IMPROVEMENT OF SOUND CONDUCTION EFFICIENCY FROM THE VIEWPOINT OF VIBRATION CHARACTERISTICS OF THE HUMAN MIDDLE EAR

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ABSTRACT

When the middle ear is damaged by various ear diseases, the linkage of the auditory ossicles may be reconstructed using the column article called the columella, or artificial stapes. In tympanoplasty, operations are carried out based on the workmanship and experience of the surgeon. We have proposed a new method for estimating the hearing restoration effect prior to the tympanoplasty operation. In this method, a geometric model of the human middle ear is constructed using SolidWorks based on CT scanning data. Then, frequency response characteristics of the stapes displacement in sound conduction are calculated using finite element harmonic vibration analysis. The hearing restoration effect can be estimated by a comparison of the differences in the stapes displacement between the reconstruction model and a healthy subject. Through the study of our method, it has been clarified that a maximum displacement of 5.0 nm of a III-i type operation model for chronic otitis media achieves a response of about 98% compared to a healthy subject.

Furthermore, several models in which an annular ligament becomes more rigid through otosclerosis and related operation models using artificial stapes are constructed and analyzed. As much as the annular ligament stiffened, it followed that sound conduction efficiency decreased. Frequency characteristics of the conductive hearing loss due to otosclerosis thus could be reproduced. According to operation models using artificial stapes, it is possible that the stapes displacement increases, that is, the sound conduction efficiency is improved, more than the result in which an annular ligament becomes highly rigid.

From the vibration analysis of these models, our proposed estimation method for reconstruction of the auditory ossicles was verified. Through this study, the optimization of structures and materials for columella and artificial stapes becomes possible. Finally, the efficacy of predicting the hearing restoration effect prior to an operation was verified.

Keywords: artificial stapes, auditory ossicles, FEM, geometric model, human middle ear, solidworks, sound pressure, tympanic membrane, tympanoplasty operation.

1 INTRODUCTION

Sound from outside is transmitted to the tympanic membrane through the ear canal. The vibration of the tympanic membrane is amplified by the auditory ossicles and transmitted to the inner ear. The hearing disorder caused by an abnormality in the sound conduction organ to the cochlea is called conduction hearing loss.

A geometric model of the middle ear on the basis of the computerized tomography (CT) scan data was constructed. Frequency response characteristics of the stapes displacement in sound conduction are clarified using three-dimensional finite element harmonic vibration

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analysis. We have proposed that the hearing restoration effect can be estimated by a comparison of the displacement of the stapes basal plane prior to the operation. In previous research [1, 2], several kinds of tympanoplasty models for a middle ear damaged by chronic otitis media have been constructed and analyzed by FEM. By comparing those analytical results with the result for a healthy model as a standard, the possibility of a clinical application of our method has been verified.

In this research, the harmonic vibration analysis result of a healthy subject is shown at first. Next, the case in which the medical device, called columella, is substituted for the deficient auditory ossicles is analyzed. Especially, the columella is attached between the umbilical region, that is, the tip of the malleus, and stapes, which is the most effective region for hearing restoration. Furthermore, several models in which an annular ligament becomes more rigid through otosclerosis are analyzed. In order to verify the effect of the degree of hardening, models in which the Young's modulus of ligament was increased in steps are made. Finally, related operation models with otosclerosis using artificial stapes are constructed and analyzed. These results are compared with the result for a healthy subject and the validity of the prediction method which we have proposed is verified.

2 EAR STRUCTURE AND FUNCTIONS

The ear is the organ that controls the sense of hearing and human body balance. The ear is composed of external, middle and inner parts as shown in Fig. 1. The external ear is composed of the pinna, ear canal and tympanic membrane. The function of the pinna is to collect sonic reflections, and the function of the ear canal is as a resonance tube.

The middle ear as shown in Fig. 2 is composed of auditory ossicles and the auditory tube which connects with the hole of nose. Auditory ossicles behind the tympanic membrane are in a small space (tympanic cavity) filled with air, and they connect the tympanic membrane with the cochlea of the inner ear. The vibration of the tympanic membrane is amplified by the auditory ossicles and transmitted to the inner ear.

