Analysis of Tympanic Membrane Reconstruction with Various Thickness Cartilage Plates

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Abstract
The purpose of this research is to investigate an appropriate design of the sliced cartilage used for the reconstruction of the tympanic membrane (TM). A great number of people are suffering from TM perforation caused by diseases or accidents. A surgical procedure, called cartilage myringoplasty, can save the people from hearing loss by replacing the damaged part of the membrane with thin-sliced cartilage. In this research, as the first step of designing the sliced cartilage, we established a three-dimensional finite element model of the human ear for numerical analysis. The ear model consists of the middle ear (TM, ossicular chain, ligaments, muscle), and inner ear cochlea. The joints between ear bones were also modelled with softer tissues. The analysis result of the frequency response shows a good correspondence with measurement results reported by other researchers. Then, using the numerical model, we investigated the optimal thickness of the cartilage plate. The TM was cut at the bottom position with a size of about 40% of TM and filled by cartilage plate with the thickness of 0.1mm to 0.7mm. Comparing with the frequency response of the healthy ear, we found that the optimal thickness of the plate is different in a various frequency range. The reason is considered as the difference of material properties between the membrane and the cartilage. Finally, to evaluate the performance of repaired models in all frequency range, we proposed an equation of matching rate as the evaluation equation. The results show that 0.5mm cartilage plate model shows a better performance at peak response area (600Hz-1kHz), and 0.3mm. cartilage plate model shows better average performance in the total frequency range.

1. Introduction
The human ear is divided into three sections, namely the outer ear, middle ear, and inner ear. The middle ear system is a complicated mechanism, which consists of the TM, three tiny bones called ossicular chain (malleus, incus, and stapes), the ligaments and the muscle. The TM is a thin and semi-transparent membrane located between the outer and middle ear that vibrates after it is hit by sound pressure. Many people have conductive hearing loss due to a problem on the TM such as eardrum...
perforation. Cartilage myringoplasty is a surgical procedure commonly performed by an otolaryngologist for closing TM perforation and improving hearing ability.

In recent years, a number of studies on TM perforation closing by cartilage myringoplasty have been reported by many researchers. Some reported the dynamic behaviour and the numerical modelling of the TM using a numerical and experimental method [1-5]. An experimental and theoretical approach to TM perforation which causes hearing loss in the human middle ear, has been reported [6]. Other papers investigated the experimental result of cartilage in varying thicknesses to determine the acoustics transfer characteristics of cartilage used in the reconstruction of the TM [7-8]. Furthermore, a few studies investigated the experimental result of cartilage in varying thicknesses to determine the acoustics transfer characteristics of cartilage used in the reconstruction of the TM [7-8]. The numerical models they used are simplified to some extent, especially in regards to the treatment of boundary condition of TM, the joints of ear bones, and the ligaments.

In this study, the investigation of the optimal thicknesses of the sliced cartilage closing the TM perforation is carried out. First, a three-dimensional finite element model of human ear consisting middle ear (TM, ossicular chain, ligaments, and muscle) and cochllea in the inner ear is generated by using finite element analysis software. As for the connection of the ossicular chain, the softer tissue is modelled as joints between the ear bones. Then, a part of the TM is replaced by sliced cartilage. The values from 0.1mm to 0.7mm are used as thicknesses of the sliced cartilages to perform frequency response analysis. In the frequency response analysis, the optimal thickness of sliced cartilage used in myringoplasty is calculated by comparing with the healthy ear in the frequency range of 100Hz to 10kHz.

2. FE Modelling of Middle Ear System

To perform the numerical analysis and to investigate the dynamic characteristics of the middle ear, a 3D FE model was established. The geometric data is downloaded from the website, which is a CT scan data obtained from a 75 years old male, and provided by De Greef et al. [11].

2.1. FE Model of middle ear system

Geometric data of each part of the ear was downloaded with STL format, and imported to NX-Nastran, a general-purpose FEM software, to be discretized from the geometrical data into solid elements. After assembling each part, the FE model of the total ear system was built up as shown in Figure 1. It consists of the TM, ossicular chain (malleus, incus, and stapes), ligaments, joints, stapedius muscle, manubrial fold and others. The TM is separated into 3 parts, TM tension, TM relaxation, TM annular ring, and given with different material properties. The part names corresponding to the numbers are shown in Table 1.

