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Research Paper

Elasticity modulus of rabbit middle ear ossicles determined by a novel micro-indentation technique ☆

Joris A.M. Soons *, Jef Aernouts, Joris J.J. Dirckx

Laboratory of Biomedical Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

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ABSTRACT

For the purpose of creating a finite element model of the middle ear, the ossicles can be modelled as rigid bodies or as linear elastic materials. The general elasticity parameters used are usually measured on larger bones like the femur. In order to obtain a highly realistic model, the actual elastic modulus (Young's modulus) of the ossicles themselves is needed. We developed a novel 2-needle indentation method of determining the Young's modulus of small samples based on Sneddon's solution. We introduce the second needle in such a way that small specimens can be clamped between the two needles and a symmetry plane is obtained, so that geometry-dependent sample deformations are avoided. A finite element calculated correction factor is used to compensate for the small thickness of the samples. The system was tested on several materials with known parameters in order to validate the technique, and was then used to determine the elasticity parameters of incus and malleus in rabbit. No significant differences between measurement locations were found, and we found an average Young's modulus of 16 ± 3 GPa.

1. Introduction

Finite element (FE) models have been widely used recently to investigate biomechanical systems (Elkhouri et al., 2006; Koike et al., 2002; Lee et al., 2006; Mikhael et al., 2004; Prendergast et al., 1999; Sun et al., 2002). Such models need geometric data, boundary conditions and material properties. Developing a highly realistic middle ear (ME) model is difficult because of the microscale 3D geometry, the uncertainty in boundary conditions and difficulties in determining the material properties.

In many current FE models, the ossicles are treated as rigid bodies. Implicit in this treatment is the assumption that mechanical loads seen by the ossicles are insufficient to cause changes in their shape. Due to changes in altitude, meteorological changes (Didyk et al., 2007), etc., the ear is subject to pressure variations with frequencies far below the acoustic range, often referred to as quasi-static pressure changes. The amplitudes of these pressure variations can be hundreds and even thousands of Pascals, which is many times larger than the amplitude of the highest sound pressures. Due to these large pressures, it may be necessary to include the possibility of bending of the ossicles (Dirckx et al., 2006; Dirckx and Decraemer, 1992, 2001). Also in the high frequency acoustic range, it may be perfectly possible, even plausible, that thin parts of the ossicles may show bending. Especially in animal models such as gerbil or rabbit, the ossicles include extremely thin structures such as the wedge-shaped manubrium. Indeed, bending of the manubrium has been observed in cat and gerbil (Decraemer et al., 1991; La Rochefoucauld and Olson, 2009). In those cases, rigid body modelling no longer suffices, and accurate elasticity parameters for the ossicles are needed (Elkhouri et al., 2006). Few material-elasticity parameters are available for ossicles (Speirs et al., 1999). Generally, values for larger bones, like the femur, which are obtained by tensile experiments are used (Evans, 1973). Table 1 gives an overview of the available values.

It is difficult to perform tensile methods on small objects such as ME ossicles. First, the 3D geometry of the material has to be known exactly: in practice, this usually means that the sample needs to be formed into a cylinder or beam. Secondly the contact surfaces at both ends of the small and relatively hard bone have to be controlled precisely. For uni-axial tensile experiments, two rigid contacts with no slipping or stretching are necessary; for axial compression tests, perfect sliding contacts are necessary. It is extremely difficult to realize either situation. Speirs et al. (1999)

Abbreviation: FE, finite element; ME, middle ear; E, Young's modulus; ν, Poisson's ratio; a, indenter radius; h, material thickness; κ, correction factor; w, indentation depth; F, reaction force; HSS, high speed steel; A-D/D-A, analog-to-digital/digital-to-analog converter; I/O, input/output; Al, aluminum; PVC, polyvinyl chloride; PMMA, polymethyl methacrylate or acrylic glass; PA6, polycaprolactam or nylon 6; OPFOS, orthogonal-plane fluorescence optical-sectioning tomography; E_{ASTM}, Young's modulus obtained with ASTM d695-02a test; $E_{\text{indentation}}$, Young's modulus obtained with our indentation test

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* Corresponding author. Tel.: +32 3 265 34 38; fax: +32 3 265 33 18.
E-mail address: joris.soons@ua.ac.be (J.A.M. Soons).

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Table 1
Overview of mechanical properties of bone. The values of Evans (1973) were obtained on unembalmed wet cortical bone of the human femur, the values of Dempster and Liddicoat (1952) were obtained on wet adult human compact bone by a compression test and the values of Speirs et al. (1999) were obtained on ME ossicles by an axial compression test.

Author	Modulus of elasticity (GPa)
Evans (1973)	12 ± 3
Dempster and Liddicoat (1952)	14 ± 8
Funnell et al. (1992)	20
Speirs et al. (1999)	3.8 ± 0.5

used an axial compression test to determine the material properties of ME ossicles and concluded that there might be some systematic error inherent in their protocol.

