FINITE-ELEMENT MODELLING OF THE NEWBORN EARDRUM

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Abstract

There are a lot of changes in the anatomy of the middle ear between newborn and adult. Our work focuses on the development of finite-element models that describe the biomechanics of the newborn middle ear. The finite-element model has realistic dimensions and geometry based on very high-resolution histological data sets. Ranges of plausible values for the thickness, stiffness and Poisson's ratio of the eardrum were used and simulated displacement patterns of the eardrum were studied.

Keywords: Finite-element Method; Newborn; Eardrum; Mechanics

Introduction

Finite-element analysis is an important tool in biomechanics. It provides a better understanding of the mechanics of the middle ear based on the anatomy, physiology and material properties of the system studied.

The first finite-element model of the eardrum was presented by Funnell and Laszlo [1]. Since then, the finite-element method has been used for the human middle ear by several groups [2-4], but no finite-element models of the newborn middle ear have been made. Such models are desired because of the importance of understanding the mechanics underlying screening and diagnostic tests for newborn hearing.

There are a lot of changes in the anatomy of the middle-ear between newborn and adult. Anatomical observations indicate that at birth the tympanic membrane is almost adult-sized but the thickness of the newborn tympanic membrane is far greater than that of the adult [5]. There is much unresolved mesenchyme and other material in the newborn middle ear and the newborn tympanic membrane has a more horizontal position than in the adult [6].

In this study, by applying image-processing and 3-D reconstruction software developed by our group, a 3-D finite-element model of a newborn eardrum was generated. The model has realistic dimensions and geometry. In this model, the data are generated and used in the following sequence: data acquisition (histological data sets), image segmentation, mesh generation, finite-element modelling, visualization of results. The goal of this paper is to understand the importance of membrane parameters such as thickness, Young's modulus, and Poisson's ratio, which control the displacement of the newborn eardrum. To simplify the situation, the initial modelling is focused on the eardrum with manubrium fixation, thus eliminating the effects of the ossicular and cochlear loads.

Methods

For our model, we used 156 individual serial histological sections of a newborn right middle ear. These sections were digitized with a resolution of 2700_2700 pixels. Each section is 20 μm in thickness, and the distance between consecutive sections is 100 μm.

Images for the newborn middle ear were segmented using our Fie program. The cross-sections of the eardrum and ossicles were traced using this program. After the contours have been traced, the vertices are imported into a 3-D surface triangulation program (Tr3) designed by our group. Tr3 generates the surface by optimally connecting contours in neighbouring slices with triangles.

Although the geometry and anatomical detail of the middle-ear structures are complex, the biggest difficulty associated with finite-element modelling remains that of obtaining reliable soft-tissue material properties.

The eardrum appears structurally to be anisotropic. Funnell and Laszlo [1] reported, however, that their finite-element model of the middle ear of a cat reproduced real middle-ear vibrations well without the introduction of anisotropy to their model. Therefore, all parts of our model were also assumed to be isotropic. The present model of the newborn eardrum is made up of 5117 isoparametric thin-shell elements. The eardrum is modelled as a uniform, homogeneous curved shell. The thicknesses of the different regions of the eardrum were determined based on the studies of Ruah [5].

Simulation Results

The acoustical input is a uniform sound pressure of 2.828 Pa, which is equivalent to 100 dB SPL. The frequency is taken to be low enough that the inertial and damping effects can be ignored. Since the values for the Young's modulus and the Poisson's ratio are uncertain, we have explored a range of plausible values. For simplicity, in our preliminary simulations the manubrium has been clamped, although we recognize that it is an over-simplification.

In order to examine the effects of variations of eardrum thickness on the displacement of the eardrum, two groups of models were constructed. Because the pars flaccida has a greater and more uniform thickness [5,6], the pars flaccida thickness is assumed to have the same value, 2.25 mm, in both groups. In the first group the pars tensa thickness is assumed to be uniform; thickness values of 50 μm, 100 μm, 150 μm, 225 μm, 350 μm and 500 μm are used. In the second group the pars tensa's thickness is set differently in four quadrants: (a) the posterosuperior quadrant is 450 μm; (b) the posteroinferior quadrant is 125 μm; (c) the anterosuperior quadrant is 200 μm; and (d) the anteroinferior quadrant is 125 μm.

