Modeling sound transmission of human middle ear and its clinical applications using finite element analysis

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Abstract We have developed a new finite element (FE) model of human right ear, including the accurate geometry of middle ear ossicles, external ear canal, tympanic cavity, and mastoid cavity. The FE model would be suitable to study the dynamic behaviors of pathological middle ear conditions, including changes of stapedial ligament stiffness, tensor tympani ligament (TTL), and tympanic membrane (TM) stiffness and thickness. Increasing stiffness of stapedial ligament has substantial effect on stapes footplate movement, especially at low frequencies, but less effect on umbo movement. Softer TTL will result in increasing umbo and stapes footplate displacement, especially at low frequencies ($f < 1000$ Hz). When the TTL was detached, the vibration amplitude of umbo increased by 6 dB at 600 Hz and two peaks (300 and 600 Hz) were found in the vibration amplitude of stapes footplate. Increasing the stiffness of tensor tympani resulted in a slightly decreased umbo amplitude at very low frequencies ($f < 500$ Hz) and significantly decreased displacement up to 12 dB at middle frequencies (1000 Hz $< f < 4000$ Hz). However, the amplitude change of stapes footplate is very sensitive to the TTL stiffness, especially at low frequency ($f < 1000$ Hz). The increased stiffness of TM resulted in reduced umbo and stapes footplate displacement at frequencies $<1500$ Hz and increased displacement at frequencies $>1500$ Hz. As (TM) thickness was increased, the umbo displacement was reduced, especially at very low frequencies ($f < 600$ Hz). Otherwise, the stapes displacement was reduced at all frequencies.

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Introduction

The human middle ear consists of the tympanic membrane (TM), three auditory ossicles (malleus, incus, and stapes), ligaments/tendons, the tympanic cavity, and the mastoid cavity. Sound collected in the ear canal and passed to the middle ear through the TM initiates the acoustic—mechanical transmission in the ear [1]. The middle ear functions as an impedance matching device between the low impedance of air and high impedance of cochleae fluid. The primary transfer function of the middle ear describes the efficiency with which sound energy is transferred from air to the fluid within the cochlea [2]. A number of parameters, such as the shape and stiffness of the TM, shape and volume of the external ear canal, and volume and pressure of the middle ear cavity, directly affect the acoustic—mechanical transmission through the middle ear. Changes in these parameters are often related to pathophysiological conditions of the ear. Disruption to the middle ear structure will cause a reduction of the efficiency of the middle ear transfer function [3].

Finite element (FE) analysis is a computer simulation technique used in engineering and biomechanical analysis. The first FE model of the cat ear drum was reported by Funnell and Laszlo [4]. Since then, FE modeling of middle ear biomechanics has become a rapidly growing area of research. A thorough literature survey of the FE modeling of ear mechanics was summarized in Sun et al.’s publication [5]. The FE analysis approach provides a useful tool to simulate accurately the anatomical structures of the middle ear by breaking them down into many simple elements. Behavior of each individual element can be described with a relatively simple set of equations. Finally, middle ear function can be calculated by combining the individual elements.

The advent of high-resolution computed tomography (HRCT) made it possible to perform virtual instead of physical sectioning, and computer assistance facilitated the construction of reliable three-dimensional (3D) mathematical anatomic models. Using the combined technologies of FE analysis and 3D reconstruction of the middle ear from HRCT, we developed an FE model of the human middle ear with TM, ossicular bone, middle ear ligament, and middle ear boundaries [6]. This model was validated by comparing its data with published experimental measurements, and it was tested in several otological applications [7, 8]. In 2009, we extended a new FE model of human right ear including the accurate geometry of middle ear ossicles, external ear canal, tympanic cavity, and mastoid cavity [9]. The model was then validated by comparing the results with published experimental measurements [10, 11]. Acoustic—structural coupled analysis was performed to determine the function of human middle ear and some otological applications.

Materials and methods

HRCT of temporal bone

In this study, HRCT scanning was performed in a 47-year-old man with normal hearing and no previous otological disorders. Otoscopic evaluation and pure tone audiometry were performed prior to HRCT examination. Temporal bone images obtained from the right ear were used for evaluation and reconstruction. The parameters of HRCT were described in our previous reports [6]. Characteristic dimensions of the middle ear components were measured from the geometric model and compared with the published anatomic data and the data from our previous middle ear model [6].

