euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Development and evaluation of prediction method for sound conduction efficiency of human middle ear

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Abstract
When the human 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 a tympanoplasty operation, the sound conduction efficiency changes according to differences in 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 a new method for estimating the hearing restoration effect prior to the operation. In this method, a geometric model of the 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 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. In this study, as a part of the optimum design of the columella with the aim of better sound conduction, the correlation of columella volume and hearing restoration effect was clarified. In the medical field, the audiogram is made by precise audiometry, and the degree of improvement of hearing ability is evaluated in pre- and post-operation. Audiogram is the record of the value of hearing level, at the minimum audible threshold of every frequency in the hearing test. The calculation formula which obtains the hearing level from the stapes displacement using finite element analysis was devised. This formula was applied to operation models for otosclerosis. The degree of hearing amelioration can be evaluated quantitatively. Through this study, the optimization of reconstruction of the middle ear using the columella becomes possible. Finally, the efficacy of predicting the hearing restoration effect prior to an operation was verified.

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

1. Introduction

When the middle ear has been damaged by various ear diseases, the linkage of the auditory ossicles is reconstructed using the column article of the columella. This is called 'tympanoplasty' or auditory ossicles reconstructive surgery. Based on our previous research [1], we have proposed that the hearing restoration effect can be estimated by a comparison of the stapes displacement with the result for a healthy subject as a standard prior to the operation. Influence of the columella shape and its mounting position to hearing ability was clarified.

In this study, the correlation of hearing restoration effect and the columella volume is examined by the analysis of the tympanoplasty model. In this model, the columella is attached between the malleus and stapes instead of the damaged incus.

In the medical field, the audiogram is made by precise audiometry, and the degree of improvement of hearing ability is evaluated in pre- and post-operation. The audiogram is the record of the value of hearing level or minimum audible threshold at every frequency in the hearing test. A calculation formula which is able to obtain hearing level from the stapes displacement using the finite element analysis was devised. The degree of hearing amelioration can be evaluated quantitatively by this formula. In this study, our proposed method is applied to operation models for otosclerosis, and its validity is discussed.

Through this study, the optimization of the reconstruction of the middle ear using the columella becomes possible.

2. Influence of columella volume on sound conduction

2.1. Geometric modeling

In this research, as part of the optimum design, the correlation of hearing restoration effect and the columella volume is examined. There are four models in which the columella volume is different. The standard model is shown in Figure 1. The additional models were twice, three times, and four times the volume of the standard model. In the analysis of these models, only the size of the columella width was changed.

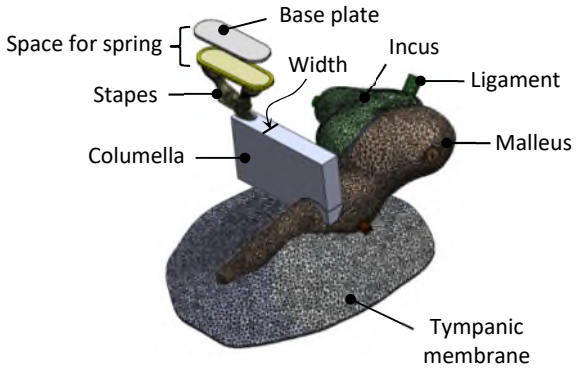

Figure 1. Standard model for tempanoplasty.

2.2. Finite element analysis

In this research, harmonic vibration analysis was performed as a dynamic analysis using the finite element method. Figure 2 shows the harmonic vibration analysis results of four models varying in the volume of the columella. The stapes displacement increases gradually with an increase in the volume of the columella. By increasing the columella volume, it is possible to more firmly connect the columella on the malleus or stapes. Therefore, it appears to improve the transfer efficiency of sound.

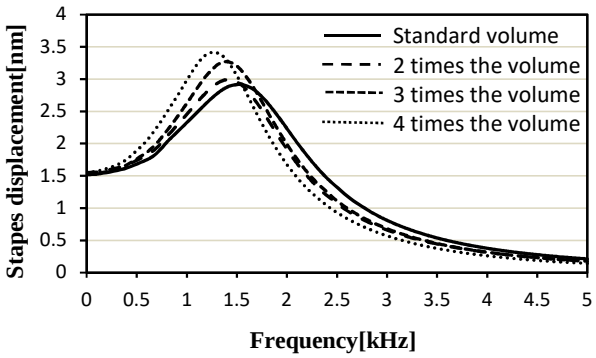

Figure 2. Comparison of frequency response graphs for models varying in columella volume.

