# The Natural Vibration Characteristics of Human Ossicles

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**Background:** Recently, a model of the ossicular chain for finite element analysis has been developed. However, the natural vibration characteristics of human ossicles have never been studied. Herein, we investigated the dynamic characteristics of the coupling of in-vivo ossicles using finite element analysis.

**Methods:** The geometry of the ossicular chain was obtained by high-resolution computed tomography of the temporal bone, and a 3D model of the ossicular chain was reconstructed by the medical imaging software, Amira®. The file was then imported into the finite element analysis software, ANSYS®. The natural vibration characteristics of human ossicles were measured by finite element analysis.

**Results:** The characteristic dimensions of the model were measured and compared with previously published data. The malleus resonated to sound stimuli at 3 kHz and 4 kHz; the incus and stapes did not resonate to sound stimuli at any frequency. A coupling of the incus and malleus easily resonated to sound stimuli at 5 kHz. A coupling of the incus and stapes easily resonated to sound stimuli at 3 kHz. The coupling of the ossicular chain easily resonated to sound stimuli at 5 kHz, 6 kHz and 8 kHz.

**Conclusion:** The dynamic characteristics of the ossicular chain were analyzed by finite element analysis method. The characteristics of a free vibration model of the ossicles could be determined, which would be helpful in evaluation and consultation for ossicular prosthesis development.

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**Key words: ossicles, vibration analysis, finite-element method, high-resolution computed tomography**

The human middle ear, including the tympanic membrane and the three auditory ossicles (malleus, incus, and stapes), is the mechanical system for sound transmission from the outer to the inner ear. Vibration of the ossicles generates a wave in the cochlea. An accurate three-dimensional geometric model of the human middle ear is a critical first step in visualizing its spatial structure and carrying our further morphologic studies.

Many quantitative models of the middle ear conduction have been derived to adequately predict some behaviors of the normal and pathologic middle ear.(1-4) Finite element modeling has distinct advantages in modeling the middle ear over circuit models that correspond indirectly with its structure and geometry. Funnell and Laszlo published the first finite element model of the middle ear in 1978,(5) simulating the cat tympanic membrane. With the

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addition of inertial and damping effects and footplate and cochlear impedance to the existing tympanic membrane model,(6) a three-dimensional finite element model of the cat middle ear was later developed.(7) Lesser and Williams created a two-dimensional cross-sectional finite element model of the human tympanic membrane with the malleus and analyzed the static displacements of the tympanic membrane and malleus under a uniform load.(8) Lesser et al. and Williams et al. then examined the effects of several tympanic membrane parameters on the natural frequencies in an finite element model of the human tympanic membrane and the resulting mechanical effects of positioning tissue grafts on reconstructed ossicular chains.(9-11) A three-dimensional finite element model of the middle ear was reported by Wada et al. to investigate vibration patterns at resonance frequencies with characteristics of pressure transmission in normal middle ears and those with pathologic conditions.(12) The finite element models of Beer et al. were based on more accurate middle ear geometry obtained by laser scanning microscopy.(13,14) Prendergast et al. also reported a three-dimensional finite element model of the middle ear,(15) which included the tympanic membrane, the ossicles, and some attached soft tissues. All these models have contributed to a better understanding of human middle ear biomechanics. To the best of our knowledge, the natural vibrations of the ossicles have never been studied.

Herein, we developed a finite element model for analysis of the naturally resonant frequency of in-vivo human ossicles. The characteristics of a free vibration model of in-vivo ossicles could be determined.

## METHODS

The geometry of the ossicles was acquired by computed tomography (CT) imaging of one patient in this study. High-resolution computed tomography (HRCT) of the temporal bone was performed on a 64-slice CT scanner (Aquilion TSX-101 A, Toshiba Medical Systems Corporation, Japan). A 3D model of the ossicles was reconstructed by the medical imaging software, Amira®, version 4.1 (Mercury Computer Systems Inc., Chelmsford, MA, U.S.A.), as shown in Fig. 1. The file format of the 3D model was transformed from the .stl file format into the .sat file format (SAT) by computer-aided design and then the SAT file was imported into the finite element analysis software, ANSYS®. A finite element model of the ossicles was built by adopting the SOLID185 program from ANSYS and by the free meshing method shown in Fig. 2. The repeated nodes between ossicles were assumed to be combined as one single node. The finite element model of the ossicles was then built up. The material parameters for each part of the ossicles were different. Only Poisson’s ratio for the overall structure was assumed to be 0.3 because the parameter used in most studies was quite close to this value. Based on a previous study by Funnell and Laszlo,(16) the analysis of the dynamic characteristics of the ossicles was not affected by Poisson’s ratio significantly. The damping matrix is shown below:

