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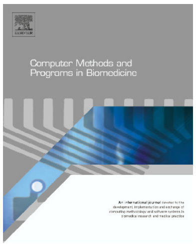

Estimation of the quasi-static Young's modulus of the eardrum using a pressurization technique

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ABSTRACT

The quasi-static Young's modulus of the eardrum's pars tensa is an important modeling parameter in computer simulations. Recent developments in indentation testing and inverse modeling allow estimation of this parameter with the eardrum *in situ*. These approaches are challenging because of the curved shape of the pars tensa which requires special care during experimentation to keep the indenter perpendicular to the local surface at the point of contact. Moreover, they involve complicated contact modeling. An alternative computer-based method is presented here in which pressurization is used instead of indentation. The Young's modulus of a thin-shell model of the eardrum with subject-specific geometry is numerically optimized such that simulated pressurized shapes match measured counterparts. The technique was evaluated on six healthy rat eardrums, resulting in a Young's modulus estimate of 22.8 ± 1.5 MPa. This is comparable to values estimated using indentation testing. The new pressurization-based approach is simpler to use than the indentation-based method for the two reasons noted above.

1. Introduction

Myringotomy is a surgical procedure in which a small incision is made in the eardrum to alleviate ear infections. Myringotomy with tube insertion is used to treat middle-ear infections, and for children under 15 years of age, it is the second most common surgical procedure in the United States next to circumcision [1]. Surgical residents are taught the procedure at a very early stage through observations and limited practice on patients. A major challenge is that a high level of dexterity, practice, and experience are needed to operate under a microscope, insert a blade through the narrow ear canal, and create the incision.

Over the last few decades, virtual-reality (VR) technology consisting of computers and 3D human–computer interfaces has been utilized to simulate various surgical procedures for training purposes. The major benefits of VR-based surgical simulation include patient safety, availability of immediate training opportunities, broadening surgical training through the provision of different virtual patient types, and the ability to quantify surgical performance. Recently, we reported the first VR-based simulator for training in myringotomy [2,3]. In the current implementation, the eardrum is treated as a

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static structure: It does not deform nor does it perforate when contact is made with a virtual myringotomy blade. A user evaluation questionnaire administered to surgical staff and senior surgical residents indicated that simulating the deformation would greatly add to the realism of the simulator and could provide clues to the trainee with regard to the amount of deformation required to perforate the eardrum.

The eardrum is situated at the most medial end of the ear canal and separates the canal from the middle-ear cavity. The outline of the eardrum as viewed from the ear canal ranges from circular in some species (humans) to elliptical in others (*e.g.*, rat). The eardrum is a thin membrane composed of two major sub-surfaces: the pars tensa and pars flaccida. For reference, the various parts of the eardrum are shown in Fig. 2 on an FE mesh described in Section 2.3. The pars tensa plays a key role in the transfer of sound waves in the ear canal to mechanical vibrations of the middle-ear bones.

Thin-shell theory has been used to model both the quasi-static and dynamic mechanical behaviors of the eardrum. Typically, these models are solved using the finite-element (FE) method; a thorough review of existing models of the eardrum is given by Volandri et al. [4]. For surgical simulation, a quasi-static model is an accepted approximation because movements during surgery are typically slow. For modeling quasi-static and low-frequency dynamics, isotropic models of the eardrum fit experimental data well [5,6]. For high frequencies, it is important to take into account the anisotropies in the eardrum [5,7], but this is not relevant to the application being considered. Furthermore, even for fairly large loads, a linear elastic material model for the pars tensa, characterized by a single Young's modulus and Poisson's ratio, may be sufficient in explaining some of the observed nonlinearities in eardrum response if geometric nonlinearity is taken into account [8].

The accuracy of isotropic models depends critically on several modeling parameters, particularly the Young's modulus of the pars tensa portion of the eardrum [9]. There is substantial disagreement in reported estimates of the Young's modulus of the eardrum. Several authors have attempted to estimate the Young's modulus of the eardrum on strips of tissue cut from the eardrum [10–16]; however, cutting the eardrum can lead to compromising its structural integrity, thus altering its mechanical properties.

In an attempt to refine measurements of the eardrum's Young's modulus, we recently reported a technique in which force–displacement curves where measured using an indentation apparatus. The Young's modulus of the eardrum's model with subject-specific geometry was numerically optimized such that simulated force–displacement curves matched their measured counterparts, thus yielding an estimate of the Young's modulus of the actual eardrum [17]. Aernouts et al. [18] have also developed an indentation technique similar to ours and have applied it to the rabbit eardrum. A major contribution of both reported indentation approaches is that they permit mechanical testing *in situ* on intact eardrums, *i.e.*, strips need not be cut out and the eardrum need not be removed from its natural attachments to the ear canal or malleus, the middle-ear bone attached to the eardrum.

Performing indentation testing is challenging because during the experiment, the indenter must remain perpendicular to the local eardrum surface in order to avoid slippage of the indenter relative to the eardrum surface. This is difficult because the eardrum has a conical shape with the sides of the cone being curved. Moreover, simulating an indentation experiment using the FE method involves contact modeling which is a complex problem that is prone to convergence issues. In this work, we modified the model-based optimization approach by applying static pressures using air instead and measuring the resulting shape of the eardrum; see Section 2.2 for a definition of shape. Subject-specific models were then used to estimate the Young's modulus by optimizing the Young's modulus of the models so that the eardrum's deformed shape calculated using the models matched experimentally measured corresponding shapes. The Young's moduli of all samples were assumed to be in the same bounded range. The use of air pressure avoids the need to indent the eardrum, thereby simplifying both experimental measurements and modeling. The objective of this paper is to present the computerized method for estimating the Young's modulus from pressurized shape measurements and to evaluate it by applying it to rat eardrums. The experimental approach, including measurement of the eardrum's pressurized and unpressurized shapes which are required as input to this computerized approach, is discussed in detail.

2. Materials and methods

2.1. Specimen preparation

Measurements were made on six healthy eardrums from adult Sprague Dawley rats. The rats were euthanized in accordance with Western University's Animal Use Subcommittee. Rats were used because they are a valuable animal for middle-ear research [19] and because estimates of the Young's modulus of the rat eardrum are available from our previous work [17] for evaluation of the new technique. For each rat, the temporal bone was removed 30 min post mortem. The ear canal was resected within 0.5 mm of the eardrum in order to obtain a good view of the eardrum for shape measurement. 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 [20]. The eardrum was left intact, *i.e.*, the eardrum was not dissected from its attachments to the ear canal or to the manubrium of the malleus. For pressurization, the middle-ear bony wall was drilled to make a small hole leading to the middle-ear cavities. As shown in Fig. 1, pressure was applied to the middle-ear cavities *via* this hole using a 3.0 mL syringe. The pressure was monitored using a digital manometer (model HHP680 from Omega, Quebec, Canada). The manometer has a resolution of 2.5 Pa for pressures less than approximately 2.49 kPa and 25.0 Pa for higher pressures. To prevent air leakage, all connections were sealed using silicone rubber. The shape measurement technique used in the experimental protocol (see next section) requires a diffusely reflecting surface with good contrast. Therefore, as in previous work, a thin white coating was applied to the eardrum [17]. Specifically, a spray-on coating was used (Spotcheck SKD-S2 Developer, Magnaflux, Glenview, IL). The effect of similar coatings on pressurized and