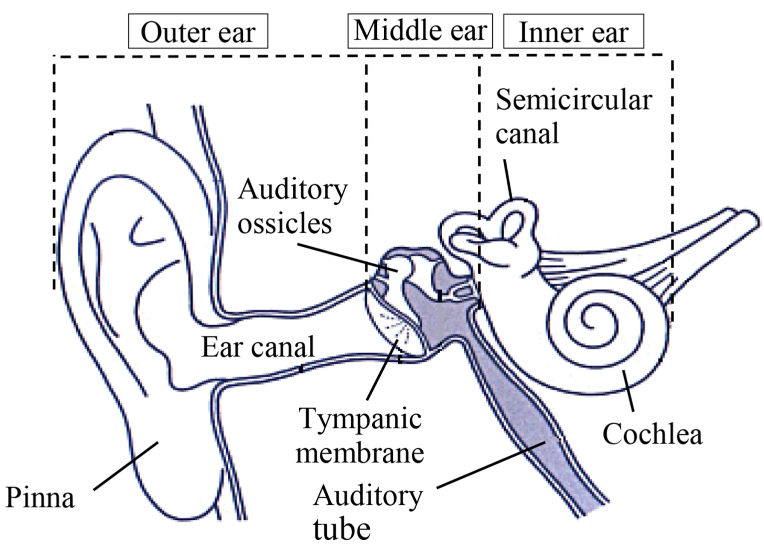


Figure 1: Ear structure.

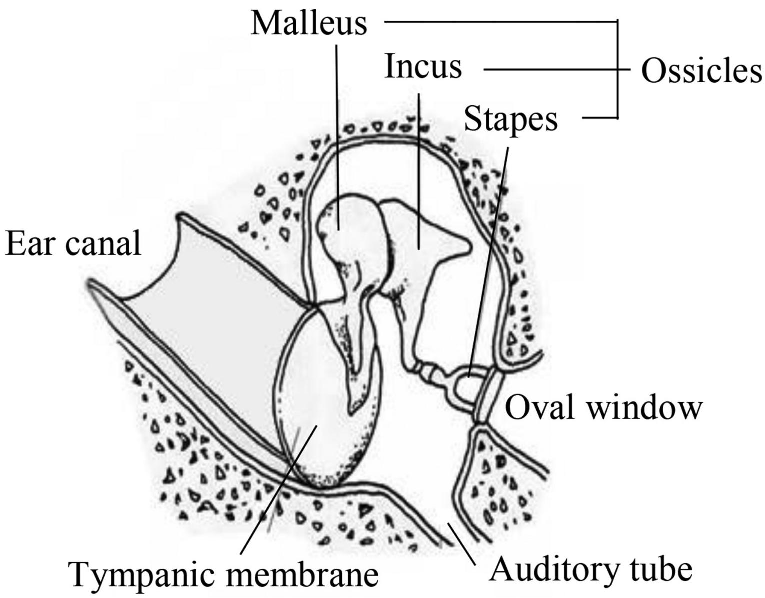


Figure 2: Middle ear structure.

The inner ear is composed of the cochlea and semicircular canal. In the inner ear, the vibration induced by auditory ossicles is transmitted to the labyrinthine fluid which converts it to electric signals. Finally, it is recognized in the brain as sound.

3 HARMONIC VIBRATION ANALYSIS OF MIDDLE EAR

3.1 Geometric modeling of healthy subject

The geometric model for a healthy subject for finite element harmonic vibration analysis is shown in Fig. 3. This model is composed of the tympanic membrane, auditory ossicles, ligaments, joints, stapedial muscle and others. In order to construct a geometric model, the region which contains those ear parts was separated from the CT scanning data of the human head. These CT scanning data were converted to DICOM data, and in addition, converted into STL data, which were imported into SolidWorks.

3.2 Material data

Material data of the analysis model are shown in Table 1 [3–5]. The anatomical parts name number in the table corresponds to the number in Fig. 3. The base plate ⑭ is a virtual part for supporting the spring. Therefore, its Young's modulus can be assumed to be that of a rigid body.

3.3 Boundary conditions

The tympanic membrane circumference, edges of ligament and muscle, and base plate were perfectly fixed in load conditions. A sound pressure of 90dB was converted into pressure using the eqn (1) as load conditions.

