a). In the actual situation, it is difficult to measure accurately these parameters directly from the apparatus. A calibration procedure is thus used to determine the ratio between h and d in Eqn (1) (Ortiz and Patterson, 2003). A cone with known dimensions that approximately match the features (radius and depth) of the TM was used for calibration. By comparing the phase map with the known geometry, the ratio of h to d was determined.

2.2. Experimental setup

Fig. 1(b) shows the actual experimental setup. The chinchilla bulla was placed on a gimbal holder attached to a temporal bone bowl, which allowed the orientation of the TM surface to be adjusted for micro-fringe projection as well as for observation by a camera. A set of X-, Y- and Z- (*XYZ*) linear translation stages was used to hold the temporal bone bowl, to position the TM within the field of the projected fringes and field of view of the camera. A micro-fringe projector, including a set of lenses, grating, and fiber optic light source was used to project fringes onto the TM in the bulla. The projector consisted of a 100 W fiber optic lamp, two condenser lenses (Edmund Optical Sci., #89-038), a grating and an objective lens (Fujinon Photo Optical Co., 611374). The focal length of the objective lens was adjustable so that an in-focus pattern of equidistant pitch fringes was projected onto the reference plane and the object. The grating used had a square wave transmission profile, namely the Ronchi rulings (Edmund Optical Sci., #58-777) with pitch density of 20 cycle/mm. A digital camera (Nikon D7000,