875. Modeling the dynamic characteristics of human ossicles

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(Received 10 August 2012; accepted 4 December 2012)

Abstract. The dynamic characteristics of human ossicle responses to stimulus frequencies of 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz were analyzed using a 3D image model that was constructed using the finite element method. The 3D image model of the ossicle chain was based on images previously obtained from high-resolution computed tomography (CT) scans of the middle ear region of patients. The displacement at the footplate in the 3D model showed essentially no response when the ossicles were subjected to sound stimuli with frequencies above 2 kHz. However, the ossicles responded to sound stimuli with frequencies below 1 kHz, and the vibration of the ossicles was equivalent to the amplitude of the sound stimuli.

Keywords: ossicles, finite element method, vibration analysis, high resolution computed tomography.

Introduction

Otorrhea and tympanic membrane perforation are common symptoms of chronic suppurative otitis media (CSOM). CSOM is associated with bacterial infection in the middle ear. Damage to the tympanic membrane may be corrected using ossiculoplastic surgery. Congenital hearing losses associated with ossicular disruptions resulting from congenital abnormalities of the middle ear can also be improved by ossiculoplasty [1].

However, ossicle conduction may be reduced following ossiculoplasty. The vibration of ossicles can also be affected by the positive and negative non-atmospheric pressures that may result in the middle ear [2-3], inducing conductive hearing losses. To address such problems, the generalized circuit model has been used to simulate the vibration of ossicles [4]. The malleus vibration audiometer has also been used for the evaluation of ossicular function and integrity [5]. However, the heavier parts of ossicles, such as the malleus head and the incus body, could not be measured directly. The finite element method was developed to analyze the vibration mode of ossicles [6-7]. The finite element model of ossicles was constructed based on histological section images [6] and computed tomography (CT) images of human ossicles in vivo [7].

The objectives of our study were to construct a 3D model of ossicles that was based on the geometry of ossicles calculated from CT images of in vivo ossicles obtained during clinical evaluations, and to characterize the harmonic vibration characteristics of ossicles using a finite element method.

Materials and Methods

The geometry of ossicles was calculated based on the CT images of patients that were previously evaluated. The 3D model of ossicles was constructed using the medical imaging software Amira®. Note that the format of 3D model was STL. Then, the file format of the 3D model was transformed from STL into SAT by CAD, and the SAT file was imported into the finite element analysis software ANSYS®. The finite element model of ossicles was constructed using the SOLID185 (SolidWorks®) and the free meshing methods. The repeated nodes between ossicles were combined into a single node. The finite element model of ossicles was then built. The joint between the incus and stapes was considered because of the large value of Young's modulus. The COMBIN14 Spring-Damper was used for the vertical and horizontal axes on the stapes footplate. The vertical and horizontal spring elements are shown in Figures 1(a) and 1(b), respectively.

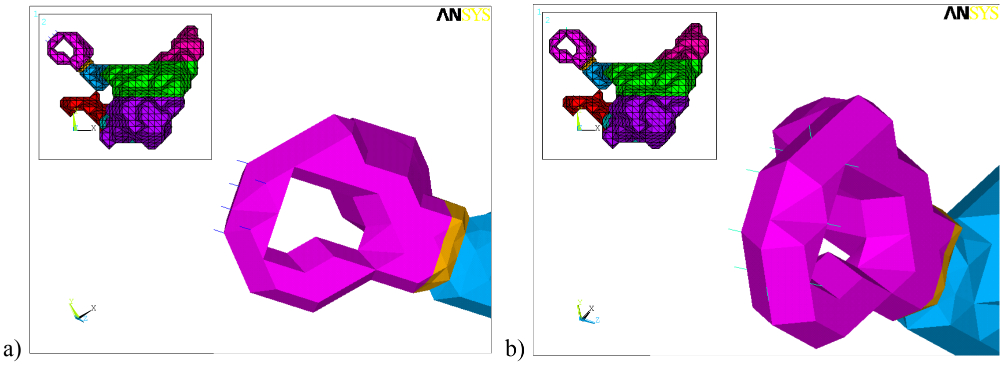

Fig. 1. The spring element at stapes footplate: a) the vertical direction, b) the horizontal direction

