

Clinical Applications of a Finite-Element Model of the Human Middle Ear

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Abstract

Computer-generated models are increasingly being used in otolaryngology for teaching purposes, preoperative planning, and clinical simulations, especially when dealing with small, complex areas such as the middle ear. One technique used to analyze the mechanics of complex models is the finite-element method, whereby the system of interest is divided into a large number of small, simple elements. The mechanical properties and applied forces are represented by functions defined over each element, and the mechanical response of the whole system can then be computed. We present a unique three-dimensional finite-element model of the human eardrum and middle ear. Our model takes advantage of phase-shift moiré shape measurements to precisely define the shape of the eardrum. The middle ear geometry is derived from histologic serial sections and from high-resolution magnetic resonance microscopy of the human ear. We discuss the importance of this model in terms of understanding and teaching the mechanics of the human middle ear, simulating various pathologic conditions, and designing ossicular prostheses.

Sommaire

La modélisation par ordinateur est de plus en plus utilisée en ORL, soit à des fins d'enseignement, de planification préopératoire ou de simulation clinique, en particulier en rapport avec des régions complexes et exiguës comme l'oreille moyenne. Une technique utilisée pour analyser la mécanique de modèles complexes est une méthode où le système à l'étude est divisé en un grand nombre d'éléments simples. Les propriétés mécaniques et les forces appliquées sont représentées par des fonctions définies pour chacun des éléments et la réponse du système en entier est ensuite calculée. Nous présentons un tel modèle pour l'oreille moyenne et le tympan. Il utilise le déphasage des formes moiré pour définir précisément la forme du tympan. La géométrie de l'oreille moyenne est dérivée de sections histologiques et de microscopie par résonance magnétique à haute résolution. Nous discuterons l'importance d'un tel modèle pour la compréhension et l'enseignement de la mécanique de l'oreille moyenne humaine en simulant différentes conditions pathologiques et pour la conception de prothèses ossiculaires.

Key words: clinical applications, finite-element model, human, middle ear, moiré, ossicles

Computer technology has improved dramatically over the past few years, concomitantly with major advances in imaging tools. This has led to revolutionary

changes in our medical practice such as presurgical and intraoperative three-dimensional visualization of structures, numerous virtual endoscopic techniques ranging from colonoscopy to bronchoscopy, angiography, and otoscopy.¹ There have also been remarkable advances in vibration measurement technology. In the early years of middle ear research, scientists like Helmholtz and Politzer had to resort to rudimentary methods such as gluing rods or bird feathers to the ossicles to detect vibrations with auditory stimulation of the middle ear.² During these experiments, the sound intensity required to detect the vibrations was very large, resulting in non-physiologic behaviour of the middle ear. Commercially available laser Doppler vibrometers now permit accurate assessment of middle ear mechanics with physiologic sound pressures. Displacements in the ear down to 10⁻⁴ µm can easily be measured over a wide range of frequencies, allowing us to validate theoretical models in an experimental setting.³

The combination of the improvements in computers, imaging, and measurement has made it possible to

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construct, simulate, and validate detailed computer-based models of the ear that previously would not have been feasible.

Why Have a Finite-Element Model?

The function of the middle ear is intrinsically complex. The classic teachings are overly simplified and misrepresent the real dynamics of the middle ear.

The middle ear acts as a coupler that matches the low impedance of air to the high impedance of the liquid in the inner ear. The main transformer action results from the fact that the force produced by the acoustic pressure acting on the eardrum is applied to a much smaller surface area at the footplate. According to classic theory, the transformer ratio has two components:

1. One component was said to result from the ratio of the effective tympanic membrane surface area to the surface area of the footplate. Since it was believed that "the whole eardrum except the extreme periphery vibrates as a stiff surface along with the manubrium,"⁴ the "effective area" of the eardrum would thus simply be the area of the stiff part.
2. The second component was said to result from the lever ratio corresponding to the length of the malleus (from the point of rotation to the umbo) divided by the length of the incus (from the point of rotation to the incudostapedial joint). Calculation of the lever ratio in this way assumes that the malleus rotates around a fixed axis and that all of the force of the tympanic membrane is applied at the umbo.