$$[c] = \alpha\,[M] + \beta\,[K]$$

where [M] and [K] indicate the mass matrix and

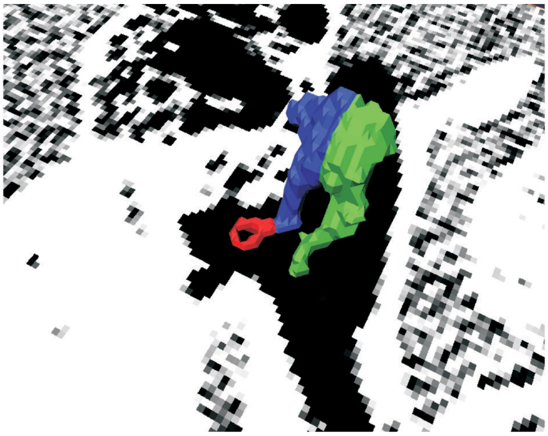

**Fig. 1** A three-dimensional image of in-vivo human ossicles.

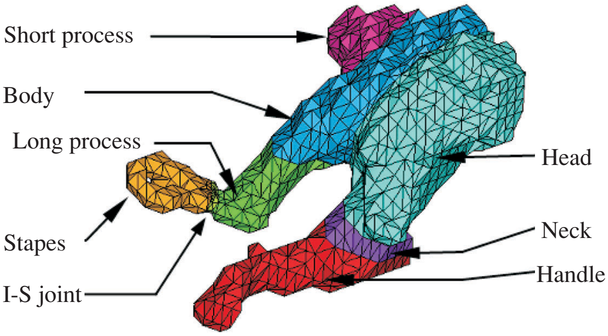

**Fig. 2** A finite element model of the ossicles.

stiffness matrix, respectively; $\alpha$ and $\beta$ indicate the damping parameters.(17) The overall structure consisted of the three ossicles, the joints between the incus and stapes, and the springs on the stapes.

The incudomalleolar joint (I-M joint) was adopted based on previous study which reported that there is no relative motion between the malleus and incus at low frequencies (< 3 kHz). Therefore, the Young's modulus was assumed to be 14.1 GPa. The nodes that connected the malleus and incus were combined into one node in this study. The joints between the incus and stapes were adopted according to a previous study which reported that there is no stiffness displacement on the joints under circumstance of the serious variety of noise and pressure.(18) In addition, there was some relative motion between the incus and stapes. The inner ear was protected and would not be damaged by the large displacement of the stapes footplate. Additionally, the joints between the incus and stapes were assumed to be homogeneous materials and equivalent, and the Young's modulus was 0.6 MPa.(19) The material properties adopted in this study are shown in the Table 1. The analysis focused on 6 combinations of ossicles including individual ossicles, coupled ossicles and the ossicular chain. The naturally resonant frequency and the modal vector were obtained with free-free conditions by the block Lanczos method. Then the solution of the model was obtained by transforming the system to the modal coordinates. The naturally resonant frequencies of the ossicles including the malleus, the incus and the stapes, and the dynamic characteristics of the 6 coupling effects among the ossicles based on audible frequencies at 250/ 500/ 750/ 1k/ 2k/ 3k/ 4k/ and 8k Hz were obtained.

