Numerical modelling and vibration analysis of human middle ear for application in sound conduction reconstruction

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Abstract. In this paper, we introduce a new numerical approach for estimating the hearing restoration effect prior to the tympanoplasty operation using the finite element harmonic vibration analysis. This kind of approach makes it possible to propose a new medical treatment for the recovery of conductive or cochlear hearing loss. First of all, precise geometric models of the middle ear, including healthy type model and tympanoplasty type models, are constructed on the basis of the computerized tomography (CT) scanning data. Then, frequency response characteristics of the stapes displacement in sound conduction are clarified using the three-dimensional finite element harmonic vibration analysis. Based on the investigation results, we propose that the hearing restoration effect can be estimated by a comparison of the differences in the stapes displacement between the reconstruction model and the healthy subject.

1. Introduction
The conductive hearing loss occurs when the middle ear is damaged by various ear diseases, and sounds hardly transfer through the ear canal to the eardrum and three ossicles. The chronic otitis media or middle ear cholesteatoma in which the ossicular chain in middle ear is damaged causes severe conductive hearing loss. The tympanoplasty operation is often carried out to reconstruct the damaged ossicular chain, and to improve the sound conduction efficiency. In the ossicular chain reconstruction, the column article called columella is produced and used instead of incus which is generally broken. In this operation, the sound conduction efficiency changes by the variations in the shape, material and mounting position of the columella.

Several experimental researches have been carried out to investigate the dynamics characteristics of the middle ear [1-3]. However, it is extremely difficult for the experimental researches to deal with the individual variations of the dynamic characteristics, because experiments on live humans and cadavers are very limited. On the other hand, many researchers use the finite element analysis (FEA) in their study. The FEA is a powerful tool to analyse the vibration of a middle ear because the middle ear has a complicated shape [4-7]. Nevertheless, there are few studies regarding clinical applications and aiming at the improvement of the sound conduction efficiency in tympanoplasty.
In this paper, we introduce a numerical approach for estimating the hearing restoration effect prior to the tympanoplasty operation using the harmonic vibration analysis. By the approach, it is possible to find an optimal operative method for the sound conduction reconstruction. First of all, precise geometric models of the middle ear, including healthy type model and tympanoplasty type models, were constructed through CT data. Then, the harmonic vibration analysis was carried out to investigate the frequency response of the stapes footplate. Moreover, III type and IV type operation models in which mounting positions of the columella are umbilical and intermediate parts of the malleus were analyzed as an application.

2. The human middle ear and its function
The ear is the organ of controlling hearing and balance, and has three parts: the outer ear, the middle ear and the inner ear as shown in figure 1. The middle ear connects the eardrum of the outer ear and the oval window of the inner ear. The main function of the middle ear is to efficiently transfer the vibrations of the eardrum to fluid waves within the cochlea. As shown in figure 2, the middle ear contains three small ossicles: malleus, incus and stapes, which are connected to each other by the joints and supported by ligaments and muscles. By the rotary motion of the auditory ossicles, the vibration on the tympanic membrane can be amplified and transmitted to the stapes footplate, which moves the labyrinthine fluid in the internal ear to generate electrical signals. Then, the electrical signals are sent directly to the brain to be recognized as a sound.

3. Geometric modelling of a middle ear
A precise geometric model of ossicles can be created through CT scanning of the human head. As shown in figures 3-5, the two-dimensional slice images of the CT scanning data were converted into three-dimensional solid geometries using a post-processing software and the region which contains the three ossicles can be extracted. Then, the 3D geometries were refined and transformed to the DICOM data, and further transformed into the STL data, which were imported into a general-purpose structure analysis software to create a FEA model. The FEA model of a healthy subject is shown in figure 6 which contains the tympanic membrane, auditory ossicles chain (malleus, incus and stapes), ligaments, joints, stapedial muscle and others. The anatomical name of each part in figure 6 is given in table 1.
4. Dynamic characteristics of a healthy middle ear
Firstly, dynamic characteristics of a healthy model was investigated by the harmonic vibration analysis using a general-purpose finite element method code.