This classic theory corresponded to a simple mechanical system and was well represented by lumped-parameter circuit models, as described below. Unfortunately, various experiments have shown that the situation is more complicated. Von Békésy himself observed that above 2.4 kHz, "the conical portion of the eardrum loses its stiffness, and the manubrium in its motion lags behind the motion of the adjacent portion of the membrane."⁴ Even at low frequencies, however, the motion of the eardrum is not that of a hinged stiff plate. Khanna and Tonndorf showed this conclusively using time-averaged holography.⁵⁻⁷

Furthermore, the ossicular rotation around a fixed axis running from the anterior process of the malleus to the posterior incudal ligament, as described by Bárány⁸ and von Békésy,⁹ has been radically refuted by recent experimental measurements. Decraemer et al. have shown that the position of the axis of rotation changes greatly with frequency and even within each cycle of oscillation.^{10,11} But the reality is even more complex: by measuring malleus vibrations along the three axes *x*, *y*, and *z*, they showed that the motion of the malleus has both rotational and translational components in each of the three dimensions.^{12,13}

From these experimental measurements, it becomes evident that the concept of fixed lever and area ratios is inaccurate and that middle ear dynamics are extremely complicated. Sophisticated numeric models are required to quantitatively explain the mechanical behaviour of the middle ear.

Evolution of Middle Ear Models

Electrical Circuit Models

Many mathematical models have been constructed over the past few decades, mostly in the form of mechano-acoustic or electrical circuit models. In these models, the behaviour of the anatomic structure studied is represented by the combination of three kinds of idealized circuit elements: a point mass, an ideal spring, and an ideal damper. The parameter values in the model are obtained by trying to match the behaviour of the model with the experimental results. Examples of such models are the ones described by Zwislocki,¹⁴ Shaw and Stinson,¹⁵ and Vlaming.¹⁶ Although these so-called "lumped-parameter" techniques can lead to models able to replicate specified experimental data, their main disadvantage lies in the fact that their parameters are not closely tied to anatomic or physiologic data independent of the behaviour being modelled.

Finite-Element Models

The finite-element method is a numeric technique that has found application in many areas. It consists of dividing the system of interest into a number of discrete two- or three-dimensional subregions called elements. These elements can have various shapes such as triangles and quadrilaterals (plates), tetrahedra (pyramids), and hexahedra (bricks). The process of dividing a region into elements is known as mesh generation. The mechanical behaviour of each element is then analyzed, and its response to applied loads is expressed in terms of the displacement of its edges. The result of the relatively simple element analysis is a matrix equation relating the response of the element to the applied forces. The components of these matrix equations are functions of the shapes and material properties of the elements. Finally, all of the individual element matrix equations can be combined into a global matrix equation describing the behaviour of the entire complex structure.

The finite-element method has many attractive features. It can easily handle irregular boundary shapes, nonlinearities, complex geometries, and inhomogeneities. More importantly, the model can accurately represent the anatomy, physiology, and biomechanical properties of the system studied rather than rely on an electrical circuit with variously assigned parameters. The finite-element model has relatively few free parameters for which values need to be adjusted to fit the experimental data. The parameters have a very direct

relationship to the structure and function of the system analyzed and can be estimated independently of the experimental situation being modelled.

The first finite-element model of the eardrum and middle ear was that of Funnell and Laszlo^{17,18} for the cat, based on an extensive review of the anatomic, structural, and biomechanical nature of the eardrum.¹⁹ Over the past decade, it has become clear that the complex geometry and mechanical properties of the middle ear cannot be adequately modelled using circuit models, and the finite-element method has become the technique of choice. Several researchers have recently presented finite-element models of the human middle ear.²⁰⁻²² Our recently developed model of the human middle ear is unique in that it uses exact anatomic data derived from moiré shape measurements of the tympanic membrane, histologic serial sections, and high-resolution magnetic resonance images (MRIs).²³ We feel that designing a realistic anatomic three-dimensional model is of primary importance to reduce the number of free parameters in the model.

Materials and Methods

Representing Middle Ear Anatomy

The first step in generating complex three-dimensional models is a geometric representation of the structure of interest.