**Table 1.** Material Properties of the Ossicles

| Structure | | D (kg/m$^3$) | E (N/m$^2$) |
|---|---|---|---|
| Malleus | Head | $2.55*10^3$ | $1.41*10^{10}$ |
| | Neck | $4.53*10^3$ | |
| | Handle | $3.70*10^3$ | |
| Incus | Body | $2.36*10^3$ | $1.41*10^{10}$ |
| | Short process | $2.26*10^3$ | |
| | Long process | $5.08*10^3$ | |
| Stapes | – | $2.20*10^3$ | $1.41*10^{10}$ |
| | I-S joint | $1.2*10^3$ | $6*10^5$ |

## RESULTS

A 3D ossicular model was established by finite element analysis using HRCT of the temporal bone (Fig. 2). The three-dimensional model created by the finite element method is close to the bounds of the experimental curves of Nishihara's, Huber's, Gan's, Sun's and Lee's data.(20-24) The vibration charateristics of the ossicles were then analyzed. As shown in Fig. 3, the free vibration at the point of coupling of the umbo of the eardrum and malleus was evaluated at 8 frequencies (250/ 500/ 750/ 1k/ 2k/ 3k/ 4k/ and 8k Hz) Based on the modal analysis of the ossicles, we found that the malleus resonated to sound stimuli at 3 kHz and 4 kHz; the incus and stapes would not resonate to sound stimuli at any frequency. For the couped structures of the ossicles, the coupling of the incus and malleus easily resonated to sound stimuli at 5 kHz. The coupling of the incus and stapes easily resonated to sound stimuli at 3 kHz. The coupling of the ossicular chain easily resonated to sound stimuli at 5 kHz, 6 kHz and 8 kHz. According to these results, resonance between the structures of the ossicles occurred at 3 kHz, 4 kHz and 8 kHz, which means these three audible frequencies can induce damage to inner ear by resonance.

## DISCUSSION

A 3D model of the ossicles was successfully reconstructed with CT imaging of in-vivo human ossicles in this study. Then the dynamic characteristics of the ossicles were analyzed by finite element analysis. Based on a 3D model, a clinician could immediately know the distribution of ossicles for patients. In-vivo ossicular geometry has benefits in developing proper prostheses for middle ear reconstruction. After understanding the dynamic characteristics using the finite element method, evaluation for substitute implants could be offered preoperatively. In our study, the three ossicles resonated to sound stimuli at different frequencies. The coupling structure was also evaluated. According to the above results, resonance between ossicles occurs at 3 kHz, 4 kHz and 8 kHz, which means these three audible frequencies can induce damage to the inner ear by resonance. However, the induced resonance did not damage the structure of the ossicles, because the ligaments and muscles in the normal ossicular chain reduce the resonance.

The individual ossicles did not easily resonate to frequencies used for clinical hearing tests. However, the natural frequency of the coupling of the ossicles would be similar to sound stimuli frequencies used

