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Research Paper

Measuring the quasi-static Young's modulus of the eardrum using an indentation technique

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ABSTRACT

Accurate estimation of the quasi-static Young's modulus of the eardrum is important for finite-element modeling. In this study, we adapted a tissue indentation technique and inverse finite-element analysis to estimate the Young's modulus of the eardrum. A custom-built indentation apparatus was used to perform indentation testing on seven rat eardrums *in situ* after immobilizing the malleus. Testing was done in most cases on the posterior pars tensa. The unloaded shape of each eardrum was measured and used to construct finite-element models with subject-specific geometries to simulate the indentation experiment. The Young's modulus of each specimen was then estimated by numerically optimizing the Young's modulus of each model so that simulation results matched corresponding experimental data. Using an estimated value of 12 μm for the thickness of each model eardrum, the estimated average Young's modulus for the pars tensa was found to be 21.7 ± 1.2 MPa. The estimated average Young's modulus is within the range reported in some of the literature. The estimation technique is sensitive to the thickness of the pars tensa used in the model but is not sensitive to relatively large variations in the stiffness of the pars flaccida and manubrium or to the pars tensa/pars flaccida separation conditions.

1. Introduction

Finite-element (FE) models of the eardrum are numerical models used to simulate the eardrum's response to static or quasi-static stimuli (Ladak et al., 2006) as well as to dynamic stimuli (e.g., Tuck-Lee et al., 2008; Gan et al., 2006; Koike et al., 2002; Beer et al., 1999; Eiber, 1999; Ferris and Prendergast, 1999; Funnell et al., 1987). Static refers to a stimulus that does not vary with time, whereas quasi-static refers to a slowly varying stimulus. The stiffness of isotropic tissues, which exhibit similar mechanical response in all directions, can be characterized by the Young's modulus defined as the ratio of stress over strain within the tissue's linear regime in a uniaxial experiment. The response of FE models is sensitive to the specific value of the Young's modulus used for the pars tensa when creating the models. For instance, Funnell and Laszlo (1978) found that doubling the Young's modulus of the pars tensa in an FE model of the cat eardrum reduced maximal eardrum displacement by about 48%, whereas cutting the Young's modulus in half increased the maximal displacement by 79%. There is substantial variability in estimated values of the Young's moduli reported in the literature, even for the same species. Although intra-specimen variations may account for a portion of the variability, differences in experimental protocol and in simplifying assumptions used in the calculations can also give rise to the large differences in values reported by various authors.

Since the Young's modulus of tissues varies with frequency (Luo et al., 2009; Fung, 1993), it is important to determine both the static or quasi-static Young's modulus as well as its variation with frequency. Estimates of the static and quasi-static (Békésy, 1960; Cheng et al., 2007; Gaihede et al., 2007) as well as dynamic (Kirikae, 1960; Decraemer et al., 1980; Fay et al., 2005) Young's modulus have been reported in the literature. The focus in this paper is on estimating the quasi-static Young's modulus of the pars tensa which, for example, would be needed for modeling of clinical tympanometry. Note that modeling all aspects of tympanometry (e.g., hysteresis and not just overall volume displacement) would

Abbreviations: 2D, two dimensional; 3D, three dimensional; CT, computed tomography; FE, finite element; GPa, giga pascal; M, meters; mN, millinewtons; N, newtons; MPa, mega pascal; TFI, trans-finite interpolation; TM, tympanic membrane; μm, micrometers

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require characterizing this behaviour in addition to estimating the Young's modulus. FE modeling could potentially be useful in extracting more diagnostic information from tympanometry, thus leading to improved diagnosis (Daniel et al., 2001). Previously, we have tested and applied an indentation technique to measure the Young's modulus of various soft tissues (e.g., Samani et al., 2003, 2007). The objective of the current work is to apply the technique to estimate the Young's modulus of the pars tensa using this approach, and to quantify the sensitivity of the technique to modeling parameters that are not accurately known.

2. Methods

2.1. Indentation apparatus

Tissue indentation can be used for measuring the stiffness of tissues with complex geometry and boundary conditions. It involves indenting the tissue, acquiring its indentation force–displacement data followed by determining the tissue's stiffness parameters using data inversion or optimization. The system used to measure indentation force–displacement curves is shown in Fig. 1. It consisted of two main components: tissue actuation and force measurement. The tissue actuation component was comprised of an indenter attached to a servo motor, motion controller, and a computer to provide the controller with loading instructions. The force measurement component consisted of a load cell sensor. This sensor is an electronic device that senses force via contact and converts it to an electrical signal proportional to the force. Load cells have limited precision and their reading error is a fraction of their maximum loading capacity. They are sensitive to background electrical and mechanical noise in the measurement laboratory. The sample was placed in a cylindrical holder that was mounted on the load cell. This sample holder had three tapped holes on its perimeter that fitted three screws used to secure temporal bone specimens after the eardrum was properly oriented with respect to the indenter. The load cell in turn was attached to the rectangular base of measurement system. The servo motor was mounted to a stand that was bolted to the base.

