Numerical simulation of the human ear and the dynamic analysis of the middle ear sound transmission

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Numerical simulation of the human ear and the
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\textbf{ABSTRACT:} Based on the clinical CT of normal right ear, a 3-D finite element (FE) model of the human ear consisting of the external ear canal, middle ear (tympanic membrane, ossicular chain, ligaments, tendons), and inner ear (including semicircular canals, vestibular, spiral cochlear) was constructed in this paper. The complicated structures and inner boundary conditions of middle ear were described in this model. Model analysis and acoustic-structure-fluid coupled dynamic frequency response analysis were conducted on the model. The validity of this model was confirmed by comparing the results with published experimental data. The amplitudes and velocities of tympanic membrane and stapes footplate, sound pressure gain across the middle ear, and the cochlear input impedance were derived. Besides, it was concluded that the ear canal can amplify the sound signal in low frequencies. The modes of vibration of middle ear auditory ossicles, oval window and round window have been analysed. This model can well simulate the acoustic behavior with the interaction of external ear, middle ear and inner ear, which can supply more valuable theoretical support for development and improvement of hearing-aid and artificial inner ear.

\textbf{KEYWORDS:} Medical-image reconstruction methods and algorithms, computer-aided so; Simulation methods and programs; Image reconstruction in medical imaging; Computerized Tomography (CT) and Computed Radiography (CR)

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1 Introduction

Life science is one of the foundation natural science most concerned about in the world. It has been a hot spot that mature mechanics and structural engineering analysis thought have been applied to research and analysis of body structure. The middle ear of human body is a typical conduction vibration structure excited by acoustic waves. Sound conduction is a complicated dynamic transmission process combined with solid dynamics and fluid dynamics.

Use mechanics principle to study the human ear structure began at the end of of the 20th century. On one hand, analytic equation has been derived by mechanics theory, such as mathematical physics equation of basement membrane and cochlear wall [1], partial differential equation of ear cavity gas diffusion [2], tympanic membrane vibration equation and analysis method of artificial auditory ossicle detection [3, 4]. On the other hand, finite element simulation and analysis is hot research. In 1992, Wada et al. [5] established finite element model including tympanic membrane and auditory ossicle chain, and used the experiment to measure mechanics properties of the middle ear tendon [6]. With the development of imaging technology, people used CT scan and MRI nuclear magnetic resonance imaging to obtain anatomical structure data of middle ear in human
physiological state, and constructed entity model in exaggerated scale [7–9]. In 1998, E. W. Abel et al. reported using magnetic resonance to get auditory ossicle chain image, and establish finite element model by using the image to measure size dimension [10]. In 1999, Predergast et al. created a simple three dimension finite element model of the middle ear [11]. From 2002 to 2004, Takuji and Gan [12, 13] established three dimension finite element model of middle ear and the whole ear by tissue slice, and acoustic — solid-liquid coupling calculation was made by this model.

Since human ear structure is intricate, the finite element model established has been improved continuously, from replacing cochlear function by equivalent mass, spring and damper unit to simplified cochlea. So far, cochlear in the whole numerical model of hearing system at home or abroad [14–19] has all been simplified, namely basement membrane without cochlear niche or rectilinear basement membrane.

In view of this, this paper established the finite element model of the real whole ear (including outer ear, middle ear, and inner ear including scala vestibuli, scala tympani, and basement membrane with three dimensional helical structure), and gas-solid-liquid coupling analysis, modal analysis and harmonic response analysis were made for ear structure. The model reflected complicated mutual relationship of each part, besides, the interosseous membrane and bone were specially handled in order to make the simulation more realistic. Dynamics characteristic parameters were analysed, such as tympanic membrane vibration, stapes foot plate vibration, middle ear pressure gain, cochlear impedance and so on. Effects of external ear and inner ear on sound transmission mechanism were studied, and vibration mode of ossicles, ossicular chain, round window, oval window were obtained.