The model used here does not consider the inclination of the eardrum. At low frequencies, the orientation of the eardrum can be ignored [3, 7].

To investigate the effects of variations of the material properties, various values of Young's modulus and Poisson's ratio were used for stress-strain analysis of the eardrum. For both thickness groups, the typical human adult's Young's modulus was used, namely, 20 MPa [2], and it was also varied by ±25% and ±50%. Therefore, the pars tensa was given Young's moduli ranging from 10 MPa to 30 MPa. The Young's modulus of the pars flaccida has been taken as one third that of the pars tensa [3,4]. For both pars flaccida and pars tensa the Poisson's ratios range from 0.1 to 0.4.

The eardrum is taken to lie in the *x*-*y* plane. Thus both the *x*-axis and *y*-axis displacements are in-plane displacements while the *z*-axis displacement is the out-of-plane displacement. The *z*-axis displacement is the most important component of eardrum displacement because it is the predominant effective input to the ossicles.

Figure 1 shows the *z*-direction displacement of the eardrum in the first group as a function of thickness. The *z*-direction displacement of the eardrum varies significantly with different thicknesses of the pars tensa. As shown in Figure 2, the *z*-direction displacement is inversely proportional to the pars tensa thickness to the power 1.5.

Figure 3 shows the maximal eardrum displacement along the *z*-direction at the fixed Poisson's ratio (0.25) as functions of the Young's modulus of the eardrum, for both groups of thickness parameters. Although the finite–element models in the first group were constructed using the mean value of the pars tensa thickness, it can be seen that variation of the thickness in different regions of the pars tensa results in a difference of approximately 300% in *z*-direction displacement. It is also seen that the *z*-direction displacement is inversely proportional to the eardrum's Young's modulus, as shown in Figure 4.

Figure 5 shows the *z*-direction displacement for the second group as a function of the Poisson's ratio. It is seen that the Poisson's ratio of the eardrum has little effect on the *z*-direction displacement of the eardrum.

Figure 1

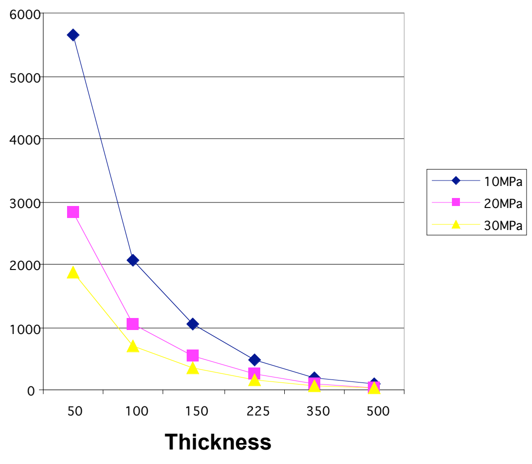
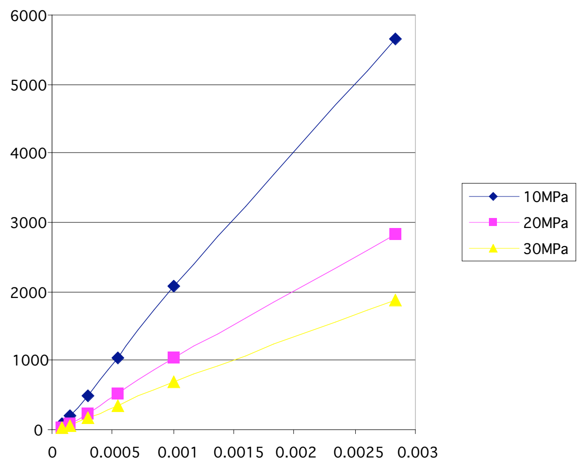


