NON-LINEAR FINITE-ELEMENT MODELLING OF THE NEWBORN EAR CANAL AND MIDDLE EAR

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INTRODUCTION

Hearing loss is one of the most frequently occurring disorders in newborns, but early diagnosis is difficult. It is recommended that newborn hearing screening be done for all infants by 1 month of age, assessment by 3 months of age, and intervention by 6 months of age[1]. Currently, evoked otoacoustic emissions (OAEs) and auditory brainstem responses (ABRs) are being used for screening. Although OAE and ABR tests are fast, objective and accurate examinations, neither can distinguish conductive hearing loss from sensorineural hearing loss, which require different medical approaches.

Tympanometry (the measurement of acoustical admittance in the presence of static pressures) is a fast and accurate hearing test routinely used in clinics for the evaluation of conductive hearing loss in older children and adults. When the frequency is less than about 2 kHz, the air enclosed in the external auditory canal (EAC) between the probe tip and the eardrum can be assumed to be a purely compliant element in parallel with the middle ear[2]. Thus, the middle-ear admittance (Y_{ME}) can be calculated from the admittance measured at the probe tip (Y) using

$$Y_{ME} = Y - Y_{EAC} \quad (1)$$

where Y_{EAC} is the admittance of the volume of air between the probe tip and the eardrum.

Tympanometry results in newborns are difficult to interpret. Studies have shown that Y_{ME} differs significantly between newborns and adults due to anatomical and physiological differences in the outer and middle ear[3]. Among other things, due to the compliance of the newborn ear canal wall, the newborn canal undergoes large deformations under the high static pressures of tympanometry. The accuracy of Y_{ME} relies on obtaining accurate estimates of ear-canal volume. If the Y_{EAC} is overestimated then Y_{ME} would be underestimated, and vice versa.

To the best of our knowledge, the only study to investigate the behaviour of the newborn ear canal under high static pressures was conducted by Holte et al.[4] They measured the ratio of the maximum canal-wall displacement to the resting canal diameter under high static pressures. Recently we presented a non-linear hyperelastic newborn ear-canal model and compared its behaviour with the results of Holte *et al.* and with tympanometric admittance measurements in two newborns[5].

The purpose of this study is two-fold. First, we present a preliminary non-linear finite-element model of a newborn eardrum and middle ear. The simulated eardrum volume displacement under high static pressures is compared with available experimental results. Second, we further investigate our newborn ear-canal model[6] by comparing simulation results with different tympanometry results than used before

MATERIALS AND METHODS

3-D reconstruction

The geometry of our model was derived from a 47-slice X-ray CT scan of a 22-day-old male newborn, as used for our previous ear-canal model. A solid-element model with 10-node tetrahedral elements was then generated from the triangulated surface by Gmsh (http://www.geuz.org/gmsh/) and imported into COMSOL™ (version 3.2) for finite-element analysis. The middle-ear model is shown in Figure 1.

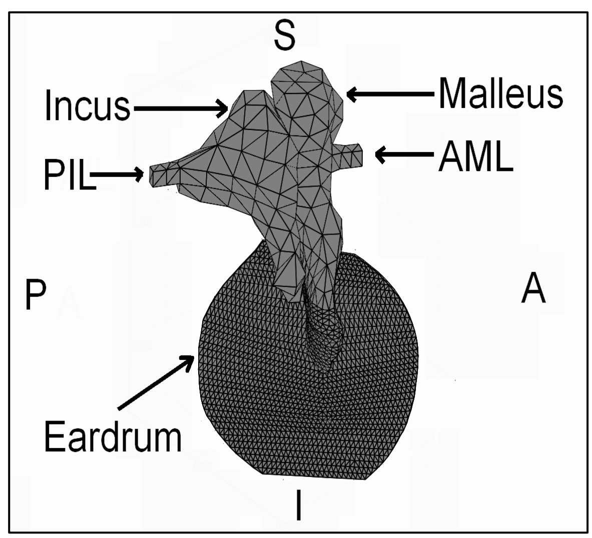

Figure 1: shows the middle-ear model. S is superior. I is inferior. A is anterior. P is posterior. PIL is posterior incudal ligament. AML is anterior mallear ligament.