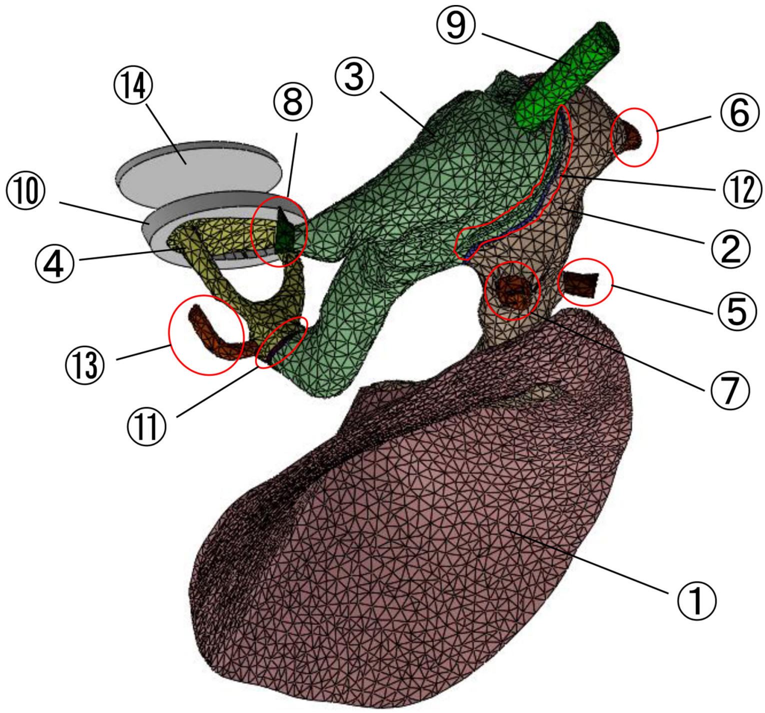


Figure 3: Geometric model of middle ear.

$$L_p = 20\log_{10}(p / p_0). \tag{1}$$

In eqn (1), $L_p = 90\text{dB}$ is the setting sound pressure (a relative noisy level) and $P_0 = 20\times10^{-6}\,\text{Pa}$ is a standard value (the lowest value of the sound intensity which is audible for humans). As a result, a pressure of $P = 0.632\text{Pa}$ was obtained. However, in this analysis, $P = 15.2\text{Pa}$ was given at the contact surface of the tympanic membrane and malleus. The ratio 15.2/0.632 equals the ratio of the total area of the tympanic membrane to the contact surface area of the tympanic membrane and malleus. A spring of 40 N/m spring constant was installed between the stapes and the base plate referring to the research of Gan *et al*. [6]. Rayleigh damping was assumed and damping factors of $\alpha = 0\text{s}^{-1}$ and $\beta = 7.5\times10^{-5}$.

3.4 Finite element analysis results

In this research, harmonic vibration analysis was done as a dynamic analysis using the finite element method. Figure 4 shows the harmonic vibration analysis results for a healthy subject. The longitudinal axis shows the displacement of the stapes bottom in a perpendicular direction to the basal plane, and the lateral axis represents the frequency. In cases of a healthy subject, it is said that there is a resonance region of the middle ear at 0.5～2 kHz in frequency, that is, conversation range. Average displacement of the stapes basal plane shows the peak of the resonance to be near 1.3 kHz in frequency in the analytical results for a healthy subject. This displacement decreases gradually with an increase in frequency over 2 kHz. It is possible to reproduce the resonance phenomena to some extent by our finite element model. Figure 4

Table 1: Material data.

Anatomical parts name	Young's Modulus [MPa]	Density [kg/m^3]	Poisson's ratio
① Tympanic membrane	33.4	1,200	
② Malleus	13,436	4,350	
③ Incus			
④ Stapes			
⑤ Lateral mallear ligament	21	2,500	
⑥ Superior mallear ligament			
⑦ Anterior mallear ligament			
⑧ Posterior incudal ligament	0.65		0.3
⑨ Superior incudal ligament			
⑩ Stapedial annular ligament			
⑪ Incudostapedial joint	6	1,200	
⑫ Incudo mallear joint			
⑬ Stapedial muscle	0.52	2,500	
⑭ Base plate	1×10^{10}	–	