![Figure 1. FE-model of total middle ear system.](image)
2.2. Material properties of the middle ear

Table 1 shows the material properties of all components in the middle ear model. The values in Table 1 were decided by considering the references [3, 5].

| No. | Anatomical name                  | Young's modulus (MPa) | Poisson's ratio | Density (kg/m³) |
|-----|----------------------------------|-----------------------|-----------------|-----------------|
| 1   | TM tension                       | 33.4                  | 0.3             | 1200            |
| 2   | TM relaxation                    | 11.1                  | 0.3             | 1200            |
| 3   | Tympanic annular ring            | 0.6                   | 0.3             | 1200            |
| 4   | Malleus                          | 14000                 | 0.3             | 2390            |
| 5   | Incus                            | 14100                 | 0.3             | 2150            |
| 6   | Stapes                           | 14000                 | 0.3             | 2200            |
| 7   | Tensor tympani                   | 5                     | 0.3             | 2500            |
| 8   | Anterior malleolar ligament      | 21                    | 0.3             | 2500            |
| 9   | Posterior incudal ligament       | 4.8                   | 0.3             | 2500            |
| 10  | Lateral mallear ligament         | 6.7                   | 0.3             | 2500            |
| 11  | Stapedius muscle                 | 0.38                  | 0.3             | 2500            |
| 12  | Annular ligament                 | 0.15                  | 0.3             | 2500            |
| 13  | Incudomallear joint              | 7                     | 0.3             | 2500            |
| 14  | Incudostapedial joint            | 6                     | 0.3             | 2500            |
| 15  | Manubrial fold                   | 3.34                  | 0.49            | 1200            |

2.3. Boundary conditions

Some researches modelled the boundary conditions of the edge of TM with torsion springs or combination springs [1, 3]. In this study, the nodes at the circumference of the tympanic annular ring were fixed. Notice that the Young’s modulus of the ring is quite smaller than that of the TM tension. This boundary condition is more suitable to express the translation and bending motions at the edge area of the TM. The ends of tensor tympani, anterior malleolar ligament, posterior incudal ligament, lateral mallear ligament and stapedius muscle were also fixed. As for the load condition, the pressure, converted from the sound pressure was applied at the normal direction of the TM surface.

3. Analysis and Verification of Numerical Model

A dynamic analysis was performed, and the result was compared to the measurement results reported from other researchers to examine the validity of the numerical model.

3.1. Sound pressure

The frequency response analysis of the middle ear model was performed in the frequency range from 100 Hz to 10 kHz. NX Nastran was used as the solver of the analysis. For the convenience of comparing to the measurement results, the sound pressure was set at 90 dB, and it was converted into pressure using equation (1).

\[ L_p = 20 \log_{10} \left( \frac{p}{p_0} \right) \]  

where \( L_p = 90 \) dB is the relative sound pressure, and \( p_0 = 20 \times 10^{-6} \) Pa is the reference sound pressure. The pressure of \( p = 0.632 \) Pa was obtained and applied on the surface of the TM.
3.2. Damping
Some researchers have suggested using Rayleigh's damping for the analysis of the middle ear [1, 3]. Since the software we use cannot select the Rayleigh's damping in frequency response analysis, structural damping was used. Then, the equation of motion of the finite element model can be written as follows:

\[ [M] \ddot{\mathbf{x}} + (1 + jG)[K]\mathbf{x} = \{F\}e^{j\omega t} \quad (2) \]

As for the structural damping coefficient \( G \), it is assumed as a function of frequency \( f \), and determined as below:

\[ G = 0.00021f^2 + 0.4 \quad (3) \]

The initial value \( G_0 = 0.4 \) refers to the research of Hidayat et al. [4], and the coefficient 0.00021 is determined by try-and-error to fit the analyses frequency response curve to the measured one.

3.3. Result and Consideration
Figure 2 shows a frequency response curve obtained by the finite element analysis. It presents the relation between the normal displacement of stapes-footplate and frequency. The normal displacement of stapes-footplate, of which the direction is towards to the cochlea, is considered as an intensity index of the sound wave hitting the cochlea. As a comparison, a measurement curve, which is a mean curve measured from 17 subjects by Gan et al. [2], is also shown in Figure 2. It is concluded that the analyses curve is roughly matched to the measurement curve. Especially, the peak position and peak value of the two curves are almost the same. Therefore, it is reasonable to consider this numerical model can reflect the dynamic behaviours of a healthy ear. This model was used as a reference model to evaluate the repaired model later.

![Figure 2. Comparison of analysis result and experimental result [2].](image)

4. Repairing TM by Cartilages of Various Thickness
Cartilage myringoplasty is an operative procedure that fixes the TM perforation by thin-sliced cartilage. In this study, as a fundamental research for the optimization of this surgery, we investigated the optimal thickness of the sliced cartilage for closing the TM perforation.
4.1. Perforated TM model and sliced cartilage model
As an example, a perforated TM model was created by cutting about 40% area of the TM at the bottom area, as shown in Figure 3. Replacing the perforated part with sliced cartilage, the repaired model was created as can be seen in Figure 4. The red area shows the sliced cartilage plate attached to the TM. The values from 0.1mm to 0.7mm were used as thicknesses of the sliced cartilages to perform frequency response analysis. We attempted to find the optimal thickness of sliced cartilage used in myringoplasty by comparing the frequency response curve with that of the healthy ear in the frequency range of 100Hz to 10kHz. The Young’s modulus and density of the cartilage are 2.8Mpa and $1.3 \times 10^3 \text{kg/m}^3$, respectively.