A 3D FE model of the middle ear

To prepare for FE analysis of the middle ear, the 3D model was translated into Patran (MSC Software, Perth, Australia) and ANSYS (ANSYS Inc., Canonsburg, PA, USA), two commercially available FE modeling packages. On the basis of the model, FE meshes of the ear were created using Patran. To facilitate the acoustic—structural coupled analysis, the mesh of the FE model was slightly modified in this study. The TM was meshed using three layers with a total of 4293 eight-node hexahedral solid elements instead of the shell element, because the coupled analysis requires the TM to be a 3D solid structure. Using one layer of shell element with acoustic—structure interfaces (FSIs) on both sides does not work because each node in the shell element would have the same pressure on each side of the shell. Finally, the vibration amplitudes in a mathematical model would be more precise and reasonable than one layer. Accordingly, the tympanic annulus was meshed using three layers with a total of 408 eight-node hexahedral solid elements instead of shell elements. Other meshes of the FE model remained the same as in our previous middle ear model [6]. The ossicles, ligaments, and tendons are considered to be isotropic materials, whereas the TM is considered to be an orthotropic material. Mechanical properties of the TM, ossicles, and joints in the model were adopted based on the results reported by Gan et al. [1]. Structural boundaries of the middle ear include the tympanic annulus, middle ear suspensory ligament, stapedial annular ligament, and cochlear fluid. Poisson’s ratio was assumed to be 0.3 for all materials of the middle ear system. The element-damping matrix for the solid elements was expressed by

\[
[C] = \alpha[M] + \beta[K]
\]

where \([M]\) and \([K]\) were element mass and stiffness matrices of the solid and shell elements, respectively, and \(\alpha\) and \(\beta\) were the damping parameters. The action of the cochlear fluid on the stapes footplate was modeled as a set of 49 spring—dashpot elements distributed on the footplate, as in our previous work [6]. Fig. 1A shows the FE model of the human right ear including the external ear canal, ossicles with attached ligaments/muscles, and tympanic cavity. Fig. 1B shows the extended middle ear FE model to the aditus, mastoid antrum, and mastoid cavity. The tympanic cavity and mastoid cavity were displayed transparently.

FE analysis

The acoustic analysis in ANSYS (ANSYS Inc.) programs involves modeling of only the fluid medium and the
surrounding structure [9]. A coupled acoustic analysis takes the fluid–structure interaction into account. The acoustic pressure in the fluid medium is determined by the wave equation. The interaction of the fluid and the structure at a mesh interface caused the acoustic pressure to exert a force applied to the structure and the structure motion produces an effective fluid load. The governing FEM matrix equations produce the following:

\[
\begin{bmatrix}
M_s & 0 \\
p_0 R & M_f
\end{bmatrix}
\begin{bmatrix}
\dot{U} \\
p
\end{bmatrix}
+
\begin{bmatrix}
K_s & -R \\
0 & K_f
\end{bmatrix}
\begin{bmatrix}
U \\
p
\end{bmatrix}
=
\begin{bmatrix}
F_s \\
F_f
\end{bmatrix}
\] (2)

\(P\) and \(U\) are the fluid pressure and the structure displacement, respectively. \(M_s\) is the structure mass matrix and \(K_s\) is the structure stiffness matrix. Correspondingly, \(M_f\) is the fluid mass matrix, \(p_0\) is the fluid density, and \(K_f\) is the fluid stiffness matrix. \(F_f\) is the applied fluid pressure vector at the interface obtained by integrating the pressure over the area of the surface. \(R\) is a coupling matrix that represents the effective surface area associated with each node on the FSI. Both the structural and acoustic load quantities that are produced at the acoustic–structure interface are functions of unknown nodal degree of freedom. Equation (2) implies that nodes on an FSI have both displacement and pressure degree of freedom. The coupling matrix \(R\) also takes into account the direction of the normal vector defined for each pair of coincident acoustic and structural element faces that comprise the interface surface. The ear consists of a solid structure and acoustic media that belong to different engineering disciplines and result in different boundary conditions. Air in the external ear canal and inside the middle ear cavity was modeled as an acoustic element and governed by an acoustic wave equation under the assumptions that the fluid is compressible and inviscid with uniform mean density and pressure:

\[
\frac{1}{C^2} \frac{\partial^2 P}{\partial t^2} = \nabla^2 P \tag{3}
\]

where \(P\) is the acoustic pressure, \(C\) is the speed of sound and \(C = \sqrt{\kappa / p_0}\) in the fluid medium (where \(p_0\) is the mean fluid density and \(\kappa\) the bulk modulus of fluid), and \(t\) is the time. The speed of sound and density of air were assumed as 343 m/s and 1.2 kg/m\(^3\), respectively. The acoustic absorption coefficient of FSI (\(\mu\)) is defined as the fraction of absorbed acoustic energy to total incident energy [1,5]. The absorption coefficient values are 0.007 (TM), 0.02 (canal wall), 0.04 (cavity wall), 0.04 (ossicles), and 0.02 (ligament/muscles) [1].