Anatomy of the Eardrum. The precise three-dimensional shape of the eardrum, with its boundary definition and displacement measurements in the presence of various static pressures applied, was obtained using phase-shift moiré topography. This is an optical technique that involves projecting a grating of parallel lines onto the surface being measured, thereby offering a noncontacting method for assessing the shape of the object of interest.²⁴ The images produced have pixel values that are directly related to the *z* coordinates.

Figure 1 shows the example of a moiré image obtained by W.F. Decraemer (University of Antwerp-RUCA) for one ear with no static pressure applied ($p = 0$). Horizontal and vertical profiles through the umbo are shown for $p = 0$ and for applied pressures of ± 400 and ± 800 Pa (± 4 and ± 8 cm H₂O). The displacements are nonlinear and are smaller for positive pressures than for negative ones.

The shape of the pars tensa in this model was derived from the moiré data using the same techniques that we have previously used for the cat²⁵ and the gerbil.²⁶ The outlines of the eardrum and manubrium are obtained from visual inspection of the shape profiles.

Anatomy of the Middle Ear. The anatomy of the middle ear ossicles, ligaments, and muscles was reconstructed from magnetic resonance microscopy (MRM) data from the Center for In Vivo Microscopy (Duke Univer-

sity), based on ears prepared by M.M. Henson and O.W. Henson Jr. (University of North Carolina-Chapel Hill).^{27,28} For our model, we used a human middle ear sectioned horizontally into 180 individual slices with voxel sizes of about 120 μ m each. This particular data set was chosen from among several available based on its completeness.

Horizontal and vertical histologic serial sections of the human middle ear were also used. These sections were digitized and scaled. Each section is about 20 μ m in thickness, and the distance between consecutive sections is approximately 200 μ m. Histology is very useful to complement the MRI, especially in defining the exact origins, insertions, and dimensions of the ligaments and to view the details of the incudostapedial joint.

Segmentation

Each digitized slice was imported into a locally developed computer program, Fie, and was manually processed. Anatomic structures of interest were individually delineated, and their contours were colour coded consistently from slide to slide. This process is referred to as segmentation. For the finite-element model, the eardrum, ossicles, muscles, and ligaments were included. Other structures, such as nerves and vessels, are not mechanically significant but could nonetheless be very useful from a teaching perspective. They were therefore included in a separate model, which is used only for visualization purposes and not for finite-element modelling.

Triangulation

The segmented contours were then imported into a locally designed three-dimensional triangulation pro-

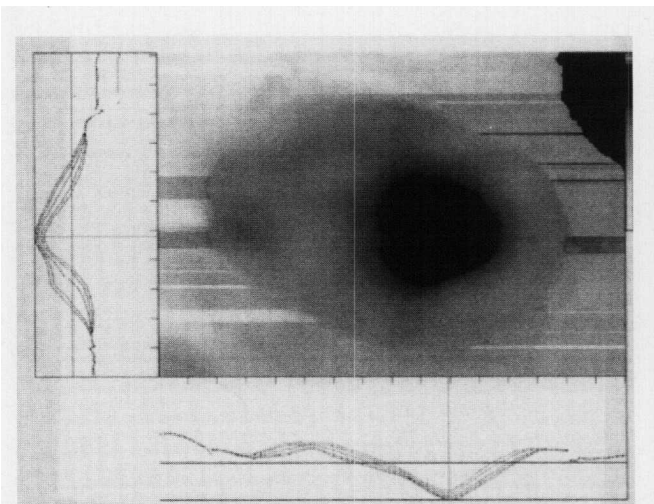


Figure 1 Example of a moiré image obtained by W.F. Decraemer (University of Antwerp-RUCA) for one ear with no static pressure applied ($p = 0$). Horizontal and vertical profiles through the umbo are shown on the *x* and *y* axes, respectively. These profiles are shown for $p = 0$ (middle line) and for applied pressures of ± 400 and ± 800 Pa (± 4 and ± 8 cm H₂O).

gram (Tr3). This software generates a mesh over each segmented structure by optimally connecting contours in neighbouring slices with triangles. Each small triangle is assigned mechanical properties such as material stiffness (Young's modulus) and boundary conditions (free or clamped), as well as visualization properties such as transparency. A decision is made as to how many elements should represent the structure, for example, into how many small triangles the stapes footplate should be divided. The finer the mesh, the more accurate is the representation of the structure. Unfortunately, the greater the number of elements in the structure, the greater the amount of time needed to solve all of the equations in the system. Thus, a very fine mesh is computationally very demanding. A very coarse mesh would consume much less time, but the displacements of the model would not be as accurate. Therefore, it is important to find an appropriate mesh resolution for the model.