2 Methods

2.1 Establishment of the middle ear FE model

Based on the normal human right ear specimen supplied by Zhongshan Hospital of Fudan University, imaging experiment was made using synchrotron radiation X ray in Shanghai Synchrotron Radiation Facility (SSRF), Chinese Academy of Sciences, combined with CT scan images from Zhongshan Hospital of Fudan University on the normal human middle ear. By further treatment of the image, three-dimensional finite element model of human ear structure (including external auditory canal gas, tympanic membrane, middle ear ossicular chain, ligament tendons of middle ear, and inner ear including scala vestibuli, scala tympani, and basement membrane with three dimensional helical structure). The model was divided into grid, and its boundary conditions and the material parameters were defined, and a three-dimensional finite element model of human ear structure was obtained in NASTRAN (As is shown in figure 1, 2, 3, 4).

3 Units setup

The gas in the external ear canal is meshed by 7200 eight-noded hexahedral (Hex8) fluid elements. The number of nodes is 7581. The tympanic membrane is meshed by 30 three-noded triangular (Tria3) two-dimensional membrane elements and 330 four-noded quadrangular (Quad4) two-dimensional membrane elements. The number of nodes is 360. The ossicular bones, all ligaments and tendons are meshed by 21438 four-noded tetrahedral (Tet4) solid elements. The number of nodes is 6065.
In order to simulate transfer relationship between bones and particularity of bone in sound process, bone membrane was simulated by interface unit in the model. MPC unit (Multi-point constraints unit) was made between posterior incudal ligament and malleus side in order to connect malleus and incus. Four-noded tetrahedral (Tet4) solid elements were made around MPC elements, in order to make certain movement between malleus and incus in order to solve the special problems such as joints make torsion and relative movement in sound transmission.

Grid division of inner ear structure was as follows: the fluid near stapes in vestibule is meshed by four-noded tetrahedral (Tet4) fluid elements, and the other fluid is meshed by eight-noded hexahedral (Hex8) fluid elements. The total number of fluid elements is 4391, and the number of node is 6817. All the fluid elements properties were defined as fluid material properties. The width of basement membrane near stapes footplate is 0.1mm, and the thickness is 0.0075mm. The width of
basement membrane near cupula cochleae is 0.5 mm, and the thickness is 0.0025 mm. Basin-  
membrane is meshed by 400 quadrangular (Quad4) two-dimensional membrane elements. 
Oval window is meshed by 56 two-dimensional membrane, and the total number of node is 37. 
Round window is meshed by 16 two-dimensional membrane, and the total number of node is 25.

4 Boundary conditions

(1) Uniform pressure of 90 dB SPL (0.632 Pa) was applied on the opening surface of the external 
ear canal (from 200 Hz to 10000 Hz) in order to simulate pressure stimulation of pure tone, 
as was shown in figure 4.

(2) The stiffness of external ear canal wall is larger than those of air and tympanic membrane, 
and it can be regarded as rigid wall. The gas element in the external ear canal was re-
strained rigidly.

(3) Tympanic membrane annular ligament around tympanic membrane was embedded into the 
bone wall tympanic antetheca. Therefore, peripheral nodes of tympanic membrane annular 
ligament were fixed, and displacement in each direction was zero. The positions of soft tissues 
tensor tympani, superior malleolar ligaments, anterior malleolar ligaments, lateral mallear 
ligament, superior incudal ligament, posterior incudal ligament, stapedial tendon) associated 
with the temporal bone were defined as the fixed constraint;

(4) One end of tensor tympani, superior malleolar ligaments, anterior malleolar ligaments, lateral 
mallear ligament, superior incudal ligament, posterior incudal ligament, stapedial tendon was 
connected with auditory ossicles, and the other end is connected to tympanic wall. The end 
connecting ligaments and tympanic wall in finite element model were defined as the fixed 
constraint.