3. Otosclerosis operation model

Figure 3 shows the harmonic vibration analysis results for otosclerosis models [2]. The solid line is the result for a healthy subject. The dotted line is the annular ligament hardening model in which the Young's modulus increased to 100 times that of the healthy subject due to otosclerosis. The dashed line is the result of the operation model using an artificial Teflon piston as the stapes. This model is about 2.36 nanometer in the displacement of the stapes at the resonant frequency. The maximum displacement is lower by about 46% in comparison with the healthy subject (5.09 nanometer). However, this is greater than the result for the annular ligament strongly hardened model.

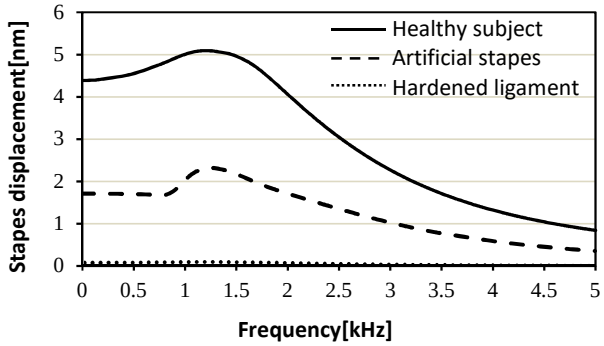

Figure 3. Comparison of frequency response graphs for otosclerosis and its operation models.

4. Evaluation method for hearing ability

The calculation formula of the audiogram which was able to obtain hearing level from stapes displacement using the finite element analysis was devised as follows:

$$L_{HL} = 20\log_{10}(\delta_0/\delta) \qquad (1)$$

In equation(1), L_{HL} is the hearing level that shows the minimum audible threshold (L_{HL} = 0 [dB], for a healthy subject). δ_0 is the stapes displacement for a healthy subject and δ is the stapes displacement for a patient.

Table 1. Hearing level in pre- and post-operation.

Frequency [Hz]	Our analysis results [dB]		Measured results by Moriyama et al. [dB]	
	Pre-operation	Post-operation	Pre-operation	Post-operation
250	33.6	8.01	48	15
500	33.6	8.31	39	8
1000	33.3	7.77	35	6
2000	33.3	7.2	25	5
4000	32.4	6.02	25	6

The hearing level which was calculated by equation (1) using the results of Figure 3 is shown in table 1. Results of Moriyama et al. in table 1 show the mean value of audiometry results which was carried out in pre- and post-operation for 16 otosclerosis patients [3]. Figure 4 shows the audiogram made by using the results of table 1. Our pre-operation results correspond to the result of annular ligament hardening model (dashed line) and our post-operation results correspond to the result of the operation model using an artificial Teflon piston (solid line).

Though some differences are observed in our analytical results and experimental results of Moriyama et al., both results are quite similar. It seems possible to reproduce the audiogram using our method. The hearing restoration effect can be estimated quantitatively prior to the operation using our proposed method.

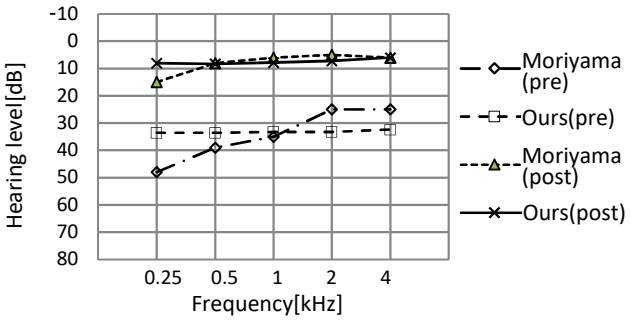

Figure 4. Comparison of audiogram for otosclerosis operation.

5. Conclusion

In order to verify our proposal about prediction and evaluation of hearing ability, various types of operation models were analyzed using harmonic vibration analysis. As part of the optimum design of columella, the correlation of hearing restoration effect and the columella volume was clarified. Furthermore, the calculation formula which obtains hearing level was devised. This equation was applied to operation models for otosclerosis. The degree of hearing amelioration can be evaluated quantitatively. Through this study, the optimization of reconstruction of the middle ear using the columella becomes possible. Finally, the efficacy of predicting the hearing restoration effect prior to an operation was verified.

References

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