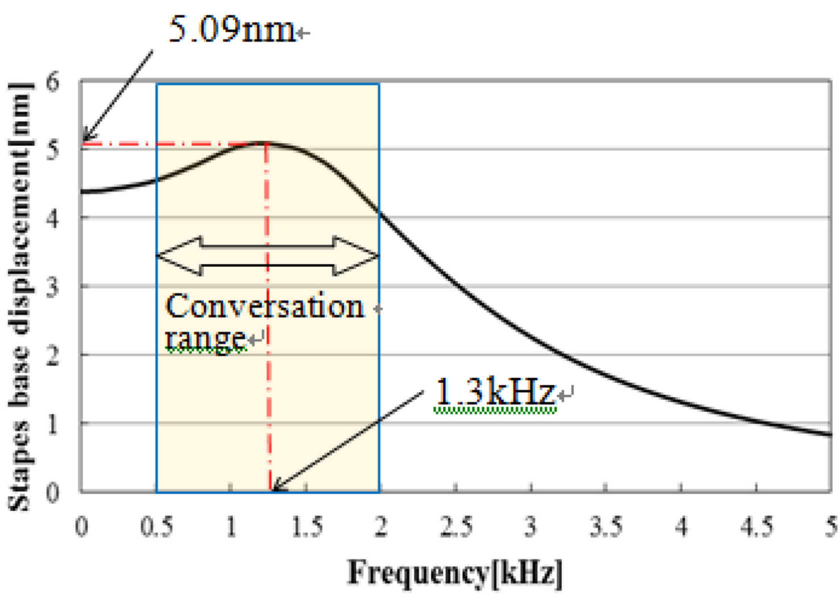


Figure 4: Frequency response graph of healthy subject.

shows that the average displacement of the stapes base for the sound pressure of 90 dB is 5.09×10^{-6} mm, which was used as a standard value in this study. If the change in this displacement is compared, the hearing restoration effect can be estimated, in the case where the medical device, called columella, is substituted for the deficient auditory ossicles, or in the

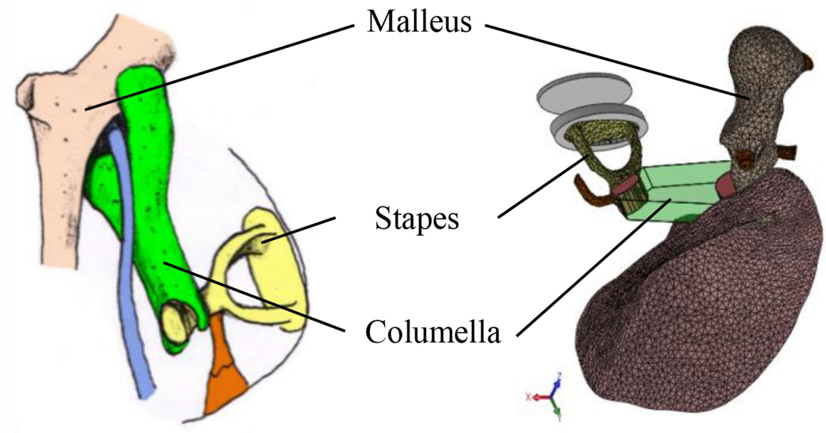


Figure 5: Example of a III-i type tympanoplasty model.

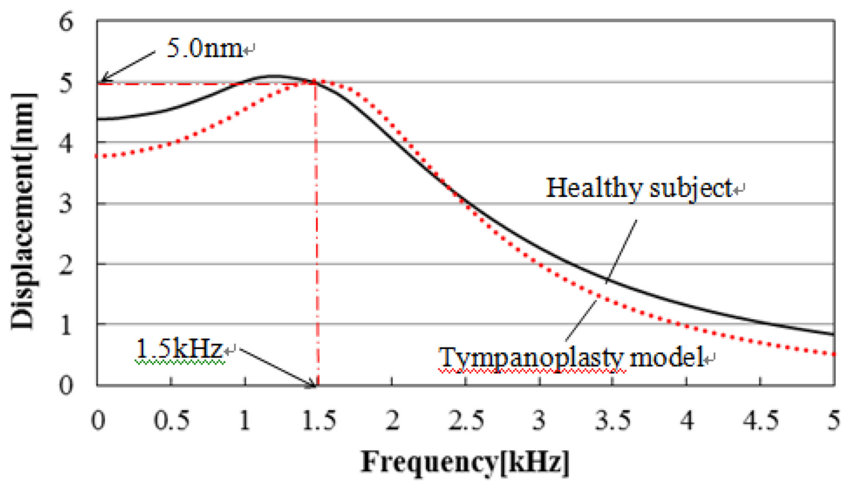


Figure 6: Frequency response graph of healthy subject and tympanoplasty model.

case of stiffening of the ligament. An example of a III -i type tempanoplasty model is shown in Fig. 5.