(5) Inward flange of stapes annular ligament was connected with outer edge of stapes footplate. 
The stapes annular ligament was embedded into bone wall of tympanic cavity, at the oval 
window. Inward flange of stapes annular ligament was connected with stapes footplate, and 
outer edge was defined as the fixed constraint in the finite element model.

(6) Oval window membrane was at oval window membrane, and oval window membrane was 
closed. Outer edge of oval window was embedded in the bone wall, at outer edge of 
shapes annular ligament. The shapes of stapes annular ligament and outer edge of oval 
window membrane are same in the model, and the peripheral nodes were defined as the fixed constraint.

(7) Round window was behind oval window membrane, and it is embedded in the bone wall of 
tympanic cavity. The outer side is middle ear cavity, and inner side is lymph in scala tympani. 
Peripheral nodes around round window membrane were defined as fixed constraint.

(8) Both ends of basement membrane were defined as the fixed constraint.

(9) Tympanic membrane, stapes footplate, annular ligament, and basement membrane were 
fluid-structure coupling interfaces.
5 Material properties

6 Gas-solid-liquid coupling control equation of hearing system

Control equation of sound field is as follows:

\[
\frac{1}{C^2} \frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \quad \text{Internal sound field} \quad (6.1)
\]

\[
\left( \frac{r}{\rho_0 C} \right) \frac{1}{C} \frac{\partial P}{\partial t} = 0 \quad \text{Fixed interface} \quad (6.2)
\]

\[
\{n\} \cdot \{\nabla P\} = P_0 \quad \text{Free interface} \quad (6.3)
\]

\[
\{n\} \cdot \{\nabla P\} = -\rho_0 \{n\} \cdot \frac{\partial^2 \{u\}}{\partial t^2} \quad \text{Coupling interface} \quad (6.4)
\]

In the equation above, \(C\) is sound velocity, \(P\) is sound pressure, \(r\) is acoustic absorptivity, \(n\) is direction cosine at the interface, \(P_0\) is initial pressure, \(\rho_0\) is air density, \(t\) is time, \(u\) is solid displacement of fluid-structure coupling interface.

Governing equation of solid is as follows:

\[
\nabla \sigma + b + c \dot{u} = \rho_1 \ddot{u} \quad \text{In solid} \quad (6.5)
\]

\[
\sigma_{ij}n_j = f \quad \text{Force boundary} \quad (6.6)
\]

\[
\sigma_{ij}n_j = Pn_k \quad \text{Fluid structure interaction surface} \quad (6.7)
\]

\[
u = \bar{u} \quad \text{Displacement boundary} \quad (6.8)
\]

In the equation above, \(\sigma\) is tensor of stress for solid, \(b\) is physical vector, \(c\) is damping coefficient, \(\rho_1\) is solid density, \(f\) is solid surface force, \(\bar{u}\) is initial displacement of solid.

Eq. (6.4) is fluid-structure interaction interface boundary condition, which represents the relation between the normal acoustic pressure gradient of momentum equation of fluid and normal acceleration of solid. Thus, by means of eq. (6.4), the discretized control equation of sound field with consideration of sound-structure interaction can be obtained. On this basis, the finite element equation of fluid structure interaction can be derived as follows, according to the aforementioned governing equations of sound field and solid.

\[
\begin{bmatrix}
[M] & [0] \\
[M^{fs}] & [M^P]
\end{bmatrix}
\begin{bmatrix}
\{\dot{u}\} \\
\{\dot{P}\}
\end{bmatrix} +
\begin{bmatrix}
[C] & [0] \\
[0] & [C^P]
\end{bmatrix}
\begin{bmatrix}
\{\ddot{u}\} \\
\{\ddot{P}\}
\end{bmatrix} +
\begin{bmatrix}
[K] & [K^{fs}] \\
[0] & [K^P]
\end{bmatrix}
\begin{bmatrix}
\{u\} \\
\{P\}
\end{bmatrix} =
\begin{bmatrix}
\{F\} \\
\{0\}
\end{bmatrix} \quad (6.9)
\]
Table 1. Material properties used for the middle ear structure in the finite element model [13, 18].