Validation of the FE model

The FE model was first tested and validated by comparing the responses of the middle ear system to harmonic pressure on the lateral surface of the TM between the FE analysis and published experimental measurements [9]. An SPL of 120 dB (20 Pa) applied to the canal, which was the same as in McElveen’s experiments; the harmonic analysis was conducted on the model over a frequency range of 200–8000 by using ANSYS. McElveen et al. [11] conducted a total of six temporal bone experiments to study the effect of mastoid cavity modification on middle ear sound transmission. Measurements of umbo displacement were made at 200-Hz intervals from 500 to 7000 Hz at the TM. After the initial baseline umbo displacement measurements, the

Figure 1. (A) Finite element model of human right ear including tympanic membrane, ossicles (malleus, incus, and stapes), suspensory ligament/muscles, tympanic annulus, Eustachian tube, external ear canal (large arrow), and tympanic cavity (arrow head) in anterior view. The tympanic cavity was expressed in transparency. (B) Finite element model of human right ear including tympanic membrane, ossicles (malleus, incus, and stapes), suspensory ligament/muscles, tympanic annulus, external ear canal (large arrow), Eustachian tube, tympanic cavity (arrow head), and mastoid cavity (small arrow) in anterior view. The middle ear cavity was expressed in transparency.
aditus and antrum were blocked with a saline-filled balloon (Fogarty catheter), inserted through a hole in the tegmen made prior to taking the measurements and closed with clay. The balloon was inflated, the hole on the tegmen was closed with clay, and the measurement was repeated. Peak-to-peak umbo displacement, aditus open versus closed in McElveen’s human temporal bone 3 was used for model validation. Compared with McElveen’s experiments and our previous FE model [6], the present model provides more accurate predictions on transfer function of the middle ear [9]. Thus, the FE model would be suitable to study the dynamic behaviors of normal or pathological middle ear including changes of stapedial ligament stiffness, TTL, and TM stiffness and thickness.

To simulate the stapedial ligament fixation and tensor tympani ligament (TTL) fixation, the Young’s modulus of the normal stapedial ligament and TTL was increased by a factor of 10−100. To simulate the detachment of TTL, the Young’s modulus of the normal TTL was decreased by a factor of 0.1 and 0.01. The results of all calculations performed are applying 90 dB SPL (0.6324 Pa) sound at the TM.

Results

Otological applications of the FE model

Change of stapedial ligament stiffness
Effect of material properties of stapedial ligament on dynamic behaviors of the middle ear was examined using the FE model. Fig. 2 shows the frequency response curve of malleus (Fig. 2A) and change in stapes footplate (Fig. 2B) displacements in dB predicted by the FE model when the Young’s modulus (10× normal Young’s modulus and 100× normal Young’s modulus) of stapedial ligament was changed. As can be seen in this figure, the material properties of stapedial ligament have substantial effect on stapes footplate movement, especially at low frequencies, but less effect on umbo movement. This might be due to the fact that less sound energy was transported to the stapes through the stiffer stapedial ligament, reducing the amplitude significantly. However, the umbo displacement was slightly reduced.

Change of TTL
Effects of TTL detachment or stiffness change on stapes footplate and umbo movement were tested using the validated FE model. Fig. 3 shows that softer TTL will result in increasing umbo (Fig. 3A) and stapes footplate (Fig. 3B) displacement, especially at low frequencies (f < 1000 Hz). When the TTL was detached, the amplitude of umbo increased by 6 dB at about 600 Hz and two peaks (300 and 600 Hz) were found in the amplitude of stapes footplate. One explanation of this phenomenon is that different vibration modes will appear when TTL is detached. Fig. 4 shows the vibration amplitude change (in dB) of umbo (Fig. 4A) and stapes footplate (Fig. 4B) in response to TTL stiffness changes. As can be seen in Fig. 4A, the increase of stiffness resulted in a slightly decreased umbo amplitude at very low frequencies (f < 500 Hz) and significantly decreased displacement up to 12 dB at middle frequencies (1000 Hz < f < 4000 Hz). However, as seen in Fig. 4B, the amplitude change of stapes footplate is very sensitive to the TTL stiffness, especially at low frequency (f < 1000 Hz).

