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Vibration analysis of human middle ear and an application for clinics for tympanoplasty -Development of prediction method for hearing ability restoration

Takao Higashimachi[1] and Ryuzo Toriya[2]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Sojo University, JAPAN*

[2]*Toriya ENT Clinic, JAPAN*

higashimachi@mec.sojo-u.ac.jp

Abstract
A geometric model of the human middle ear was constructed using SolidWorks based on the CT scanning data of a healthy subject. By harmonic vibration analysis, frequency response characteristics of the stapes displacement in sound conduction was clarified. The average displacement of the stapes at a sound pressure of 90 dB is about 5.0 nanometers, which was used as a standard value in our study. Assuming a case in which the auditory ossicles were deficient, a reconstruction model using the columella, instead of the damaged incus, was constructed and analyzed, and the frequency response characteristics of the stapes were clarified. We have proposed a new method for estimating the hearing restoration effect prior to the tympanoplasty operation by comparison of the difference of the stapes displacement between a healthy subject and the reconstruction model. In this study, the model which variously changed the shape (thickness and height) of the annular ligament was analyzed in order to clarify the difference between the frequency response characteristics. Furthermore, the difference when the tympanic membrane is divided into three regions (of which the rigidity differs) was compared with a single region model. The influence that the modeling method of the stapedial annular ligament and the tympanic membrane gives to the frequency response characteristics cannot be ignored. However, the simplified geometric model can be applied to predict the hearing restoration effect. As a clinical application, reconstructive surgery models of the auditory ossicles ,in which the ossicular chain was damaged by chronic otitis media, were constructed in multiple operation types. From the vibration analysis of these models, the possibility of our proposal for reconstruction of the auditory ossicles was verified. The validity of our method was confirmed by clinical applications. Finally, the efficacy of predicting the hearing restoration effect prior to the operation was verified.

Keywords: Geometric model, FEM, Vibration analysis, Human middle ear, Auditory ossicles, Hearing ability, CT, columella

1. Introduction

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. This operation is known as the 'tympanoplasty' which is a reconstructive surgery of the auditory ossicles. In this operation, the sound conduction efficiency changes by the variations in the shape, material and the mounting position of the columella. Actually, the operation is carried out based on the workmanship and experience of the surgeon. We have proposed [1] that the hearing restoration effect can be estimated prior to the operation by comparison of the stapes displacement obtained by the finite element method(FEM).

In this study, harmonic vibration analysis is carried out to investigate the effect on the frequency response characteristics caused by changes in the characteristics of the annular ligament. Furthermore, finite element analysis (FEA) is done based on the division of the tympanic membrane into three regions of which the material property differs. The result is compared with the case in which the membrane is treated as one part for simplicity. Additionally, several kinds of tympanoplasty models for a middle ear damaged by chronic otitis media are constructed and analyzed by FEM. By comparing those analytical results, the possibility of a clinical application of our method is verified.

2. Geometric modelling

2.1. Modelling of stapedial annular ligament

The finite element model is shown in Figure 1. The FEA was carried out with variations to the thickness and height of the annular ligament, and the frequency response characteristics of the stapes were evaluated in order to grasp the effect of these differences on the dynamic characteristics.

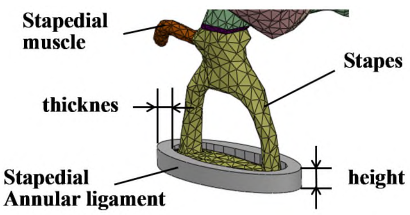

Figure 1. Finite element model of stapedial annular ligament

2.2. Modelling of tympanic membrane

The tympanic membrane has been divided into regions where the physical properties differ. However, since the extraction of each region by CT scanning is difficult, the whole tympanic membrane was modelled and analyzed as one part in our previous research [2]. In this study, the tympanic membrane was divided into three regions - that is, pars tensa, pars flaccida and annulus tympanicus. The FEA of this divided model was carried out, and the frequency response characteristics of the stapes footplate were evaluated.

3. Finite element analysis results

In this analysis, the sound pressure of 90dB was given over the tympanic membrane. Figure 2 shows the relation between the stapes footplate displacement and the frequency in a healthy subject in the case that the characteristics (thickness and height) of the stapes annular ligament vary. The maximum displacement of our standard model is about 5.0 nanometers. The shape of an annular ligament greatly influences the stapes displacement and it seems necessary to extract an exact model by CT scanning. Figure 3 shows the frequency response graph in cases where the tympanic membrane is treated as a single region, and a 3 regions model (in which the rigidity differs). The exact modelling of the tympanic membrane is necessary in order to improve the analysis accuracy. However, the exact extraction of the tympanic membrane is very difficult. If the tympanic membrane can be regarded as loading device which converts sound pressure into mechanical pressure, the prediction of a hearing restoration effect is possible using a single region model.