Finite-Element Model

The triangulated surface produced by Tr3, excluding the eardrum, is combined with the triangulated surface for the eardrum derived from the moiré data to produce a combined finite-element model of the human middle ear.

The pars tensa is modelled as a uniform, homogeneous curved shell with a Young's modulus (material stiffness) of 20 MPa and a density of 10^3 kg m^{-3} . The thicknesses of the pars tensa and of the pars flaccida were determined from our histologic sections to be 100 and 200 μm , respectively. The Young's modulus of the pars flaccida has been taken as one-tenth that of the pars tensa. The acoustic input is a uniform sound pressure of 1 Pa.

A finite-element program, SAP IV, then computes all of the element stiffness matrices and load vectors and combines them into an overall structure matrix equation. This overall equation can then be solved to give the middle ear displacements resulting from the applied sound pressure.

Results

Figure 2 shows a mesh generated over a segmented manubrium of the malleus. The segmented contour is divided into small triangles. Each triangle is assigned individual biomechanical properties. Figure 3 illustrates a combined finite-element model incorporating meshes derived from both the MRI model and the moiré data. Figure 4 shows a simulated vibration pattern at low frequencies (i.e., frequencies low enough that inertial and damping effects are negligible), with normally suspended ossicles. Displacements are qualitatively illustrated with smaller displacements coded in darker colours and larger displacements in lighter colours.

Clinical Applications

Recent studies have reported on some clinical applications of the finite-element method. For example, Prendergast et al. used finite-element analysis to simulate the effect of ventilation tubes on vibration motions in the eardrum.²⁹ They found significant biomechanical differences between various models of pressure equalization tubes. Heavy grommets such as those made of titanium or metal had an adverse effect on hearing as compared with light tubes like polyethylene. In another study, Blaney et al. described the mechanics of sound transmission at the footplate following stapedotomy.³⁰ Our group is focussing mainly on applying the finite-element model for the design of better ossicular prostheses and improving current hearing screening tools. We also plan to individualize finite-element models to simulate specific disease conditions and use them for preoperative planning and postoperative assessment.

Design of Ossicular Prostheses

Reconstruction of the ossicular chain has always been a challenge to the otologist. An ideal prosthesis should be stable, easy to insert, and, most importantly, yield optimal sound transmission. The plethora of prostheses available bears witness to our ongoing search for the perfect solution. Numerous devices have been shown to be successful in individual series, but no single tech-

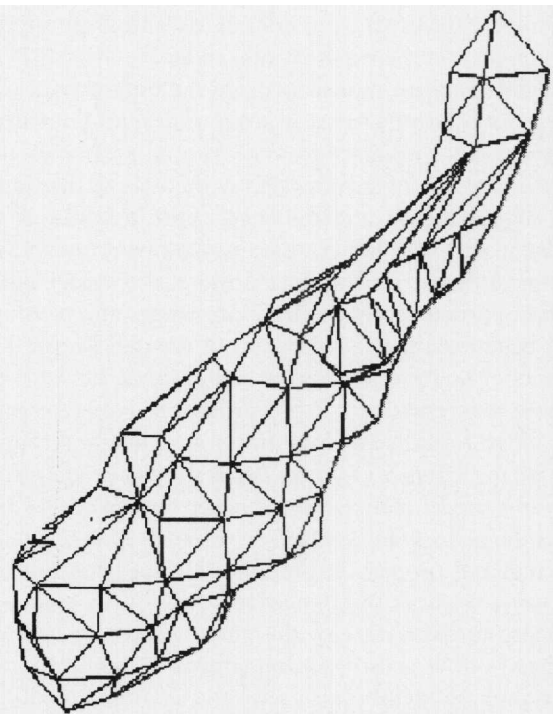


Figure 2 An example of a mesh generated over the segmented manubrium of the malleus. The contour is divided into small triangles. The mesh can be as coarse or as detailed as desired.