Several kinds of tympanoplasty models for a middle ear which was damaged by chronic otitis media were constructed and analyzed by FEM [1, 2]. By comparing those analytical results, the possibility of clinical application of our method was verified. For example, the case in which the columella is attached between the umbilical region, that is, the tip of the malleus, and stapes was analyzed. The results of the frequency response graph of the stapes bottom are shown Fig. 6. In this case, the value of the average displacement is 5.0 nm at about 1.5 kHz of frequency. The maximum average displacement of 5.0 nm is about 98% for the healthy subject. This means that hearing ability recovers to a normal level. It becomes possible to estimate the restoration ratio by comparing the stapes displacement of the tympanoplasty model with the healthy type across the entire range of frequency. The validity of our proposal that the hearing restoration effect can be estimated by the displacement of the stapes basal plane has been verified by harmonic vibration analysis.

4 OTOSCLEROSIS MODELING FOR FINITE ELEMENT ANALYSIS

4.1 Geometric modeling

In otosclerosis, abnormal bone growth occurs in the stapes anterior crus or the front edge of the oval window. For this reason, stapes usually stiffen. As one symptom of otosclerosis, conductive hearing loss occurs which induces cochlear hearing loss in severe cases. In order to verify the effect of the degree of hardening, models where the Young's modulus of a whole annular ligament and a half annular ligament increased were made. These models are shown in Fig. 7.

4.2 Finite element analysis results

In this research, harmonic vibration analysis was done as a dynamic analysis using the finite element method. The material data of Fig. 7 are the same as Table 1 and the boundary conditions of this model are the same as the conditions of 3.3. Figure 8 shows the harmonic vibration analysis results for a healthy subject and four models of an annular ligament hardened through otosclerosis.

In Fig. 8, the longitudinal axis shows the displacement of the stapes basal plane, and the lateral axis represents the frequency. The solid line is the result for the healthy subject. The thin dotted line is the result for the hardened model where the Young's modulus of the annular ligament is 2 times that of the healthy subject. The short dashed line is the result for the hardened model where the Young's modulus of the annular ligament is 10 times that of the healthy

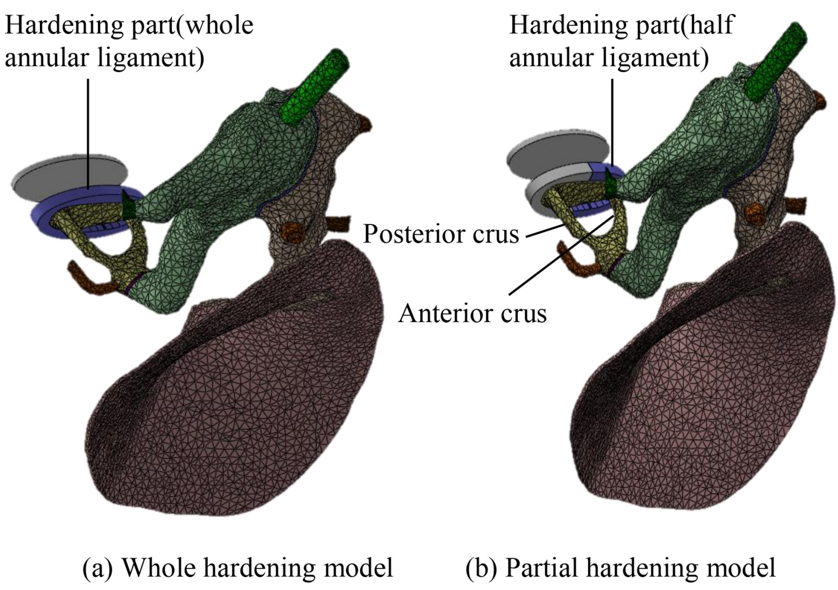


Figure 7: Geometric model of otosclerosis.

