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Research Paper

Estimation of the Young's modulus of the human pars tensa using *in-situ* pressurization and inverse finite-element analysis

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A B S T R A C T

Finite-element models of the tympanic membrane are sensitive to the Young's modulus of the pars tensa. The aim of this work is to estimate the Young's modulus under a different experimental paradigm than currently used on the human tympanic membrane. These additional values could potentially be used by the auditory biomechanics community for building consensus. The Young's modulus of the human pars tensa was estimated through inverse finite-element modelling of an *in-situ* pressurization experiment. The experiments were performed on three specimens with a custom-built pressurization unit at a quasi-static pressure of 500 Pa. The shape of each tympanic membrane before and after pressurization was recorded using a Fourier transform profilometer. The samples were also imaged using micro-computed tomography to create sample-specific finite-element models. For each sample, the Young's modulus was then estimated by numerically optimizing its value in the finite-element model so simulated pressurized shapes matched experimental data. The estimated Young's modulus values were 2.2 MPa, 2.4 MPa and 2.0 MPa, and are similar to estimates obtained using *in-situ* single-point indentation testing. The estimates were obtained under the assumptions that the pars tensa is linearly elastic, uniform, isotropic with a thickness of 110 μm, and the estimates are limited to quasi-static loading. Estimates of pars tensa Young's modulus are sensitive to its thickness and inclusion of the manubrial fold. However, they do not appear to be sensitive to optimization initialization, height measurement error, pars flaccida Young's modulus, and tympanic membrane element type (shell versus solid).

1. Introduction

The human middle ear plays a significant role in the complex hearing mechanism by transmitting sound from the environment to the cochlea. The tympanic membrane (TM) is a key component in efficiently transferring sound energy. It is anatomically divided into two major parts: the pars tensa (PT) and the pars flaccida (PF). In humans, the PT is a thin fibrous conical membrane that represents most of the surface area of the TM and is thought to play a larger role in sound transmission than the PF. By contrast, the PF is a thicker but more compliant portion of the TM with minor effects on sound transmission (Aritomo et al., 1988).

In addition to responding to dynamic acoustic stimuli in the frequency range of [20, 20k] Hz, the human ear responds to quasi-static pressure variations. Often the pressure changes at frequencies lower than 20 Hz are termed quasi-static (Dirckx et al., 2013). Quasi-static pressure changes often occur in daily life such as when using an elevator or an airplane. Quasi-static pressures are also intentionally applied in hearing tests such as tympanometry. In one form of this diagnostic procedure, the acoustic admittance of the middle ear is measured at the TM using a probe tone of a fixed frequency (e.g., 226 Hz) while the pressure in the ear canal is quasi-statically swept in the range of −3 kPa to +2 kPa. The interpretation of tympanometric data is difficult when multiple diseases affect the middle ear (Fowler and Shanks, 2002). High fidelity finite-element

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List of abbreviations

FE	finite element
FTP	Fourier transform profilometer
NURBS	non-uniform rational B-spline
PF	pars tensa
PT	pars flaccida
TM	tympanic membrane

(FE) models of the middle ear could be utilized to interpret and even improve such auditory tests (Daniel et al., 2001). However, accurate values for the mechanical properties of middle-ear structures are crucial for FE modelling. As the PT covers almost the entire TM in humans (Volandri et al., 2011), this work focuses on the Young's modulus of the PT as it is a significant contributor to the function of the middle ear. Moreover, FE models of the TM are sensitive to the Young's modulus used for the model PT. For instance, Funnell and Laszlo reported that doubling the PT Young's modulus of a cat TM FE model reduced maximal PT displacement by approximately 48%, whereas reduction of PT Young's modulus in half increased the maximal displacement by approximately 79% (Funnell and Laszlo, 1978). Sensitivity of TM models to PT Young's modulus was also reported in other studies [e.g., (Elkhouri et al., 2006; Tuck-Lee et al., 2008)].

The mechanical properties of the human PT have been estimated using three major approaches: (1) applying tensile or bending tests on strips of the tissue cut from the PT [e.g. (Cheng et al., 2007)], (2) inverse FE modelling of experimental data obtained using indentation techniques [e.g. (Aernouts et al., 2012; Daphalapurkar et al., 2009)] and (3) by estimating the properties using measured TM collagen fibre density and size [e.g. (Fay et al., 2005)]. Note that the third approach reports on the collagen fibre layers only. Recently published values for the human PT Young's modulus [e.g., (Aernouts et al., 2012)] are smaller than previously reported estimates, motivating further investigation of the effects of modelling assumptions on estimates obtained using inverse methods.

