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Three approaches for estimating the elastic modulus of the tympanic membrane

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Abstract

The function of the middle ear is to resolve the acoustic impedance mismatch between the air in the ear canal and the fluid of the inner ear. Without this impedance matching, very little acoustic energy would be absorbed into the cochlea. The first step in this process is the tympanic membrane (TM) converting sound in the ear canal into vibrations of the middle ear bones. Understanding how the TM manages its task so successfully over such a broad frequency range should lead to more satisfactory and less variable TM repairs (myringoplasty). In addition, understanding the mechanics of the TM is necessary to improve the coupling between ossicular prostheses and the TM. Mathematical models have played a central role in helping the research community understand the mechanics of the eardrum. However, all models require parameters as inputs. Unfortunately, most of the parameters needed for modeling the TM are not well known. In this work, several approaches for inferring the material properties of the TM are explored. First, constitutive modeling is used to estimate an elastic modulus based on the elastic modulus of collagen and experimentally observed fiber densities. Second, experimental tension and bending test results from the literature are re-interpreted using composite laminate theory. Lastly, dynamic measurements of the cat TM are used in conjunction with a composite shell model to bound the material parameters. Values from the literature, both measurement and modeling efforts, and from the present analysis are brought together to form a coherent picture of the TM's material properties. In the human, the data bound the elastic modulus between 0.1 and 0.3 GPa. In the cat, the data suggest a range of 0.1–0.4 GPa. These values are significantly higher than previous estimates.

Keywords: Middle ear; Tympanic membrane; Eardrum; Parameter estimation; Elastic modulus; Displacement measurements

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1. Introduction

Since Helmholtz (1868), researchers have proposed many different theories for how the tympanic membrane (TM) works. Most of the early work on the TM treated it as a rigid piston (Békésy, 1960; Zwislocki, 1962). More recently, modern mechanical analysis techniques such as finite elements or asymptotic methods have been used (Funnell and Laszlo, 1978; Rabbitt and Holmes, 1986; Ferris and Prendergast, 2000; Koike et al., 2002; Eiber, 1997; Beer et al., 1999; Williams and Lesser, 1990; Wada and Metoki, 1992). By comparing experimentally observed responses (Khanna and Tonndorf, 1972) to those predicted by theory, one can begin to sort out what physical mechanisms are important for the TM. Puria and Allen (1998) show impedance and reflectance measurements in the ear canal for an intact cochlea vs. a drained cochlea. The difference between the two is dramatic. In the intact cochlea case, the ear canal looks resistive and the TM absorbs the incoming sound. When the cochlea is drained, the damping behavior disappears and the system behaves like an inertial–elastic system with multiple modes. Unfortunately, the elastic and inertial parameters needed for modeling the TM are not

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well known. Even worse, some of the past experiments performed to elucidate these parameters can be misleading if the results are not carefully interpreted and applied. This paper seeks to interpret past experiments and present new evidence that can be used to establish upper and lower bounds for the material properties of the TM.

1.1. Tympanic membrane thickness measurements

The mammalian TM is composed of a series of layers (see review paper by Lim (1995) for a detailed description). Two of these layers contain collagen fibers. One has fibers that run in a radial pattern while the adjacent layer's fibers run in the circumferential direction. Together, the radial and circumferential fiber layers determine the stiffness properties of the TM. From electron micrographs, a quantitative measure of the thicknesses for the entire membrane, the radial fiber layer, and the circumferential fiber layer can be obtained. These thicknesses give an indication of the mass and indirectly the stiffness properties of the drum. Only two publications show a cross-section of the cat TM with a magnification that enables visualization of the individual layers (Lim, 1968; Chole and Kodama, 1989). From these micrographs, measurements of each layers' thickness were obtained (Table 1). The thicknesses vary a great deal even within a given micrograph. The ±10 μm error in the Chole and Kodoma total thickness is representative of this variation. The human TM has the same structure as the cat but is thicker and larger (Table 1).

These single point thickness measurements do not tell the whole story of the TM's internal structure. The thickness of each layer varies as one moves to different locations on the TM. In Lim (1970), the circular fibers become more apparent as one approaches the annular ligament. Eventually, the circular fibers merge with and become indistinguishable from the fibers of the annular ligament. Moving in the other direction, the circumferential fiber layer becomes very thin near the center of the TM and appears to vanish completely in the inner third. Recent thickness measurements on fresh TMs using a confocal laser scanning microscope (Kuypers et al., 2001, 2003) have shown that the cat TM is nearly 30–40 μm thick at the periphery but only 7–10 μm thick near the center. The circumferential fiber layer thickness decreases by a factor of seven, while the radial fiber layer decreases by a factor of two (Lim, 1970; Chole and Kodama, 1989; Schmidt and Hellstrom, 1991). To obtain accurate estimates of the TM's properties, these thickness variations should be included.

1.2. Previous elastic modulus measurements

In a physically based model of the TM, one of the most important parameters is the elastic modulus. Though this parameter is not well known, a few experiments can provide bounds on its value. Several researchers have performed experiments on samples cut from the TM and then calculated an effective elastic modulus from the measured load–deflection curves.

Kirikae (1960) measured the elastic modulus of a strip of human TM using a longitudinal vibration technique. He arrived at a Young's modulus of 0.04 GPa. Békésy (1960) performed a beam-bending test and found a Young's modulus of 0.02 GPa. Decraemer et al. (1980) reported results for a uniaxial tension test of the human TM. The experimental stress–strain relationship had a small slope at small strains that gradually increased to a large constant slope at high strains. At the large strains, a value of 0.023 GPa was found for the elastic modulus. To date, no experimental measurements for the cat TM elastic modulus have been reported.

2. Methods and analysis

Three approaches were used to estimate the material parameters of the TM. First, a constitutive model was used to estimate the properties based on known stiffness values for the components that make up the TM. Second, existing experimental data were re-interpreted using classical composite lamination theory. Third,

Table 1
Thickness of cat and human tympanic membrane layers period. A nominal value and variation about the nominal value are given

Species	Publication	Entire membrane (μm)	Radial fiber layer (μm)	Circumferential fiber layer (μm)
Cat	Lim (1968, Fig. 2c)	31±2	15±2	7±2
	Chole and Kodama (1989, Fig. 2b)	40±10	18±2	9±2
Human	Lim (1970, Fig. 1c)	65±7	26±5	14±4
	Lim (1970, Fig. 4)	47±3	23±2	7±2
	Schmidt and Hellstrom (1991, Fig. 8)	53±3	22±2	19±2
	Schmidt and Hellstrom (1991, Fig. 9)	89±3	30±2	
	Chole and Kodama (1989)	34±5	11±4	7±2