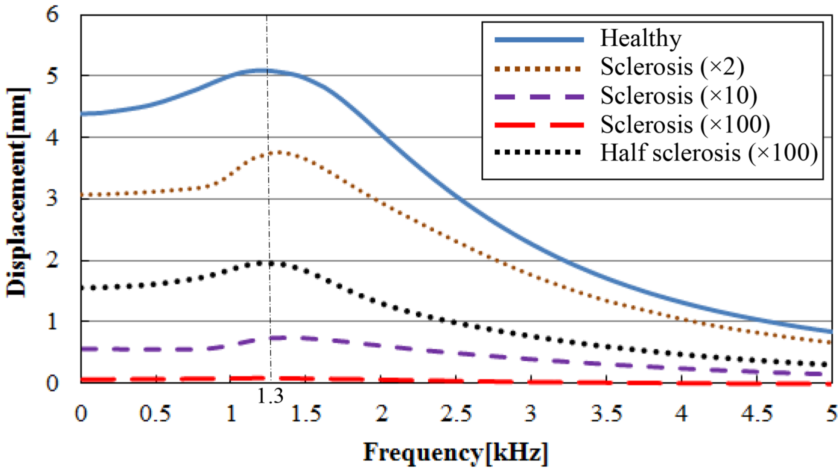


Figure 8: Comparison of frequency response graphs.

subject. The long dashed line is the result for the hardened model where the Young's modulus of the annular ligament is 100 times that of the healthy subject. The above mentioned results correspond to the hardening of the whole annular ligament.

The thick dotted line is the result of the hardened model where the Young's modulus of half of the annular ligament of the stapes anterior crus side is 100 times that of the healthy subject. In this case, the region around the stapes anterior crus stiffened due to a hardening lesion.

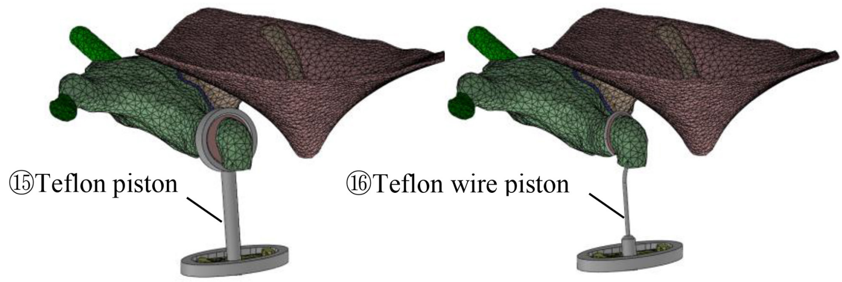
4.3 Considerations

Figure 8 shows that the displacement of the stapes base plane decreases gradually with an increase in Young's modulus of an annular ligament. It seems that the movement of the stapes was suppressed by the hardening of an annular ligament. When the frequency response graph for each model is compared with the healthy model, the resonant frequency is also near 1.3 kHz and the displacement of the stapes basal plane decreases in all frequency range. These results agree with the features in a patient with conductive hearing loss through otosclerosis. Therefore, otosclerosis can be reproduced by this analysis model. The result in which Young's modulus of half of the stapes anterior crus side of the annular ligament increased at 100 times was greater than the result in which the Young's modulus of the annular ligament is 10 times that of the healthy subject. It seems that the remaining half of the annular ligament, which does not harden, is able to serve a role in sound conduction.

5 OTOSCLEROSIS OPERATION AND FINITE ELEMENT MODELING

5.1 Geometric modeling

In otosclerosis operation, the upper part of the stiffened stapes is removed, and a small open window is made in the stapes base plate. Then, a substitute stapes is attached to the hole. As substituting stapes, a Teflon piston and a Teflon wire piston were used in this analysis. The operation model using the Teflon piston is shown in Fig. 9a, and the operation model using the Teflon wire piston is shown in Fig. 9b.Material data



(a) Operation model Ⅰ (b) Operation model Ⅱ

Figure 9: Operation model.

Table 2: Material data of artificial stapes.