Because of these difficulties and the risk of introducing errors, we have developed a new compressive indentation method. Indentation testers are widely used in material sciences to obtain Young's moduli and other mechanical properties (Sneddon's solution (Oliver and Pharr, 1992; Riccardi and Montanari, 2004; Sneddon, 1965)).[1] This method gives the solution for relatively thick materials, meaning that the diameter of the needle is much smaller than the thickness of the sample. Decreasing the needle-radius in order to be able to measure thin materials may not be valid because the needle dimensions must be biologically relevant: the needle must be significantly larger than the micro-structure of the bone in order to obtain correct elasticity parameters for the bulk material.

A second needle is added because thin materials can deform on large contact surfaces, generating artifacts: the measured force will come not only from the indentation but also from the unpredictable surface deformations on the bottom of the specimen. When a second, identical needle is used at the bottom of the specimen exactly opposite to the top indentation needle, a symmetry plane is introduced and the problem becomes equivalent to a single sided indentation of a perfectly flat, freestanding sample of half the thickness. We will demonstrate our method on several materials of known elastic parameters and then use it to perform measurements on auditory ossicles.

2. Materials and methods

2.1. Thin sample correction

As part of the adaptation of the indentation test to thin, freestanding materials, a compensation factor was needed. We obtained this compensation by introducing a correction factor κ, which we derived from FE calculations.[2] A FE simulation of the indentation test was made, using as input parameters the indenter radius, the material thickness, the indentation depth, the Young's modulus and the Poisson's ratio of the sample, and as output, the reaction force was calculated. The reaction force and the indentation depth were used to calculate the Young's modulus according to Sneddon's solution (Sneddon, 1965). This modulus was then compared to the Young's modulus used in the FE model to calculate the correction factor κ.

Changing the Poisson's ratio, the indenter radius and the material thickness gave a range of correction factors ($\kappa(a/h, \nu)$). Combining Sneddon's solution with the correction factor κ gave the following equation to calculate the Young's modulus (Hayes et al., 1972; Sneddon, 1965):

$$E = \frac{1-\nu^2}{2 \cdot a \cdot \kappa(a/h, \nu)} \cdot \frac{F}{\omega} \quad (1)$$

where

- E is the Young's modulus of the sample.
- ν is Poisson's ratio of the sample ($\nu_{bone} = 0.3$ (Elkhouri et al., 2006)).
- a is the radius of the indentation needle (60 μm).
- h is thickness of the sample.
- $\kappa(a/h, \nu)$ is a finite element calculated correction factor depending on the indenter radius versus thickness ratio (a/h) and the Poisson's ratio (ν). Some example results: $\kappa(0.1, 0.3) = 1.28$; $\kappa(0.2, 0.3) = 1.50$; $\kappa(0.5, 0.3) = 2.33$.
- ω is the indentation depth.
- F is the resulting force.

2.2. Measurement setup

A picture of the experimental setup is shown in Fig. 1. At the two contact interfaces, two needles indent the sample (1). The needle tip is the frustrum of a cone of 25° (angle to axis) truncated at 120 μm diameter. The flattened cone is custom-made out of HSS (high speed steel) with a Young's modulus of 210 GPa which is significantly higher then the tested materials. The displacement of the indentation needle was generated by a piezo transducer (2) (PI P-

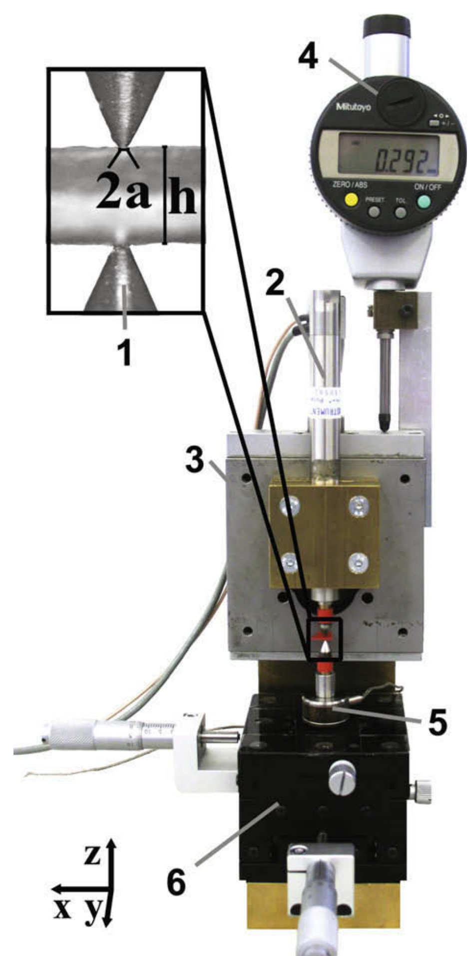

Fig. 1. Experimental setup with needles and sample (1), piezo-transducer to produce indentation displacement (2), z-translation (3), micrometer (4), loadcell (5) and x and y translation (6) (a: indenter radius, h: material thickness).

[1] The technique has also been applied in biomechanical research of cartilage (Hayes et al., 1972) and micro-surfaces (Scholz et al., 2008)

[2] Hayes et al. (1972) introduced a correction factor κ for measurements on thin cartilage, fixed at the bottom to bone. We calculate a correction factor κ to apply the indentation method to thin, free-standing materials such as the auditory ossicles.