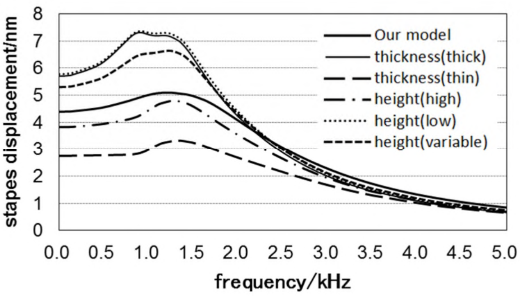

Figure 2. Frequency response graph of healthy model

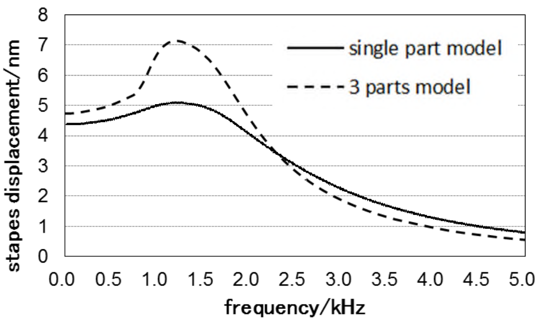

Figure 3. Frequency response in different tympanic membrane models

4. Application to middle ear operation

4.1. Auditory ossicles reconstruction model

In this study, 4 kinds of reconstruction model were constructed. In operation model ①, the columella was connected between the stapes and the damaged incus. In operation model ②, the incus was removed from the model and the columella was connected between the stapes and malleus. In operation model ②, the sound pressure received from the tympanic membrane can not sufficiently transmit to the stapes, since the auditory ossicles move from their original position due to chronic otitis media. Therefore, in operation model ③ the columella was connected between the stapes and malleus after the malleus position was moved around the anterior mallear ligament. In operation model ④ the upper part of the malleus was detached from the anterior mallear ligament and the lateral mallear ligament as is shown in Figure 4. The spring constant is 40N/m [3].

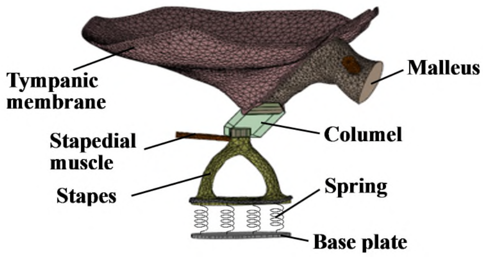

Figure 4. Operation model of ④

4.2. Finite element analysis results

Figure 5 shows the relation between the stapes footplate displacement and the frequency in the 4 operation models (technique①~④). The peak stapes displacement of operation model ④ near 1.5kHz is bigger than that of other methods. In operation model ④, the malleus became easy to move since the upper part of the malleus was detached from the superior mallear ligament. The method depicted in operation model ④ is that which is expected to result in the greatest hearing restoration effect.

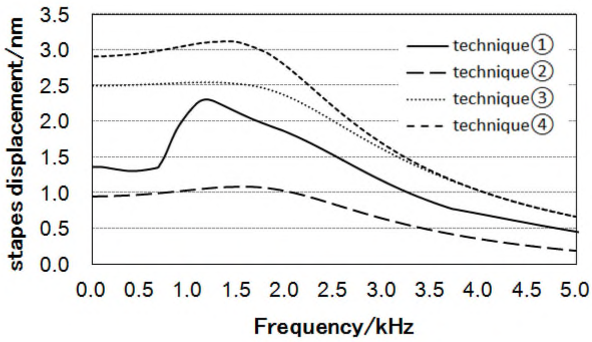

Figure 5. Frequency response of tympanoplasty models

5. Conclusions

(1)The shape of the annular ligament greatly influences the stapes displacement, so it seems necessary to extract an exact model of the middle ear by CT scanning. The exact modelling of tympanic membrane is requisite in order to improve the analysis accuracy. However, the prediction of a hearing restoration effect is possible using the single part model.
(2)In order to improve hearing ability through reconstructive surgery, it is better that the columella be connected between the stapes and the malleus rather than between the stapes and the incus. If the upper part of the malleus is detached from the superior mallear ligament, the malleus becomes easy to move and a hearing restoration effect can be improved.
(3)The validity of our method for estimating the hearing restoration rate by comparing the stapes displacement was confirmed by clinical applications. Finally, the efficacy of predicting the hearing restoration effect prior to surgery was verified.

References

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