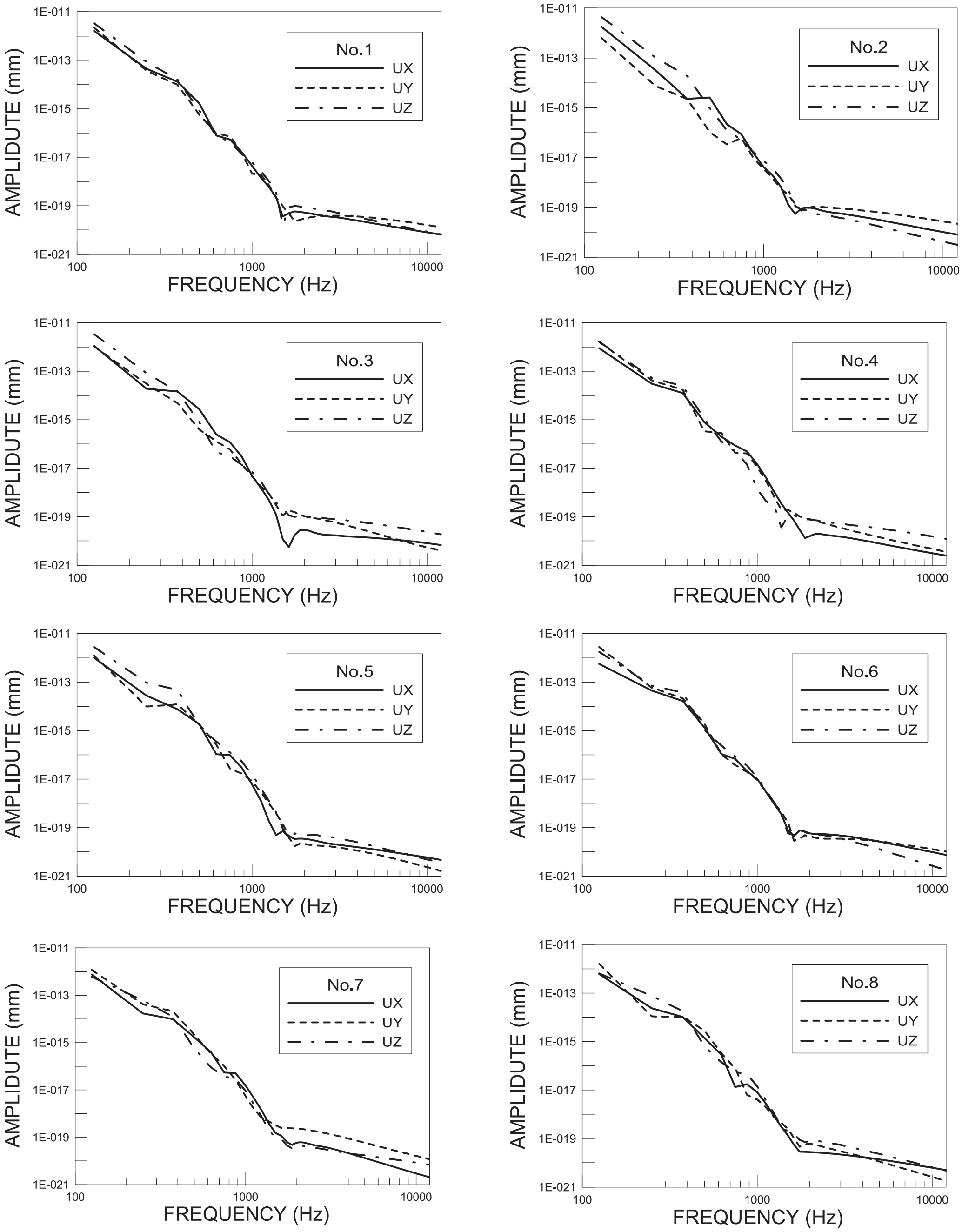

**Fig. 3** The vibration amplitudes of malleus and umbo of the eardrum based on audible frequencies at 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz and 8 kHz.

for clinical hearing tests. In addition, the structure of prostheses and the residual ossicles can be damaged because there is no ligament-like or muscle-like structure to reduce the resonance for the ossicle-sclerosis patient treated with a prosthesis. Therefore, postoperative tracking should be done to determine whether the ossicular chain and ossicle prosthesis resonate more easily to sound stimuli. We will evaluate the effects of vibration on prostheses in future research.

A finite element model can be of benefit in clinical applications, such as middle ear reconstruction, and predict the effects of vibration on ossicles. The ossicular finite element model also has potential in the study of otosclerosis, middle ear implant devices, and eardrum perforation.(23) Our model needs to be modified in several ways, such as an accurate boundary index of the intraossicular ligments and muscles in the middle ear, and the mechanical properties and interaction of the inner ear and outer ear canal.

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# 聽小骨鏈的自然振動特性

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**背景：** 近來，聽小骨鏈的有限元素分析模型已經建立，但對於聽小骨鏈的自然振動特性仍未加以研究。我們嘗試利用有限元素來分析聽小骨鏈的動態特性。

**方法：** 利用電腦斷層檢查得到聽小骨鏈的幾何圖形，透過 Amira® 建立其立體影像模組，再經由 ANSYS® 建立其有限元素模組，藉由有限元素分析聽小骨鏈的自然振動特性。

**結果：** 鎚骨在 3kHz 跟 4kHz 易產生共振；單一的鉆骨或是鐙骨與任何聲音頻率皆未產生共振；鉆骨與鎚骨偶合在 5kHz 易產生共振；鉆骨與鐙骨偶合在 3kHz 易產生共振；聽小骨鏈偶合易在 5kHz、6kHz、8kHz 等頻率產生共振。

**結論：** 本研究使用有限元素分析聽小骨鏈的動態特性，來探討聽小骨的振動模式，對於評估聽小骨義體的植入是有幫助的。

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**關鍵詞：** 聽小骨鏈，振動分析，有限元素法，電腦斷層掃描

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