The load cell was a LCL-113 model (Omega, Quebec, Canada) with a capacity of 113 g. This load cell was connected to an amplifier to augment the voltage signal and facilitate its processing to obtain force readings. The servo motor was model LAL-30 (SMAC, Carlsbad, CA, USA) with a motion range of 25 mm, resolution of 0.5 μm, and accuracy of 1 μm. The actuator was controlled by a

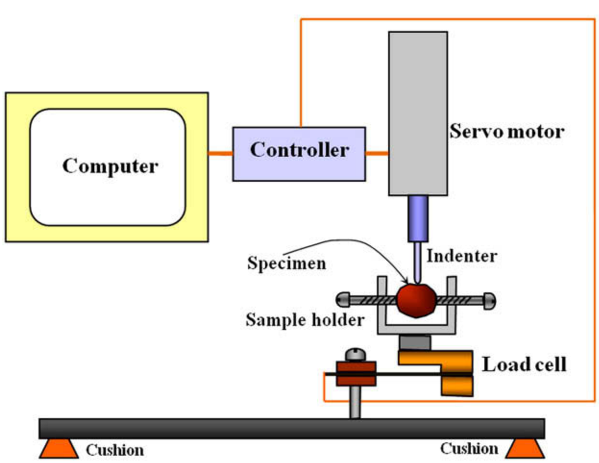

Fig. 1. Schematic of the indentation system used to acquire the force–displacement data.

6K2 motor controller (Parker Hannifin Corporation, Rohnert Park, CA, USA).

The indenter was spherical-ended with a diameter of 0.5 mm. The advantage of such an indenter over a plane-ended indenter is that the former does not have sharp edges and is associated with gradually growing contact area while the indenter moves further down. Therefore, a plane-ended indenter was not used to avoid penetration and tearing the eardrum by its edges. Both the load cell and servo motor (via controller) operations were dictated by a LabVIEW 6.1 (National Instruments, Austin, TX, USA) program. Load cell measurements were made at a sampling rate of 10,000 times per second using the NI 6020E data acquisition card (National Instruments, Austin, TX, USA). A set of 1000 samples was averaged to generate each force data point. To reduce errors introduced by laboratory bench vibration, the measurement apparatus was placed on sponge pieces that acted as shock absorbers.

2.2. Specimen preparation

Measurements were made on seven fresh temporal bones obtained from adult Sprague Dawley rats, which had been used for purposes unrelated to the auditory system. Only rats with healthy eardrums were used as confirmed by visual inspection prior to experimentation. The rats were sacrificed by CO_2 asphyxiation. The rats used in this study were euthanized in accordance with the University of Western Ontario's Animal Use Subcommittee. The temporal bones were removed from the rats approximately 30 min *post mortem*. The ear canal was resected to within 0.5 mm of the eardrum in order to provide a good view of the eardrum for shape measurement as described in Section 2.4. In order to measure the mechanical response of the eardrum without the confounding effects of the ossicular and cochlear loads, the malleus was immobilized by gluing the mallear head to the middle-ear wall as described elsewhere (Ladak et al., 2004). The eardrum was left intact, i.e., the eardrum was not dissected from its attachments to the ear canal or the manubrium. Total preparation time was about 2 h for each specimen. During the dissection and the following experimentation, the specimen was kept moist.

2.3. Indentation measurements

Before measurement, the load cell was calibrated using known weights to find the linear conversion parameter of the cell's voltage to force reading. The specimen being experimented upon was secured in the sample holder using the three screws after it was oriented properly while being placed under the indenter. The indenter descended until it just touched the surface of the eardrum and was then stopped. The point of contact was in the pars tensa. Furthermore, the orientation of the eardrum was chosen such that the indenter was normal to the surface at the point of contact in order to avoid slippage between the eardrum and indenter. The tympanic ring was tilted manually by 10–20° relative to the horizontal platform of the indenter so that the indenter contacted the pars tensa at 90° at the point of contact. The rat eardrum is a shallow cone with small curvature as evident from Fig. 4, so a small tilt angle sufficed to make the contact orientation 90°. This setup was consistent with the small-slipping contact model we developed to model the contact between the spherical-ended indenter and the eardrum as described later. After applying several sinusoidal indentation cycles of loading and unloading for preconditioning, four similar cycles of sinusoidal indentation were applied to the specimen with a frequency of 0.5 Hz. Force–displacement data corresponding to the four cycles were recorded. The purpose of applying four cycles was to have enough cycles to choose the best one from given that the quality of force–displacement curve can be affected by random mechanical vibration or electrical noise. We