<table>
<thead>
<tr>
<th>Structure</th>
<th>Young’s Modulus (Pa)</th>
<th>Density (kg.m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM pars tensa</td>
<td>3.34×10⁷</td>
<td>1.2×10³</td>
</tr>
<tr>
<td>TM pars flaccida</td>
<td>1.11×10⁷</td>
<td>1.2×10³</td>
</tr>
<tr>
<td>Tympanic annulus ligament</td>
<td>6.0×10⁵</td>
<td>1.2×10³</td>
</tr>
<tr>
<td>First connection between TM and malleus</td>
<td>3.4×10⁷</td>
<td>1.2×10³</td>
</tr>
<tr>
<td>Second connection between TM and malleus</td>
<td>3.4×10³</td>
<td>1.2×10³</td>
</tr>
<tr>
<td>Malleus head</td>
<td>2.55×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Malleus neck</td>
<td>4.53×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Malleus handle</td>
<td>3.7×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Incus body</td>
<td>2.36×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Incus short process</td>
<td>2.26×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Incus long process</td>
<td>5.08×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Incudostapedial joint</td>
<td>1.2×10³</td>
<td>6.0×10⁵</td>
</tr>
<tr>
<td>Stapes</td>
<td>2.2×10³</td>
<td>1.41×10¹⁰</td>
</tr>
<tr>
<td>Superior mallear ligament</td>
<td>2.5×10³</td>
<td>4.9×10⁶</td>
</tr>
<tr>
<td>Lateral mallear ligament</td>
<td>2.5×10³</td>
<td>6.5×10⁶</td>
</tr>
<tr>
<td>Anterior mallear ligament</td>
<td>2.5×10³</td>
<td>2.1×10⁷</td>
</tr>
<tr>
<td>Superior incudal ligament</td>
<td>2.5×10³</td>
<td>4.9×10⁶</td>
</tr>
<tr>
<td>Posterior incudal ligament</td>
<td>2.5×10³</td>
<td>6.5×10⁶</td>
</tr>
<tr>
<td>Tensor tympani tendon</td>
<td>2.5×10³</td>
<td>2.6×10⁶</td>
</tr>
<tr>
<td>Stapedial tendon</td>
<td>2.5×10³</td>
<td>5.2×10⁵</td>
</tr>
<tr>
<td>Stapedial annulus ligament</td>
<td>1.2×10³</td>
<td>4.9×10⁵</td>
</tr>
<tr>
<td>Oval window</td>
<td>1.2×10³</td>
<td>0.2×10⁵</td>
</tr>
<tr>
<td>Round window</td>
<td>1.2×10³</td>
<td>0.35×10⁵</td>
</tr>
<tr>
<td>Basement membrane</td>
<td>1.0×10³</td>
<td>2.0×10⁵</td>
</tr>
</tbody>
</table>

Table 2. Acoustic properties of ear components.

<table>
<thead>
<tr>
<th></th>
<th>Density kg/m³</th>
<th>Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>1.2</td>
<td>340</td>
</tr>
<tr>
<td>Fluid in cochlea</td>
<td>1000</td>
<td>1400</td>
</tr>
</tbody>
</table>

Basic equation of contact surface (suppose thickness of contact elements is zero):

\[
\begin{bmatrix}
\tau_x \\
\tau_y \\
\sigma_n
\end{bmatrix} =
\begin{bmatrix}
K_s & 0 & 0 \\
0 & K_{ss} & 0 \\
0 & 0 & K_n
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta v \\
\Delta w
\end{bmatrix} =
[D]
\begin{bmatrix}
\Delta u \\
\Delta v \\
\Delta w
\end{bmatrix}
\]

(6.10)
Based on the above sound field theoretical basis and control equation of fluid-structure interaction, the definition of fluid-structure interface and the solution process is achieved and completed by Patran and Nastran software in this paper.