Material properties

The material properties of the newborn ear canal and middle ear have never been measured. In this study, the Young's moduli of the canal wall, eardrum, ossicles and ligaments were estimated based on adult values[7-9] and converted to corresponding newborn values by development ratios from the published literature[10].

Table 1: Young's modulus used in this study

Structure	Young's modulus (MPa)
Ear canal	0.03, 0.06 and 0.09
Eardrum	0.6, 1.2; and 2.4
Ossicles	1000
Ligaments	1

The thickness used for the newborn eardrum is based on the measurements of Ruah et al[11,12]. The thicknesses are taken to be 100 µm for the anterior-superior, anterior-inferior and posterior-inferior quadrants; 500 µm for the poster-inferior quadrant and 750 µm for the umbo.

All tissues are assumed to be homogeneous, isotropic, and hyperelastic. The Poisson's ratio of the canal soft tissue, eardrum and ligaments are taken to be 0.475, that is, nearly incompressible. The Poisson's ratios of the ossicles is assumed to be 0.3.

Hyperelastic method

A polynomial hyperelastic constitutive law was applied, which allows us to simulate nearly incompressible biological materials with large deformations To model a hyperelastic material, a function W is defined to represent the strain energy. The formulation used here is

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{\kappa}{2}(J-1)^2 \quad (2)$$

C_{10} and C_{01} are material constants; J is the volume change ratio; κ is the bulk modulus. The ratio of C_{10}:C_{01} is here taken to be 1:1, which has been widely used for biological soft tissue.

Boundary conditions and load

In this study, the canal model is identical to the one published previously. In the middle-ear model, the boundary of the eardrum and the ends of the ligaments are assumed fixed. The static pressures are applied to the eardrum surface.

RESULTS

Eardrum volume displacement

Figure 2 shows the volume displacement of the eardrum corresponding to different Young's moduli for static pressures from –3 to +3 kPa. The volume displacements of model are asymmetrical, with larger displacements under negative pressures, which agrees with adult eardrum measurements[13,14].

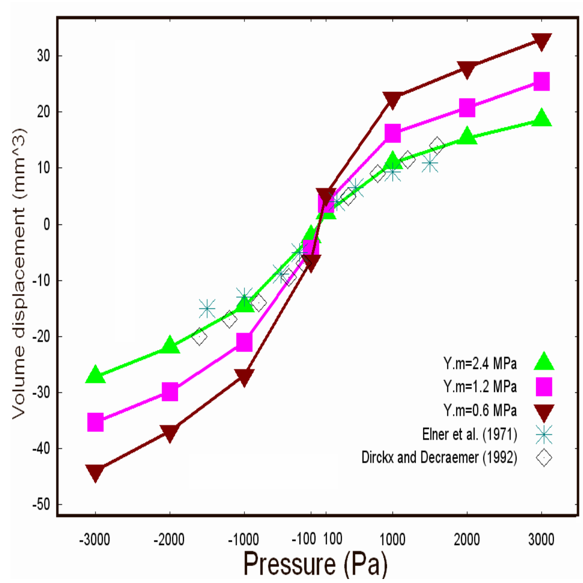

Figure 2: Eardrum volume displacements corresponding to different Young's moduli of eardrum, and experimentally measured volume displacements.

Comparisons with tympanometry data

The volume of air between the probe tip and the eardrum is estimated experimentally by measuring the admittance at high pressure, in which condition the admittance of the eardrum is assumed to be almost zero, and converting the admittance value to an equivalent volume. In this section, we compare the simulation results with equivalent-volume changes (ΔV_{eq}) between the positive and negative tails based on tympanometric measurements of admittance.

The ΔV_{eq} is computed using

$$\Delta V_{eq} = \Delta Y \rho c^2 / 2\pi f \quad (3)$$

where ΔY is the admittance change, ρ is the air density (1.2 kg/m^3), c is the speed of sound (343 m/s), and f is the frequency.