Figure 2



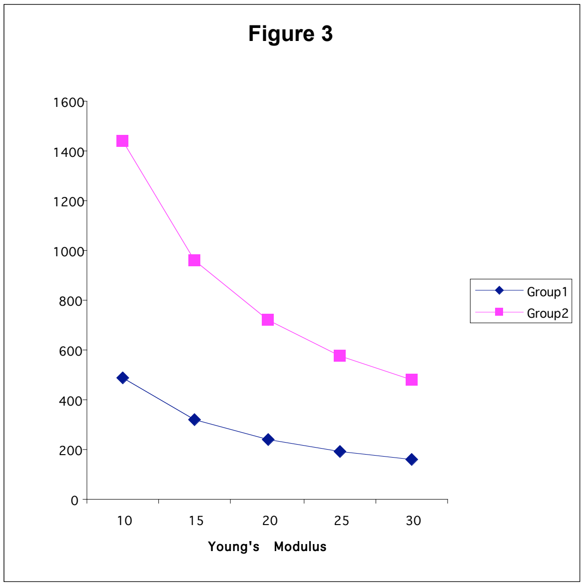


Figure 3

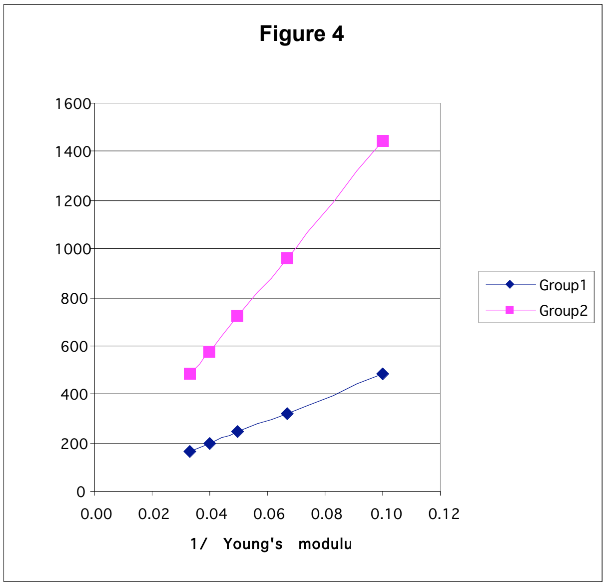


Figure 4

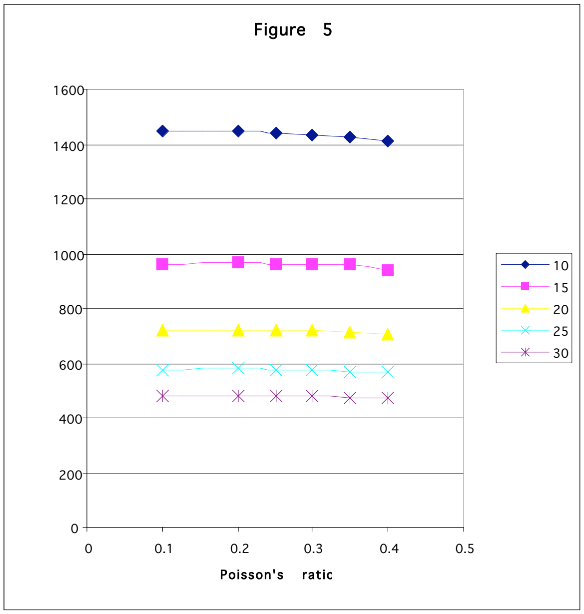


Figure 5

Conclusion

Applying our image-segmentation and triangulation software, a finite-element model of the newborn eardrum was established and the effects of different pars tensa thicknesses, Young's moduli and Poisson's ratios of the tympanic membrane on *z*-direction displacements were examined. The Young's modulus and thickness of the eardrum play important roles in influencing the displacement of eardrum, while Poisson's ratio has little effect on the displacement. The *z*-direction displacement of the eardrum is inversely proportional to the eardrum's Young's modulus, and to the pars tensa thickness to the power 1.5. The displacement of the eardrum varies significantly with nonuniformity of the thickness of the membrane. Future work will involve modelling the whole newborn middle ear and ear canal, which will allow a more detailed study of how the newborn middle ear behaves, and is expected to lead to new insights into screening and diagnosis for hearing.

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