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4pEAa11. Finite-element modelling of the newborn ear canal and middle ear
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Available hearing-screening procedures cannot distinguish clearly between conductive and sensorineural hearing loss in newborns, and the results of available diagnostic tests in very young infants are difficult to interpret. Admittance measurements can help to detect conductive losses but do not provide reliable results for newborns, where the ear is anatomically different from the adult ear. Finite-element models of the newborn ear canal and middle ear were developed and their responses were studied for frequencies up to 2000 Hz. Material properties were taken from previous measurements and estimates, and the sensitivities of the models to these different parameters were examined. The simulation results were validated through comparison with previous experimental measurements. Preliminary simulations indicate that at frequencies up to 250 Hz the admittance of the canal wall is comparable to that of the middle ear in the newborn. Above 250 Hz the canal-wall admittance remains almost constant but for the middle ear there is a clearly defined resonance peak, which produces an admittance much larger than that of the canal wall. These results suggest that admittance measurements in the vicinity of the middle-ear resonance frequency can provide clinically useful information about the newborn middle ear.

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INTRODUCTION

Hearing loss is one of the most common birth defects in newborns. If not detected and treated early, it can result in delayed language acquisition and other problems. Available hearing-screening procedures cannot distinguish clearly between conductive and sensorineural hearing loss in newborns, and the results of available diagnostic tests in very young infants are difficult to interpret.

Tympanometry is an acoustic admittance measurement in the presence of a range of static pressures. It can help to detect conductive losses but does not provide reliable results for newborns. Differences in the interpretation of results between adults and newborn arise from different anatomical and mechanical characteristics (e.g., Holte et al., 1991; Keefe and Levi, 1996).

Since there are many factors affecting experimental results, outputs are difficult to interpret (e.g., Sanford and Feeney, 2008). The finite-element method is a numerical modelling tool than can be used to simulate the behaviour of structures in conditions that cannot be achieved experimentally. Qi et al. (2006, 2008) used the finite-element method to study the response of a newborn ear canal and middle ear to the large static pressures used in tympanometry. Here we analyze the behaviour of finite-element models of the newborn ear canal and middle ear in response to the tympanometric probe tone. This work is based in part on Gariepy (2011).

MATERIALS AND METHODS

3-D Geometry

The geometry of the model is reconstructed using a clinical CT scan of a 22-day-old newborn, as described by Qi et al. (2006). Three locally developed programs, Fie, Tr3 and Fad (http://www.audilab.bme.mcgill.ca/sw/), were used to generate a surface model. Gmsh (http://www.geuz.org/gmsh/) was then used to generate a 3-D solid model with tetrahedral elements for each component of the model, and the different components were joined together using Fad. Figure 1 shows a medial view of the resulting model.

In this model, the malleus and incus, the anterior malleolar ligament and the medial and lateral parts of the posterior incudal ligament were modelled using second-order ten-node tetrahedral elements. Dirckx and Decraemer (2001), for example, found in the gerbil that the cochlea, tensor tympani, and stapes have negligible effects on eardrum deformations under quasi-static pressures of 2 kPa; these components are not included in our model. The tympanic-membrane model is composed of second-order seven-node triangular shell elements. Second-order elements can provide more accurate simulation results and save computation time.

![Diagram of the middle-ear model](image)

**FIGURE 1.** Medial view of the middle-ear model containing the tympanic membrane, malleus, incus, anterior malleolar ligament (AML), and medial and lateral parts of the posterior incudal ligament (PIL: Med and Lat). S is superior, I is inferior, A is anterior, P is posterior.
Material Properties

The results of Qi et al. (2006, 2008) indicate that the onset of non-linearity seems to occur at approximately 1000 Pa in both the ear canal and the middle ear. In our simulations the input pressure levels are kept at around 0.4 Pa (~85 dB SPL) since this is the normal amplitude of the probe tone. Therefore, linear material properties are applied to all components of the model.

Young’s modulus and thickness of the tympanic membrane

Since Young’s moduli for the newborn tympanic membrane are not available, a range of plausible values must be used instead. Qi et al. (2008) used 0.6 – 2.4 MPa for the modulus of the tympanic membrane for a static input pressure. However, since in this model the tympanic membrane experiences dynamic loads, these values may need modification. Because of the viscoelastic nature of soft tissue, the Young’s modulus is a function of the excitation frequency. Decraemer et al. (1980) showed that the modulus is approximately twice as large at higher frequencies (~100 Hz) as at lower frequencies (~0.01 Hz). Therefore, here the moduli of the canal walls and tympanic membrane will be doubled, so the final range to be tested is 1.2 – 4.8 MPa. The Young’s modulus of the pars flaccida is set to be 1/3 of that of the pars tensa (e.g., Koike et al., 2002). Based on the study of Ruah et al. (1991), in this model the thickness of the posterior-superior quadrant of the pars tensa of the tympanic membrane is 0.5 mm and that of the other three quadrants is 0.1 mm. A thickness of 2 mm is applied to the pars flaccida.