Margolis et al.[15] measured the 1-kHz admittance both in full-term healthy newborns (aged 2-4 weeks) and in newborns in neonatal intensive care units (aged 3.9±3.8 weeks, mean ± SD). They recommended using the peak-to-negative-tail difference at the 5th percentile as a pass-fail criterion for conductive hearing loss. Since middle-ear effusion (MEE) is the most common cause of conductive hearing loss in newborns, we assume that the pass-fail criterion can be used as a criterion for MEE. For newborns with MEE, the eardrum cannot move as freely as usual and therefore the admittance of the middle ear is assumed to be nearly zero. As a result, the equivalent-volume change (ΔV_{eq}) between the two tails is mainly due to the canal wall movement. Figure 3 compares the ear-canal model results with the ΔV_{eq} between negative and positive tails at the 5th percentile in both healthy and NICU newborns.

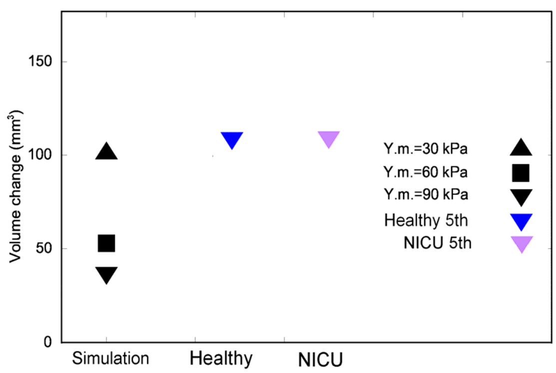

Figure 3: Comparison of simulated ear-canal volume displacements with equivalent-volume changes at 5th percentile calculated based on Margolis et al.

The equivalent-volume changes between the 5th and 95th ($\Delta V_{eq}^{5\text{-}95}$), and between the 5th and 50th percentiles ($\Delta V_{eq}^{5\text{-}50}$); may be taken respectively as measures of the maximum and average volume changes caused by the static displacement of the newborn eardrum. Figure 4 compares the simulated eardrum volume displacement with $\Delta V_{eq}^{5\text{-}95}$ and $\Delta V_{eq}^{5\text{-}50}$ in both the healthy and the NICU newborns.

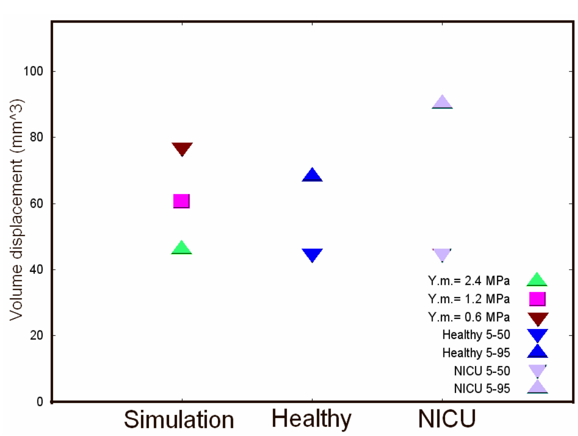

Figure 4: Comparison of middle-ear simulation results with $\Delta V_{eq}^{5\text{-}50}$ and $\Delta V_{eq}^{5\text{-}95}$ in healthy and NICU newborns.

DISCUSSION AND CONCLUSIONS

We have presented a new non-linear hyperelastic model of a newborn eardrum and middle ear. Both the new eardrum model and our previous ear-canal model exhibit non-linearity: as the pressures increase, the gradients of the displacements become smaller.

The Young's modulus of the eardrum has a significant effect on the eardrum volume displacement (Figure 2). As the Young's modulus decreases, the displacements increase and the degree of non-linearity increases.

The simulated eardrum volume displacements do not reach a plateau when the pressure is varied between −3 and +3 kPa, which agrees with reports that neither of the two extreme pressures drives the admittance of the adult eardrum to zero[16,17]. When the Young's modulus of the eardrum is 2.4 MPa, the displacements of the eardrum and umbo are similar to measurements in human adults (Figure 2). In our model the Young's moduli of the newborn eardrum, ossicles and ligaments are smaller than typical values used in adult middle-ear models, but the thickness of the newborn eardrum is much larger than that of the adult eardrum. As a consequence, the total stiffness of the newborn middle ear may be comparable to the total stiffness of the adult middle ear.