7 Dynamics behavior analysis of human ear and model verification

7.1 Stapes footplate velocity transfer function

Aibara et al. [20] used Laser Doppler Vibrometer to collect stapes velocity data of 11 fresh temporal bone samples, and draw the frequency curve of stapes speed transfer function (SVTF) in order to characterize acoustical transmission of middle ear. Sound pressure near eardrum $P_{TM}$ and vibration velocity of stapes footplate $v_s$ were obtained, $SVTF$ curve of finite element model was calculated according to equation 13. The comparison between calculation results and the experimental results was made in figure 5, the value of $SVTF$ rised in the low frequency phase, and dropped in high frequency phase. The peak value appears at $f = 1000$ Hz.

$$SVTF = \frac{V_{FP}}{P_{TM}}$$ (7.1)

In the equation above, $V_{FP}$ is stapes velocity, $P_{TM}$ is pressure value near eardrum. The speed of Node 5695 at the stapes footplate was selected as calculation result. The pressure on the eardrum is external load pressure (3.56 Pa or 0.632 Pa). Pressure of Node100000 near eardrum in the external ear canal was chosen when calculation of external ear canal was made.

Simulation results in this paper shows that average maximum value of $SVTF$ is 0.33 mm s$^{-1}$/Pa which occurs at 1 KHz. The slope from 100 Hz to 1000 Hz is 6dB/octave (SVTF value decreases when the frequency increases). Figure 5 shows comparison between calculation results of SVTF in the finite element model and SVTF data measured on 11 fresh temporal bones, indicating simulation results and experiment data are very close in trend and amplitude, which further prove the model in the paper is correct.

![Figure 5. Comparison of the stapes footplate velocity transfer function between the FE modle-predicted result and the experimental data.](image)
Figure 6. The model-predicted frequency response curve of the sound pressure gain of middle ear and the experimental data.

The calculating result and the experimental data are very close in trend and amplitude, indicating the model is accurate and meets the demand of predicting structure mechanics characteristics (amplitude, pressure, and vibration velocity, etc.) of human ear.

8 Middle ear pressure gain

Middle ear pressure gain was defined as the ratio of cochlear vestibular pressure to eardrum surface pressure, namely:

$$GME = \frac{P_{SV}}{P_{TM}}$$  \hspace{1cm} (8.1)

In the calculation process, pressure of Node 1000102 near stapes footplate in scala vestibule was the value of $P_{SV}$. External load pressure on the eardrum was $P_{TM}$. Pressure of Node100000 near eardrum in the external ear canal was chosen when calculation of external ear canal was made.

Solid line connecting solid triangle was change of middle ear pressure gain ($GME$) with the change of frequency. The calculation results were compared with experiment data of Aibara [20] and Puria [21]. The total trend of experiment data of Aibara for Middle ear pressure gain ($GME$) is as follows: the slope from 100 Hz to 1200 Hz is 6dB/octave, and the maximum is 23.5dB, which occurs at 1200 Hz. The slope above 1200 Hz is -6dB/octave. The trend of experimental data of Puria et al. is basically the same with that of Aibara, with 6dB/octave rising slope in low frequency, but the drop slope is smaller in high frequency. The trend of Middle ear pressure gain ($GME$) simulated in the finite element model was as follows: in low frequencies (from 100 Hz to 1200 Hz), rising slope is 6dB/octave, and drop slope in high frequencies is smaller, which agrees well with experimental data of Puria.

9 Input impedance of cochlear

In audiology, input impedance of cochlear $Z_c$ is defined as ratio of liquid pressure ($P_{SV}$) near oval window (or in scala vestibule near middle of r stapes footplate) to volume velocity of lymph outside
Figure 7. The model-predicted frequency response curve of the cochlear input impedance and the experimental data.

\[ Z_c = \frac{P_{SV}}{V_{FP}A_{FP}} \]  

(9.1)

Node selection of \( P_{SV} \), \( V_{FP} \) was as above. \( A_{FP} \) is area of stapes footplate (3.52 mm\(^2\) in the model), \( V_{FP} \) is velocity of stapes footplate, \( V_{FP}A_{FP} \) is volume velocity of fluid. \( Z_c \) associates excitation of middle ear to inner ear, damping effect of inner ear on middle ear with the occurrence of auditory.