<table>
<tr><th colspan="2">Anatomical parts name</th><th>Young's Modulus [MPa]</th><th>Density [kg/m^3]</th><th>Poisson's ratio</th></tr>
<tr><td colspan="2">⑮Teflon piston(PTFE)</td><td rowspan="2">500</td><td rowspan="2">2,165</td><td rowspan="2">0.46</td></tr>
<tr><td rowspan="2">⑯Teflon wire piston</td><td>Shaft(PTFE)</td></tr>
<tr><td>Wire(SUS316)</td><td>193,000</td><td>7,980</td><td>0.3</td></tr>
</table>

Teflon piston ⑮ is composed of the main part and the joint. Telfon (PTFE) was used for the main body, and cartilage for the joint. Teflon wire piston ⑯ is composed of the main body and the joint. Wire made from stainless steel was used for the part of the main body. Material data for Teflon piston ⑮ and Teflon wire piston ⑯ are shown in Table 2. Material data for the joint is the same as the value of ⑪ in Table 1. Other materials ①~⑭ are shown in Fig. 3 and Table 1.

5.2 Finite element analysis results

In this research, harmonic vibration analysis was done as a dynamic analysis using the finite element method. Boundary conditions in the analysis models of Fig. 9 are the same as the conditions of 3.3. Figure 10 shows the harmonic vibration analysis results for a healthy subject and operation models using artificial stapes. The dashed line is the result of the operation model I using an artificial Teflon piston as the stapes. The dotted line is the result of the operation model II using a Teflon wire piston as the artificial stapes.

5.3 Considerations

The resonant frequency of the operation model I using the Teflon piston and the operation model II using the Teflon wire piston is almost equal. The operation model I is about 2.36 nm in the displacement of the substitute stapes at the resonant frequency, and the operation model II is about 2.33 nm. Because the difference is slight at about 1.29%, the improvement rates in hearing ability in both operation models are almost equivalent. Both maximum displacements are lower by about 46% in comparison with the healthy subject (about 5.09 nm).

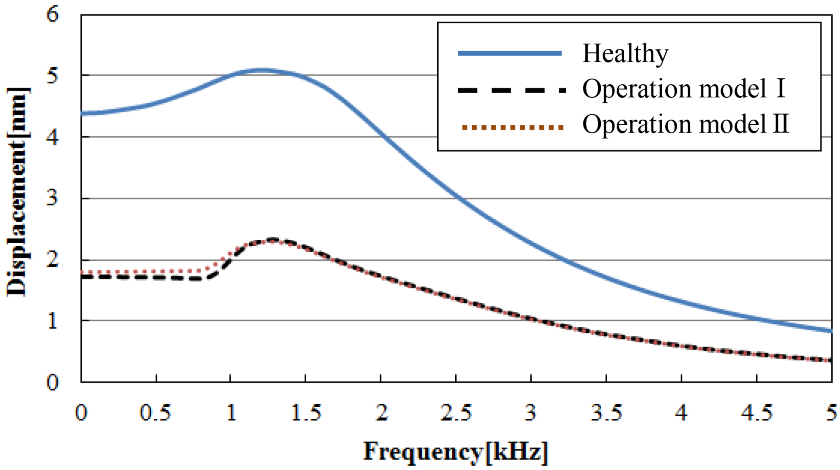


Figure 10: Comparison of frequency response graphs.

However, these were greater than the result in which the Young's modulus of the annular ligament is 100 times greater due to an annular ligament being strongly hardened by otosclerosis shown as shown in Fig. 8. Therefore, it was possible to confirm a certain hearing restoration effect.

6 CONCLUSIONS

We have proposed that the hearing restoration effect can be estimated by comparison of the displacement of stapes basal plane prior to the operation. In order to verify this proposal, various types of operation models were analyzed using harmonic vibration analysis and compared with a healthy subject. As a result, the following knowledge was obtained.

1. An effective operation method using the medical device, called columella, in place of the deficient auditory ossicles can achieve full restoration of hearing ability.
2. On the assumption of the hardening of stapes by otosclerosis, a model in which the Young's modulus of an annular ligament increased was analyzed. As the result, the displacement of the stapes base plate decreased with an increase in the Young's modulus. This phenomenon is correspondent to the frequency characteristics of conductive hearing loss and it was possible to reproduce otosclerosis by this analysis.
3. The displacements of two operation models using the artificial stapes were greater than the model in which an annular ligament strongly hardened by otosclerosis. Therefore, it was possible to confirm a certain hearing restoration effect.

The validity of our proposal was confirmed by this research. This kind of approach makes it possible to propose a new medical treatment for the recovery of conductive or cochlear hearing loss.

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