The material parameters for each part of the ossicles were different. Poisson's ratio for overall structure was assumed to be 0.3 based on the results of similar previous studies, and the analysis of the dynamic characteristics of ossicles were not significantly affected by the value of the Poisson ratio used [8]. The damping matrix was calculated as $[C]=\alpha[M]+\beta[K]$, where $[M]$ and $[K]$ are the mass matrix and stiffness matrix, respectively, and α and β are the damping parameters.

The overall structure consisted of 3 ossicles, the joints between the incus and the stapes, and the springs of the stapes. The incudomalleolar joint was adopted based the results of a previous study that showed no relative motion between the malleus and the incus at frequencies less than 3 kHz [9]. Therefore, Young's modulus was assumed to be 14.1 GPa, which indicated a linearly elastic material of equal quality and equal direction. The density of the various parts of the ossicles is shown in Table 1. The nodes that connected the malleus and incus were combined into one node in our study. The joints between the incus and the stapes were adopted according to a previous study that showed no stiffness displacement in the joints under various conditions of noise and pressure [10]. Although there was some relative motion between the incus and stapes, we concluded that the inner ear was protected, and that it would not be damaged by the large displacement of the stapes footplate. In addition, the joints between the incus and the stapes were assumed to comprise homogeneous materials, with a Young's modulus of 0.6 MPa [11, 12].

Table 1. The density of the various parts of the ossicles

		Density (kg/m^3)
Malleus	Head	2.55×10^3
	Neck	4.53×10^3
	Handle	3.70×10^3
Incus	Body	2.36×10^3
	Short process	2.26×10^3
	Long process	5.08×10^3
Stapes	-	2.20×10^3
	I-S joint	1.2×10^3

For harmonic analysis, 6 *x*-*y* plane springs were on the vertical side of the stapes footplate. The total constant of the springs, *K*, was 60 N/m. The total damping was 0.054 N/(m/s). The *K* value for the nine 3D vertical springs on the horizontal side was assumed to be 9 N/m. The vertical and horizontal springs of the stapes footplate were fixed to the UX, the UY and the UZ direction movements of the nodes of ossicles, respectively. To simulate the response of the sound transmitted through the cochlear fluid by the ossicles, the vertical direction was constrained to the 2D spring damper that could be pulled in the vertical direction only. The horizontal direction was used to simulate the actual motion of the stapes footplate. Therefore, the 3D spring damper was assumed.

The ossicles and the ligament and the spring damper of the stapes footplate were analyzed. The degrees of freedom of the 3 directions of the nodes that connected the spring damper and the stapes footplate were fixed, as shown in Figure 2. The nodes on the base area of the manubrium of the malleus were excited in the *X* direction by 90 dBSPL, as shown in Figure 3. Based on the modal superposition (MSUP) theorem, the results of the MSUP analysis were obtained by transforming to the original coordinate system. The results of the MSUP analysis were extended to the overall structure to interpret the response of the sound transmitted to the inner ear through the ossicles following excitement with the sound pressure (90 dBSPL) under stimulus frequencies of 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz, and 8 kHz.