Dotted line with hollow circle is the change situation of cochlear pressure impedance with frequency in figure 7. Calculation results of the paper were compared with experimental results of Aibara [20], Puria [21], and Merchant [22]. Figure 7 shows the total trend of \( Z_c \) experimental data is as follows: in low frequencies (the values of low frequencies are different) the amplitude of \( Z_c \) is steady, frequency-response curve is similar to straight line. In high frequencies, the amplitude of \( Z_c \) rises, the trends of rising are different. The data of Puria rises at 1000 Hz, data of others rises at 5000 Hz. Data of Aibara and Merchant drop at 7000 Hz. There are some difference between experimental data, but the total trend is the same: \( Z_c \) is small in low frequency, and increases with the increase of frequency. Simulation results of numerical model in this paper accords with the trend, and the value of accords with experimental data of Aibara et al.

10 Vibration mode

At present, resonant frequency of middle ear is about 1000 Hz, which is agreed by most scholars. Therefore, mode of vibration at about 1000 Hz was discussed, which are vibration mode of low frequency \( f_1 = 1027 \) Hz and middle frequency \( f_2 = 1597 \) Hz.

Figure 8 and figure 9 show vibration modes of auditory ossicle chain.

Figure 8 shows first mode of vibration, \( f_1 = 1027 \) Hz, malleus- incus rotates around the point on the posterior incudal ligament near malleus.

Figure 9 shows second mode of vibration, aditory ossicle chain movement at \( f_2 = 1597 \) Hz is obviously different from the first mode of vibration. The characteristic of second vibration mode is that malleus and incus rotate around axis along posterior incudal ligament. According to plan view of figure 10, translational motion of malleus can be obtained. Umbo membranae tympani and malleus move parallelly in the same direction.
Stapes motion combines two forms of motions, like piston motion, but a certain rocking motion and rotation can be observed.

Motion forms of stapes footplate can be observed according to vibration modes of round window membrane: oscillating motion, piston motion, and rotation.

11 Conclusion

Finite element (FE) model of the whole human ear was constructed based on the clinical CT, and the model was validated by relative experimental data. The characteristic of the model is that it simulated left and right inner boundaries of middle ear really. As for left inner boundary, sound stimulation was on the fluid of external ear canal, improving the simplification that sound pressure was on the eardrum. The coupling transmission between gas in external ear canal and eardrum
are considered, better reflecting sound pressure stimulation applying on the middle ear structure (eardrum) after sound transforming from external ear canal to middle ear structure (eardrum). Especially for right inner boundary, inner ear was constructed, including scala media, scala vestibuli, scala tympani, and basement membrane with three dimensional helical structure.

Fluid-solid linkage effect of lymph fluid of cochlea and basilar membrane with spiral cochlea partition, as well as fluid-solid interaction effect between scala vestibule and stapes footplate are reflected really, which better realized the simulation of impedance function of inner ear on middle ear. At the same time, sound transmission function of cochlear organum spirale is better described.

According to vibration modal analysis, characteristics of auditory ossicle chain in low-frequency mode is that malleus- incus rotates around axis connecting posterior incudal ligament and side process of malleus. Characteristics of auditory ossicle chain in intermediate frequency is that malleus and incus rotate around axis along posterior incudal ligament. Stapedial movement is piston movement mostly, accompanied by oscillating motion and rotation.

This model can reflect sound transmission behavior of interaction and auxiliary work between outer ear, middle ear, and inner ear, which supplies reasonable internal boundary conditions. The results can help us have a better understanding of the sound transmission mechanism of human ear, which can supply more valuable theoretical support for development and improvement of hearing-aid and artificial inner ear.

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