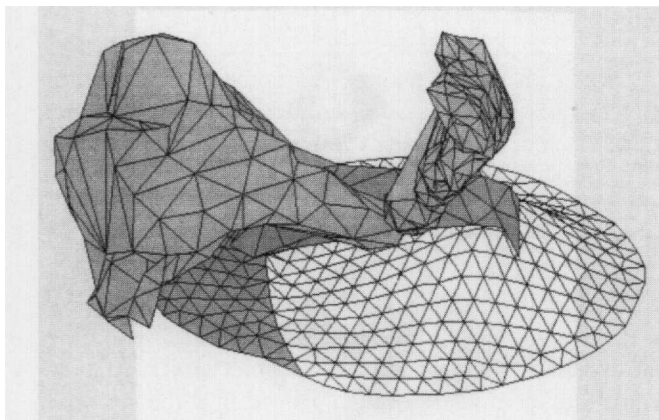


Figure 3 Combined finite-element model incorporating meshes derived from both the MRI model and the moiré data.

nique has gained universal acceptance. This is attributable to the lack of uniform criteria for measuring success, the paucity of direct comparisons between various techniques, and the limited number of long-term prognostic analyses.³¹ Furthermore, there has been little or no theoretical analysis of the mechanical performance of any of the prostheses currently available on the market. Recently, human middle ear modelling has increasingly become a focus of attention, particularly among groups interested in prosthesis design and new surgical reconstructive techniques. However, the attempts at analysis that are being made are severely limited by the crudeness of both the theoretical models and the measurements (typically impedance or single-point displacements) on the experimental models.

Finite-element models provide the only way of analyzing ossicular prosthesis issues that depend on realistic representations of anatomy and material properties. The main advantage of such models is the ease of manipulation of parameters and the exact representation of the eardrum and middle ear anatomy, allowing individualization of the treatment. Furthermore, the model allows us to import currently available prostheses and to couple their behaviour to the mechanics of the middle ear. This permits evaluation and direct comparisons between the various currently available prostheses to determine which one would be the best fit for a particular setting.

Some examples of design issues we will be addressing with our model include assessing the characteristics that affect the performance of prostheses, such as shape, mass, and material properties; the importance of reproducing the normal eardrum-ossicular coupling or ossicular suspension; the nature of the point of contact between the head of the prosthesis and either the manubrium or the tympanic membrane itself; and whether flexibility could be used to improve their effectiveness.

Although experimental work could answer parts of these questions, this would be very expensive, as each change in a given parameter would necessitate a costly

experiment. Furthermore, the settings from one experiment to the next can never be exact, due to the inherent variations in middle ear anatomy among and within different species. Nonetheless, it is evident that experiments play a major role in validating the results of a particular model.

Improving Our Screening Armamentarium

The importance of hearing screening in newborns is increasingly being recognized.³² Although otoacoustic emission detection has become a popular tool for this purpose, it cannot by itself make the important distinction between conductive and sensorineural hearing loss. Tympanometry is a possible tool for the differential diagnosis but is neither sensitive nor specific for newborns.³³ There is some evidence that high-frequency and/or wideband measurements may provide an effec-