We assumed that the 5th percentile could be used as a criterion for the presence of MEE, and thus could indicate canal volume displacement without eardrum displacement. The maximum volume displacement in our ear-canal model is comparable to the ΔV_{eq} at the 5th percentile (Figure 3), consistent with our assumption. The minimum and maximum simulated eardrum volume displacements are comparable to $\Delta V_{eq}^{5\text{-}50}$ and $\Delta V_{eq}^{5\text{-}95}$ in both full-term healthy newborns and NICU newborns (Figure 4).

Even with MEE, the eardrum may still make a contribution to the overall volume displacement. As a consequence, the $\Delta V_{eq}^{5\text{-}50}$ and $\Delta V_{eq}^{5\text{-}95}$ may both underestimate the volume displacement of the eardrum.

As a first step to modelling the newborn ear canal and middle ear, we have taken into account tissue hyperelastic properties. Further work is required to incorporate inertial and viscoelastic effects. Further validation against experimental data is also required.

ACKNOWLEDGEMENTS

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REFERENCES

[1] National Institute on Deafness and Other Communication Disorders (1993) National Institutes of Health Consensus Statement: Early identification of hearing-impairment in infants and young children. Bethesda, MD.

[2] Margolis RH and Hunter LL (1999) “Tympanometry-basic principles and clinical applications” in Contemporary perspective on hearing assessment, edited by Rintelmann WF and Musiek F (Allyn and Bacon, Boston).

[3] Saunders JC, Kaltenbach JA, Relkin, EM. (1983) “The structural and functional development of the outer and middle ear.” Development of Auditory and Vestibular Systems New York: Academic.

[4] Holte L, Cavanaugh RM Jr, Margolis RH (1990) “Ear canal wall mobility and tympanometric shape in young infants” J Pediatr 117(1 Pt 1): 77-80.

[5] Polka L, Shahnaz N, Zeitouni A (2002) “A comparison of middle ear acoustic admittance in adults and 3-week-old infants based on multifrequency tympanometry” J Acoust Soc Am 112: 2272 (abstract).

[6] Qi L, Liu H, Lutfy J, Funnell WRJ & Daniel S (2006): A non-linear finite-element model of the newborn ear canal. J Acoust Soc Am 120: 3789-3798.

[7] Cheng T, Dai C, Gan RZ. (2007) “Viscoelastic properties of human tympanic membrane.” Ann Biomed Eng. 35(2):305-314.

[8] Koike T, Wada H, Kobayashi T.(2002) “Modeling of the human middle ear using the finite-element method.” J Acoust Soc Am. Mar;111(3):1306-1317.

[9] Zhang M, Zheng YP, Mak AF (1997) “Estimating the Effective Young’s Modulus of Soft Tissues from Indentation Tests - Nonlinear Finite Element Analysis of Effects of Friction and Large Deformation” Med Eng Phys 19: 512-517.

[10] Yamada H (1970), “Strength of biological materials”, Baltimore, Williams and Wilkins.

[11] Ruah CB, Schachern PA, Zelterman D, Paparella MM, Yoon TH (1991) "Age-related morphologic changes in the human tympanic membrane. A light and electron microscopic study." Arch Otolaryngol Head Neck Surg. Jun;117(6):627-34.

[12] Ruah CB PhD Thesis, University of Lisbon University of Lisbon 1990.

[13] Elner A., Ingelstedt S. and Ivarson A. (1971) “The elastic properties of the tympanic membrane system.” Acta Otolaryng 72, 397-403.

[14] Dirckx JJ, Decraemer WF (1992) “Area change and volume displacement of the human tympanic membrane under static pressure.” Hear Res;51(1):93-105.

[15] Margolis RH, Bass-Ringdahl S, Hanks WD, Holte L, Zapala DA (2003) “ Tympanometry in newborn infants- 1 kHz norms”, J Am Acad Audiol, 14(7):383-92.

[16] Margolis RH, Smith P (1977): “Tympanometric asymmetry.” J Speech Hear Res.;20(3):437-46.

[17] Shanks JE, Lilly DJ (1981) “ An evaluatioin of tympanometric estimates of ear canal volume”, J Speech Hear Res. 24(4):557-66.