Change of TM stiffness or thickness
Effects of TM stiffness or thickness change on umbo and stapes footplate movement were also tested by using the FE model. Fig. 5 shows the amplitude change of umbo and stapes footplate in response to TM stiffness change. Young’s modulus was increased by a factor of 10 and 100 for TM in pars tensa and pars flaccida. As can be seen, the amplitude changes of umbo (Fig. 5A) and stapes footplate (Fig. 5B) are sensitive to TM stiffness. Increased stiffness resulted in reduced umbo and stapes footplate displacement at frequencies < 1500 Hz and increased displacement at frequencies > 1500 Hz. Fig. 6 shows the amplitude change of umbo (Fig. 6A) and stapes footplate (Fig. 6B) when average thickness of TM was changed by a factor of 5 and 10. The normal thickness used for FE model in this study was 0.1 mm. As TM thickness was increased, the umbo displacement was reduced, especially at very low frequencies (f < 600 Hz). Otherwise, the stapes displacement was reduced at all frequencies. These results
suggest that thickened TM after chronic middle ear inflammation or surgical treatment of TM perforation has negative effect on the movements of umbo and stapes footplate.

**Discussion**

The aim of middle ear modeling is to simulate the acoustic structure of the middle ear and its transfer function from the ear canal through ossicles into the inner ear. The FE model of human ear in this study was built from HRCT images; thus, the model was characterized by accurate structure dimensions and geometric shapes of the middle ear, external canal, tympanic cavity, and mastoid cavity. Compared with McElveen's experiments and our previous FE model [6], the present model can provide accurate predictions on transfer function of the middle ear. The validated FE model was constructed for several ontological applications to predict changes of stapedial ligament stiffness, TTL, and TM stiffness and thickness.

Our results suggest that the FE model is potentially useful in the study of middle ear biomechanics [12], and design and testing of middle ear implants and implantable hearing devices [13–15]. Validation is an important procedure to verify the validity of the newly developed FE model in order to ensure that the model simulates the physiological and some pathological conditions of the middle ear accurately [3]. In addition, FE model validation process can also be used to determine the unknown parameters and material properties used in the FE model. FE models provide a useful tool for investigating the characteristics of the middle ear system and improving our understanding of its mechanical function. Furthermore, FE models of the middle ear can also be used to simulate and evaluate the pathological changes in the conditions of middle ear disorders [16]. In the studies by Gan et al., thickness and stiffness of the TM were simulated using the FE model. As TM thickness was increased from 0.05 to 0.2 mm, stapes footplate displacement was reduced, especially at low frequencies (f < 1000 Hz). Their results also showed that increased stiffness reduced stapes footplate displacement at

![Figure 3](image1.png)

**Figure 3.** (A) Effects of TTL detachment on dynamic behaviors of umbo. The Young’s modulus was increased by a factor of 0.1 for this model. Detachment of TTL was performed. (B) Effects of TTL detachment on dynamic behaviors of stapes footplate. The Young’s modulus was increased by a factor of 0.1 for this model. Detachment of TTL was performed. TTL = tensor tympani ligament.

![Figure 4](image2.png)

**Figure 4.** (A) Effect of material properties of TTL on dynamic behaviors of umbo. The Young’s modulus was increased by a factor of 10 and 100 for this model. (B) Effect of material properties of TTL on dynamic behaviors of stapes footplate. The Young’s modulus was increased by a factor of 10 and 100 for this model. TTL = tensor tympani ligament.
frequencies <1500 Hz and increased displacement at frequencies >1500 Hz. The same results were reported by Gan et al.’s FE model [1].

It would be possible to predict how middle ear function is affected by various kinds of middle ear pathologies and to understand how individual differences in middle ear structures affect that function prior to surgery. The model could be further improved in several aspects, such as finding more accurate boundary conditions and adding the structure of cochlea and the cochlear fluid into the model [1]. An overall thickness of TM of 0.1 mm was adopted in our model. Fay et al. [12], in their study, incorporated the measurement of the geometry of the ear canal, 3D asymmetrical geometry of the eardrum, and details of the eardrum fiber structure. To develop a more comprehensive 3D FE model of human ear for multifield FE analysis using detailed TM structures and coupling the current FE model is our next goal. Further studies are needed focusing on how the alteration in structure, pathology, collagen fiber layer in TM, and different air volume sizes of mastoid cavity will affect the acoustic–mechanical transmission through the ear canal and middle ear to the inner ear.

References