4.1. Material properties and boundary conditions
Material properties used in the analysis model were determined by referring to other researches [6-8], and were summarized in table 1. The interaction between the stapes footplate
Table 1. Material properties used in the analysis model.

| Anatomical parts name                  | Young’s Modulus [MPa] | Mass density [kg/m³] | Poisson’s ratio |
|----------------------------------------|------------------------|----------------------|-----------------|
| 1 Tympanic membrane                    |                        |                      |                 |
| Pars tensa                             | 33.4                   | 1200                 | 0.3             |
| Pars flaccida                           | 11.1                   | 1200                 | 0.3             |
| Annulus tympanicus                     | 0.6                    | 1200                 | 0.3             |
| 2 Malleus                              | 13436                  | 4350                 | 0.3             |
| 3 Incus                                | 13436                  | 4350                 | 0.3             |
| 4 Stapes                               | 13436                  | 4350                 | 0.3             |
| 5 Lateral mallear ligament             | 21                     | 2500                 | 0.3             |
| 6 Superior mallear ligament            | 21                     | 2500                 | 0.3             |
| 7 Anterior mallear ligament            | 21                     | 2500                 | 0.3             |
| 8 Posterior incudal ligament           | 0.65                   | 2500                 | 0.3             |
| 9 Superior incudal ligament            | 0.65                   | 2500                 | 0.3             |
| 10 Stapedial annular ligament          | 0.65                   | 2500                 | 0.3             |
| 11 Incudostapedial joint               | 6                      | 1200                 | 0.3             |
| 12 Incudo mallear joint                | 6                      | 1200                 | 0.3             |
| 13 Stapedial muscle                    | 0.52                   | 2500                 | 0.3             |
| 14 Base plate                          | $1 \times 10^{10}$     | -                    | 0.3             |

and the cochlea labyrinthine fluid was modeled with a set of translational springs installed between the stapes footplate and a virtual base plate (a rigid body). The spring constant was given as 40N/m by considering the research of Gan et al [5]. In addition, the damping matrix $[C]$ of the solid elements was expressed in equation (1).

$$ [C] = \zeta [I] + \alpha [K] + \beta [M] $$

where, $[I]$ was the unit matrix, $[M]$ was the mass matrix, and $[K]$ was the stiffness matrix. $\zeta$, $\alpha$, $\beta$ express the damping coefficients. Rayleigh damping was only considered in this study, i.e., $\zeta = 0$, and $\alpha = 0$, $\beta = 7.5 \times 10^{-5}$ were used for the coefficients of Rayleigh damping.

As the boundary conditions, outer circumferences of the tympanic membrane and the stapedial muscle, ends of the six ligaments, and the inner side of the base plate were clamped. In the harmonic vibration analysis, a uniform pressure $p$ was applied at the whole surface of the tympanic membrane, and the applied pressure $p = 0.632$ Pa can be calculated from the definition equation of the sound pressure level (SPL) expressed in equation (2).

$$ L_p = 20 \log_{10}(p/p_0) $$

where, $L_p = 90$dB was set as the sound pressure level. $p_0 = 20 \times 10^{-6}$Pa denotes the reference value or hearing threshold of the sound pressure.

4.2. Analysis results of the healthy model

As the analysis results, the frequency responses curve of the healthy model is shown in figure 7, where the vertical axis represents the average displacement of the stapes footplate, and the horizontal axis shows the input frequency. Figure 7 shows that a resonance region appears at 0.5~2 kHz in frequency, which is called “conversation range”. The peak value of stapes footplate average displacement reaches 5.09 nm at about 1.3 kHz, and the responses falls off steadily above
2 kHz. In this study, the frequency response curve of the healthy model was used as a standard curve to be compared with that of a operation model, where the damaged auditory ossicles was substituted by the columella (a medical device). Then, it possible to find an optimal operative method for the sound conduction reconstruction.