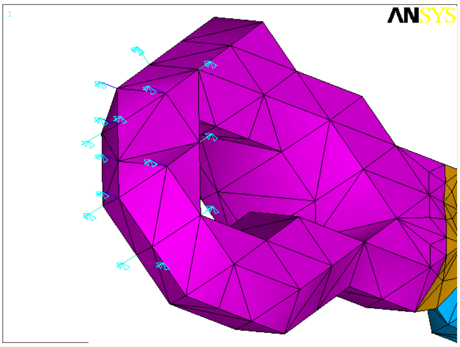

Fig. 2. The degree of freedom for the nodes at the stapes footplate

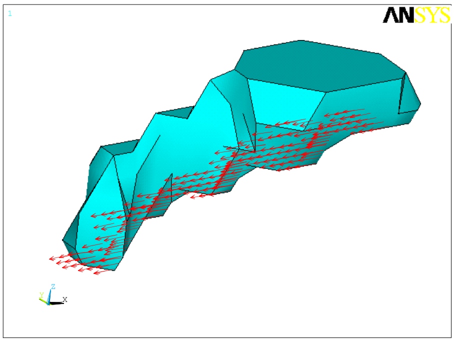

Fig. 3. The external load (90 dBSPL) for the harmonic analysis

Results and Discussion

The harmonic analysis focused on the joints of the malleus head and the tympanic membrane. The surface area of the malleus head, 3.081 mm^2, was excited by 90 dBSPL (0.623 Pa). The frequency and the amplitude response of the specific nodes (Figure 4) on the stapes footplate at 250 Hz to 8 kHz, respectively, are shown in Figure 5. The results were also observed along the *X*, *Y* and *Z* axes, as shown in Figures 6 to 13.

Based on the data presented in Figures 6 to 13, there was an apparent transition point for the 9 nodes of the stapes footplate at 1 to 2 kHz. The ossicles were excited by the stimuli at frequencies below 1 kHz. The displacement corresponded to the amplitude of the sound stimuli that were transmitted to the stapes footplate. In contrast, significant displacement was not detected when the ossicles were subjected to stimuli with frequencies above 2 kHz, and the transmission power of ossicles was adopted directly.

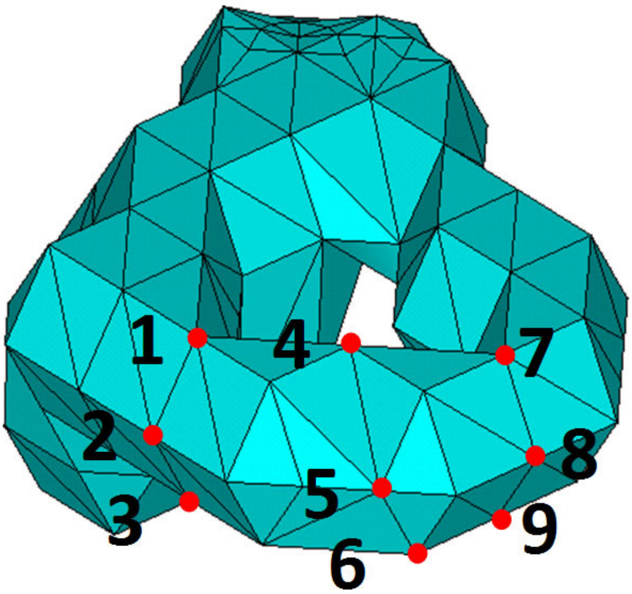

Fig. 4. The nodes, 1-9, on the footplate of stapes

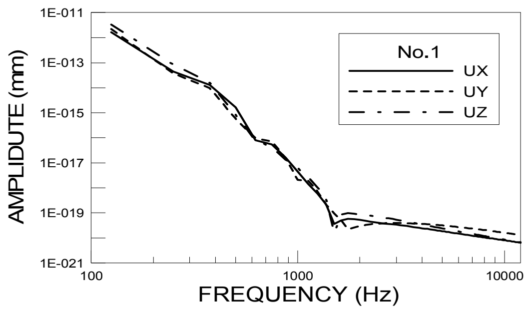

Fig. 5. The displacement at node 1 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

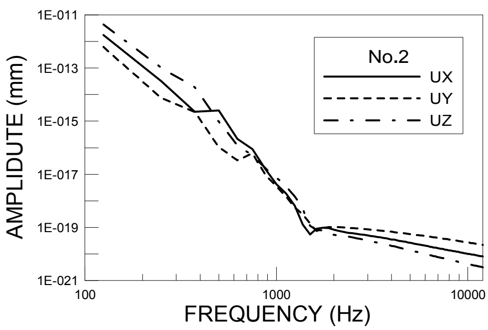

Fig. 6. The displacement at node 2 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