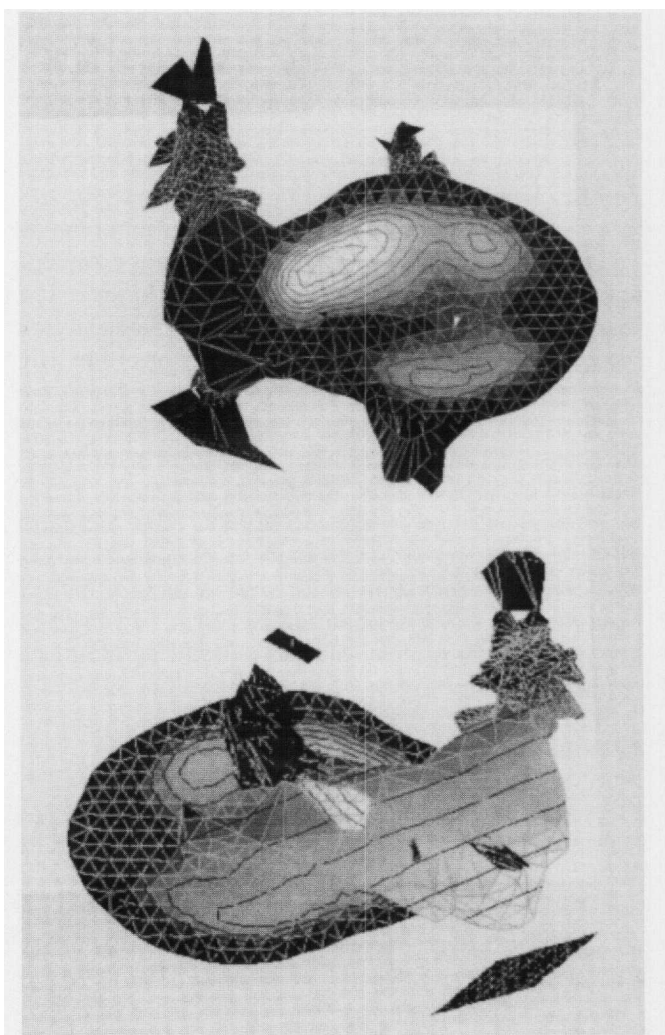


Figure 4 This is a medial and a lateral view of the middle ear and eardrum demonstrating the simulated vibration pattern at low frequencies. Displacements are qualitatively illustrated, with smaller displacements coded in darker colours and larger displacements in lighter colours.

tive test for newborns, but considerable research is still required.³⁴⁻³⁶ Finite-element modelling of the acoustics and mechanics of the newborn middle ear will make it possible to extract more diagnostic information from impedance and reflectance measurements and can also contribute toward developing improved diagnostic tools. This stems from the fact that an accurate model will predict what happens to the pliable external auditory canal and tympanic membrane of the newborn from a dynamic and biomechanical perspective, making it easier to understand the output of the system.

Assess Influence of Diseases on Hearing

Three-dimensional finite-element models can simulate various clinical conditions as parameters in the model can be modified to simulate various clinical scenarios. This includes, among others, ossicular erosion or fixation, sclerosis of the ossicular ligaments, and study of the acoustic effects of perforations in different locations of the tympanic membrane. An example was presented this year at the Association for Research in Otolaryngology meeting, where we showed that fixation of the anterior malleolar ligament affected the magnitude of ossicular displacement. This may explain the conductive hearing loss found clinically in a patient in whom the only anomaly on tympanotomy was calcification and fixation of the aforementioned ligament.²³

Preoperative Planning and Postoperative Assessment

Currently, the ossicular replacement prosthesis is often chosen in the operating room depending on what the exploratory tympanotomy reveals and the available prosthetic models. Our long-term aim is to be able to obtain a high-resolution computed tomography scan of the affected individual's ear, import the images into our finite-element model, and generate an individualized model. The model will then help to determine the most suitable prosthesis in terms of material properties and geometric shape and predict the sound transmission capacity that can be obtained. A complete model may also help us to understand the surprisingly good performance of some ears after surgery and the surprisingly poor performance of others.

Limitations of the Model

The main drawback of many previous ear models stems from the fact that the modelled normal ears do not behave the same way as pathologic ears. This does not apply to our model. In fact, the strength of our model stems from the ability to modify the variables in the system to precisely mimic any pathologic condition desired and therefore predict its behaviour.

One area that is currently being further studied is the behaviour of the model at high frequencies. This is an active area of research, and more data will be available in the near future.

Conclusion

The current model is unique in that it is the first human middle ear model that uses very precise anatomic data obtained from a combination of phase-shift moiré shape measurements, histologic serial sections, and MRM data. The model allows us not only to visualize the mechanics of the middle ear but also to change variables in the system (eroding ossicles, adding prostheses, etc.) to see how this will affect the dynamics of the system. Therefore, we can appreciate the importance of this model not only in terms of understanding the mechanics of the human middle ear but also for its clinical applications.

We foresee that this model will have a major impact in hearing research in the long term as it allows us to better understand the mechanics and acoustics of the middle ear and thus devise a better ossicular prosthesis based on biomechanical properties of the middle ear and to individualize the treatment of patients according to their anatomy.

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