An alternative to the approaches mentioned above has been developed in our laboratory but has only been tested on the rat PT (Ghadarghadar et al., 2013), not the human PT. In this technique, the TM shape is acquired before and after pressurization. An FE model specific to the TM is then generated from the shape imaged before pressurization and the model Young's modulus is numerically optimized until the simulated deformed shape of the PT portion of the TM matches the experimentally acquired shape.

The objective of this work is to apply the pressurization approach to estimate the Young's modulus of the human PT. The intent in this work is to test the fit of FE models with geometric nonlinearity but with linearly elastic PT for low static pressures where such assumptions may be reasonable (Ladak et al., 2006). This work contributes to the body of literature on this topic in three ways. First, the inverse FE modelling approach using pressurization data has never been applied to the *human* PT. Second, it provides additional estimates of the Young's modulus under quasi-static conditions and differing loading conditions that could potentially be used to understand the large range of Young's moduli values published in the literature. Third, it demonstrates inverse approaches are sensitive to modelling assumptions, and care is required in interpreting estimated values.

2. Methods

2.1. Sample preparation

Three fresh-frozen adult cadaveric temporal bones, TB1, TB2, TB3, with healthy TMs were used in this study. Cadaveric materials were donated to Western University for the purposes of medical education and research. Permission was granted for the use of the cadaveric temporal bones in the present study. Following thawing using saline, a cylindrical cutter having a 40 mm diameter and 60 mm length was used to harvest the middle ear from the temporal bones. This sample size was necessary for further imaging and provided convenient handling for the pressurization experiment.

As one of the imaging techniques used in this work (see Section 2.2) requires a view of the TM, the cartilaginous ear canal was resected and most of the bony external ear canal was drilled away to expose the TM as much as possible. As the middle ear is pressurized in this experiment (see Section 2.2), care must be taken not to accidentally create air leaks; hence, when drilling away the ear canal, 2 mm of the bony part of the ear canal, including soft tissues, were untouched. Then, an opening was made into the middle-ear air space through the superior middle-ear wall leaving the entire ossicular chain and cochlea intact. This opening was made to first immobilize the mallear head using dental cement (Prime Dental Man. Inc., IL, USA) and second to insert a pressurization tube. The former was done to isolate the deformation of the TM from the rest of the middle ear (Ladak et al., 2006; Liang et al., 2016). The latter involved inserting a tube with 1.57-mm inside diameter into the middle-ear cavity through this hole. To seal possible air leakage from the air cells in the temporal bone which changes the middle-ear pressure, dental plaster (K-Dental Inc., ON, Canada) was used to cover the air cells. During sample preparation and pressurization testing, samples were kept moist with an ultrasonic humidifier (AIR-O-SWISS, Widnau, Switzerland).

2.2. Experimental procedure

In this study, the shape of each sample TM before and after pressurization was imaged. The experimental setup includes a custom-built pressurization unit (Fig. 1) and a Fourier transform profilometer (FTP) (model MM-25D from Opton Company Limited, Seto, Aichi, Japan), a non-contacting optical device for imaging the surface shape of an object. In contrast to previous studies, no coating was applied to the TM in this study as the TM has adequate reflection for optical imaging (Das et al., 2015).

Each prepared specimen was secured in a holder, and the TM's shape was measured before applying pressure. In order to obtain

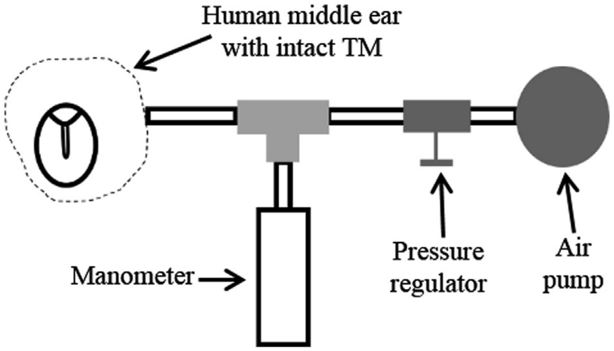

Fig. 1. Schematic of the set-up used to apply static pressure on human TM.

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