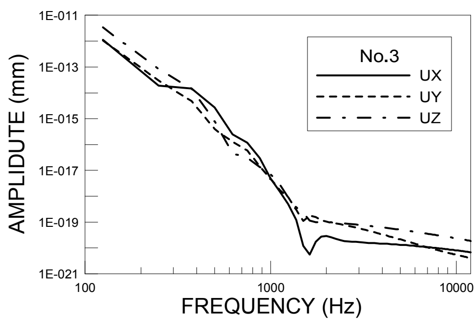

Fig. 7. The displacement at node 3 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

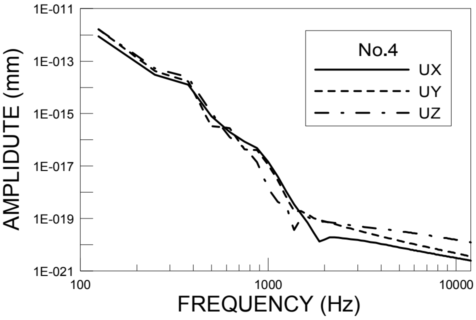

Fig. 8. The displacement at node 4 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

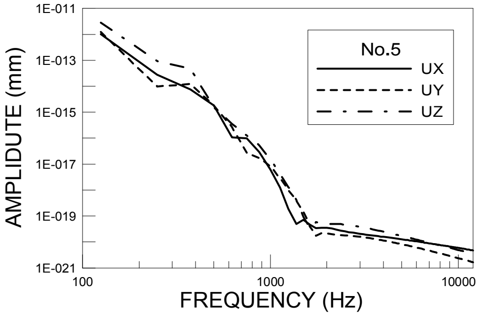

Fig. 9. The displacement at node 5 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

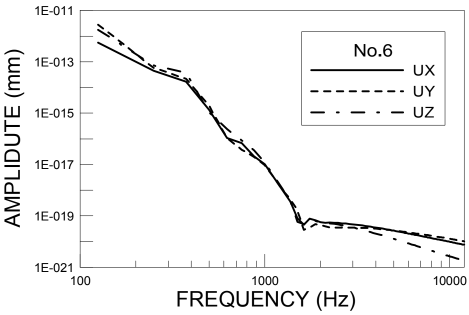

Fig. 10. The displacement at node 6 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

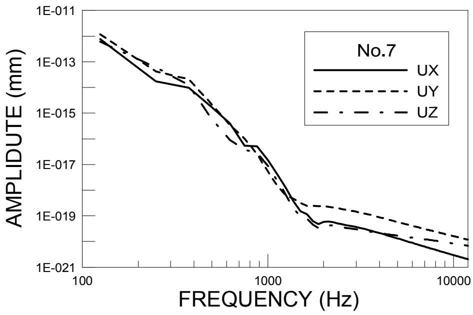

Fig. 11. The displacement at node 7 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

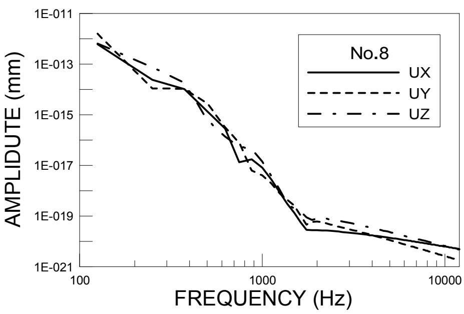

Fig. 12. The displacement at node 8 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

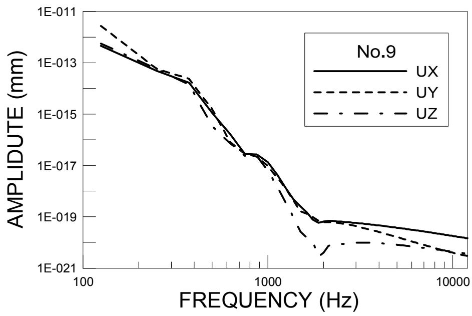

Fig. 13. The displacement at node 9 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz

Conclusions

To meet the clinical needs of otolaryngologists, a dynamic model of human ossicles was constructed from in vivo CT images to aid clinicians in the assessments of ossicle function. The 3D image of the ossicles was successfully imported into the finite element analysis software ANSYS®, and the finite element model of ossicles was constructed using the SolidWorks® SOLID185 program. When the ossicles were excited with sound stimuli at frequencies below

1 kHz, the vibration of the ossicles was equivalent to the amplitude of the sound stimuli. Significant displacement of the ossicles was not observed in response to sound stimuli at frequencies above 2 kHz, and the sound was transmitted by the ossicles directly. Analyses of the dynamic characteristics of ossicles based on this finite element model system may aid clinicians in the pre-op evaluation of substitute implants for the correction of hearing loss, such as that resulting from ossiculoplasty for the treatment of CSOM.

References

[1] **Samy R. N., Pensak M. L.** Revision ossiculoplasty. Otolaryngol. Clin. North Am., 39(4), 2006, p. 699-712.

[2] **Petrova P., Freeman S., Sohmer H.** The effects of positive and negative middle ear pressures on auditory threshold. Otol Neurotol., 27(5), 2006, p. 734-738.

[3] **Puria S., Kunda L. D., Roberson J. B. Jr., Perkins R. C.** Malleus-to-footplate ossicular reconstruction prosthesis positioning: cochleovestibular pressure optimization. Otol Neurotol., 26(3), 2005, p. 368-379.

[4] **Hudde H., Weistenhofer C.** Key features of the human middle ear. ORL J. Otorhinolaryngol. Relat. Spec., 68(6), 2006, p. 324-328.

[5] **Maassen M. M., Rodriguez Jorge J., Herberhold S., Vonthein R., Zimmermann R., Baumann I., Brosch S., Mauz P. S., Pfister M., Zalaman I. M., Lowenheim H., Zenner H. P.** Safe and reliable sound threshold measures with direct vibration of the ossicular chain. Laryngoscope, 114(11), 2004, p. 2012-2020.

[6] **Gan R. Z., Feng B., Sun Q.** Three-dimensional finite element modeling of human ear for sound transmission. Ann. Biomed. Eng., 32(6), 2004, p. 847-859.

[7] **Koike T., Shinozaki M., Murakami S., Homma K., Kobayashi T., Wada H.** Effects of individual differences in size and mobility of the middle ear on hearing. JSME International Journal, 48(4), 2005, p. 521-528.

[8] **Funnell W. R. J., Laszlo C. A.** A critical review of experimental observations on eardrum structure and function. ORL J. Otorhinolaryngol. Relat. Spec., 44, 1982, p. 181-205.

[9] **Vlaming M. S. M. G.** Middle Ear Mechanics by Laser Doppler Interferometry. Techniche Universiteit Delft, Netherlands, 1987.

[10] **Hüttenbrink K. B.** The mechanics of the middle-ear at static air pressures: the role of the ossicular joints, the function of the middle-ear muscles and the behaviour of stapedial prostheses. Acta Otolaryngol. Suppl., 451, 1988, p. 1-35.

[11] **Ferris P., Prendergast P. J.** Middle-ear dynamics before and after ossicular replacement. J. Biomech., 33(5), 2000, p. 581-590.

[12] **Wada H., Koike T., Kobayashi T.** Three-dimensional finite-element method (FEM) analysis of the human middle ear. In: Hüttenbrink K. B. (ed.), Middle Ear Mechanics in Research and Otosurgery. Department of Oto-Rhino-Laryngology, Dresden University of Technology, 1996, p. 76-80.

[13] **William A.** Yost Fundamentals of Hearing: An Introduction. 4th Edition, Academic Press, 2000.