Young’s modulus of the canal wall

Based on Qi et al. (2006), for the elastic cartilage surrounding the ear canal the Young’s modulus is taken to be in the range of 60 – 180 kPa is used. The lower boundary of this range coincides with the stiffness of some of the least stiff tissues of the human body, such as fat, while the upper boundary coincides with the stiffness of the most compliant cartilage seen in adults.

Young’s moduli of the ossicles and ligaments

The Young’s modulus of the ossicles is taken to be 3 GPa. The Young’s modulus of the ligaments is set to 3 MPa, which assumes that the ligaments have a stiffness similar to that of the tympanic membrane itself. The logic behind these choices for the modulus values is the same as that of Qi et al. (2008).

Poisson’s ratio

The Poisson’s ratio is set to 0.49 for soft tissues, which causes the tissues to behave nearly incompressibly. (An incompressible material has a value of 0.5.) For the ossicles the Poisson’s ratio is set to 0.3.

Density

The anatomical structures of soft tissues in our model are composed of 60 – 80% water while the remaining solid structure largely consists of a collagen matrix. Therefore it is assumed that the density of all these tissues lies somewhere between the densities of water and collagen (e.g., Qi et al., 2008). Therefore, for these simulations the density of these materials will be set to 1100 kg/m³. With a similar logic, the density of the ossicles in these simulations will be set at 1800 kg/m³.

Damping ratio

It has been suggested that typical human body damping ratios lie in the range from 0.15 to 0.4 (e.g., Keefe et al., 1993). The damping ratio of 0.4 is used for all components here. To obtain this damping ratio, we used Rayleigh damping and calculated the appropriate mass and stiffness coefficients to produce a damping ratio of 0.4 for each simulation frequency.
Input Pressure Signals

The dynamic simulation uses single-frequency sinusoidal input pressures. The frequency of the input is in the range from 50 to 2000 Hz with a frequency resolution of 1/6 octave, and the admittance of the model is calculated at the end of each simulation by obtaining the volume velocity and dividing it by the input pressure. The upper limit of the input frequencies is set so as to maintain the validity of the assumption that the ear canal can be modelled as a lumped acoustical element (Shanks and Lilly, 1981).

Boundary Conditions

The boundary of the tympanic membrane and the ends of the ligaments are taken to be fixed. The dynamic and static pressures are uniformly applied to the lateral surface of the tympanic membrane.

Middle-Ear Cavity

The middle-ear cavity is an air-filled space located on the medial side of the tympanic membrane; it is bounded by the temporal bone and contains the ossicles. Qi et al. (2008) estimated this volume as being between 700 and 1000 mm$^3$ based on their CT data. The finite-element simulations of the middle ear do not take the effect of the middle-ear cavity into account, and many studies have shown the large impact that this cavity can have on the admittance of the middle ear (e.g., Funnell and Laszlo, 1982). Therefore, the calculated middle-ear compliance values must be adjusted in order to compensate for this effect. The total impedance of the middle ear can be calculated by combining the impedance of the trapped air in the cavity ($Z_{cav}$) and the impedance of the tympanic membrane ($Z_{TM}$): $Z_{ME} = Z_{TM} + Z_{cav}$ (e.g., Stepp and Voss, 2005).

Software

The finite-element simulations are performed using the open-source software Code_Aster (stable version 10.8, http://www.code-aster.org). The associated package Salome-Meca (version 2012.2) is used for post processing.

RESULTS

Preliminary simulations indicate that at frequencies up to 250 Hz the admittance of the canal wall is comparable to that of the middle ear in the newborn. Above 250 Hz the canal-wall admittance remains almost constant but for the middle ear there is a clearly defined resonance peak at around 1000 Hz, which produces an admittance larger than that of the canal wall.

A sensitivity analysis has been performed to analyze the relative importance of the various parameters. We found that the main parameters that influence the simulation results are the Young’s modulus and the damping ratio of the tympanic membrane. For example, increasing the tympanic-membrane Young’s modulus from 1.2 to 4.8 MPa results in a decrease of about 50% in the overall compliance of the middle ear. For dynamic simulations, this modulus not only affects the magnitude of the resonance peak but also shifts it to higher frequencies.

Another parameter that influences the dynamic simulation significantly is the damping ratio, which strongly affects the amplitude and shape of the resonance peak.

DISCUSSION

The primary goal of tympanometry is the detection of middle-ear pathologies. It is therefore desirable that the admittance value measured in tympanometry should correspond only, or at least mainly, to the admittance of the middle ear and not to that of the ear canal. Currently, tympanometry is often performed at a frequency of 226 Hz, where the canal effects are significant. Our results suggest that admittance measurements in the vicinity of the middle-ear resonance frequency can provide clinically useful information about the newborn middle ear, but that multiple frequencies may be required to properly identify and account for the resonance.
REFERENCES


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