![Frequency response curve](image)

**Figure 7.** Harmonic vibration analysis results of a healthy model

5. Application for clinics in tympanoplasty

As mentioned in Section 1, the tympanoplasty operation is often carried out to reconstruct the damaged ossicular chain to improve the sound conduction efficiency. In the ossicular chain reconstruction, the column article called columella is produced and used instead of incus which is generally broken. Currently, the tympanoplasty operation can be classified into two types, that is Auditory ossicles formation III type and IV type. The main difference is that the stapes is kept in almost normal in the III type, but only the stapes footplate is left in the IV type.

Figure 8 shows a III type tympanoplasty model, where the columella was installed between the umbilical region (the tip of the malleus) and the stapes. Its analysis result of the frequency response curve shows that the maximum displacement of the stapes footplate is 4.7 nm near 1.5 kHz. Comparing with the displacement 5.09 nm of the healthy model, the value of this tympanoplasty model reaches about 94% of the healthy one. Figure 9 shows another model, where the columella was installed at the intermediate region, that is, between the tip of the

![Umbilical part](image)
![Intermediate part](image)

**Figure 8.** Umbilical connection model in the III type tympanoplasty.  
**Figure 9.** Intermediate connection model in the III type tympanoplasty.
malleus and the short process of the malleus. In this case, analysis results show that the maximum displacement decreases to 4.4 nm which is approximately 88% of the healthy model.

A IV type tympanoplasty model is shown in figure 10, where a columella was installed at the umbilical region. The analysis result of the frequency response curve shows that the maximum response of the stapes footplate is 3.01 nm near 1.5 kHz. This displacement of 3.01 nm is about 60% of the healthy model. As another example, a model in which the columella is installed between the intermediate region is shown in figure 11. Analysis result is shown in figure 12, in which the maximum displacement decreases to 2.79 nm which is approximately 56% of the healthy model.

The results of two tympanoplasty models, both the a III type and the IV type, shows that the connection position of the columella at the umbilical region is more suitable for obtaining a larger displacement, that contributes to a higher hearing restoration ratio. It is clear that the comparison between the stapes footplate displacement of the tympanoplasty model and the healthy one can estimate the restoration effect, not only in the III type operation but also in
the IV type operation, and then find an optimal operative method in the sound conduction reconstruction.

6. Conclusions
This paper proposed a new numerical approach for estimating the hearing restoration effect using the harmonic vibration analysis. Numerical modelling and harmonic vibration analysis of the human middle ear were carried out to investigate the dynamic characteristics. Then, the sound conduction efficiency in tympanoplasty was improved by comparison of the differences in the stapes footplate displacement between the reconstruction model and the healthy one. The validity of the proposed method was confirmed by the application of two types of operation models to find suitable connection positions of the columella.

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References
[1] H, Kobayashi T, Nagamura H and Tashizaki H 1990 Trans. Jpn. Soc. Mech. Eng. Ser. C 56 1431-4
[2] Voss S E, Rosowski J J, Merchant S N and Peake W T 2000 Hear. Res. 150 43-69
[3] Aibara R, Welsh J T, Puria S and Goode R L 2001 Hear. Res. 152 100-9
[4] Wada H, Metoki T and Kobayashi T 1993 J. Acoust. Soc. Am. JASA 92 3157-68
[5] Gan R Z, Feng B and Sun Q 2004 Ann. Biomed. Eng. 32 847-59
[6] Sun Q, Gan R Z, Chang K H and Dormer K J 2002 Biomech. Model. Mechanobiol. 1 109-22
[7] Koike T and Wada H 2002 J. Acoust. Soc. Am. JASA 111 1306-17
[8] Higashimachi T, Suga K and Sasahara H 2009 J. Japan Soc. Prec. Eng. 75 428-33