![Figure 3. Perforated TM](image1)

![Figure 4. A Repaired model with sliced cartilage.](image2)

4.2. Analysis results
The frequency response curves of repaired models of the thickness of 0.3mm/0.4mm/0.5mm/0.6mm /0.7mm cartilage plates are shown in Figure 5. Curves of a thickness of 0.1mm/0.2mm are not shown here to avoid confusion, and for other reasons which will be mentioned in Section 5. The frequency responses of the healthy ear model and the perforated model are also shown in Figure 5 as references. The following results are found from the analysis: a) As a natural result, the response of the healthy ear is higher than that of others in almost all frequency ranges. b) There is only a small difference between the responses of various thickness cartilage plates. c) And among them, the peak position and value of the response of 0.5mm plate model shows a better matching to those of the healthy ear model. d) The response of the 0.3mm plate has a better performance than others except for the range of about 600Hz to 1kHz, the neighborhood of the peak. e) The response of the perforated model shows a large difference to the healthy ear model at the low-frequency range, which is considered to be a reasonable result. However, it shows a better performance at the range of 1kHz to 5kHz. It is interesting to examine further reasons for such results.

![Figure 5. Analysis results of models with different cartilage thickness.](image3)
5. Considerations

Only from the mechanical viewpoint, the thickness larger than 0.5mm is not a choice since its frequency response has no advantage in the peak position, peak value and response performance in all frequency range. The thickness of 0.1mm/0.2mm are also not considered because of the larger gap of the peak position, and peak value to those of healthy ear. Another reason is the increased risk of the fracture using such thin-sliced cartilage in a relatively larger area.

5.1. Evaluation of the dynamic characteristics at the peak area

The frequency response curve of the healthy ear shows a peak point at about 800Hz, which is almost the same as the measurement curve. Around the peak point, there is a plateau in the frequency range of about 500Hz to 1kHz. This frequency range is important to the discrimination of the vowels since the first formants of vowels are in this range.

As for the healthy ear model, the eigen-modes mainly contributing to the plateau area are identified as shown in Figure 6 through the modal analysis.

Concerning the repaired model with 0.5mm cartilage, the eigen-frequencies in this area are obtained as mode 1: 706.9Hz, mode 2: 817.1 Hz, mode 3: 932.6Hz, mode 4: 1065.1Hz, respectively.

As for the repaired model with 0.3mm cartilage, the eigen-frequencies in this area are obtained as mode 1: 691.4Hz, mode 2: 770.0 Hz, mode 3: 915.3Hz, mode 4: 975.8Hz, mode 5: 1075.8 Hz, respectively. Comparing with 0.3mm cartilage model, the 0.5mm cartilage model shows closer performance to the healthy model in both eigen-frequencies and mode shapes in the plateau area.

5.2. Evaluation of response performance in all frequency range

In order to do a quantitative evaluation of the effect of the repaired models, we proposed an equation of matching rate defined as follows:

\[ MR = \left(1 - \sum_{i=0}^{N} w_i \frac{|X_i - X_{0i}|}{\sum_{i=0}^{N} w_i} \right) \times 100 \]

where \(X_i\) is the frequency response of a repaired model at the frequency \(f_i\) of the sampling point \(i\), and \(X_{0i}\) is the frequency response of the healthy ear model at the same sampling point. The frequencies of sampling points are decided as the formula below:

\[ f_i = 100 \times 1.1^N \text{ (Hz)}, \quad N = 0,1,2,\ldots,48 \]

The weight coefficients \(w_i\) of sampling point \(i\) should be decided according to the importance of the frequency for daily conversation. As an example, here we provided the weight coefficients as, 2 in the frequency range of 300Hz to 3kHz, and 1 in the frequency range of others.

Using the proposed equation, the matching rate of each thickness model is calculated as shown in Table 2.
Table 2. Matching rate of each thickness model

| Thickness (mm) | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | Hole |
|----------------|-----|-----|-----|-----|-----|------|
| Matching rate (%) | 76.2 | 74.7 | 73.1 | 71.3 | 69.6 | 66.8 |

As a reference, the index of the perforated model is also listed in this table. Notice that the matching rate of the healthy ear model is 100%. By comparing the values of matching rate to that of the healthy ear model, we can find that 0.3mm model is the best one for the recovery of hearing ability, while perforated model is the worst one.

6. Conclusions
In this research, the proper thickness of the sliced cartilage used for the reconstruction of the TM was investigated numerically. Firstly, a detailed 3D FE model of the human ear was established from the CT scan data. The edge of the TM, ligaments, muscle and joints were faithfully modeled. After adjusting the damping coefficient, the frequency response curve shows a good correspondence with the measurement curve. Then, the optimal thickness of the cartilage plate using for closing the TM perforation was investigated. Comparing with the frequency response of healthy ear, it is found that: 1) in the case of a hole created at the bottom of the TM with a size of about 40% of TM, thickness larger the 0.5mm is not suggestable from the mechanical viewpoint; 2) 0.5mm cartilage plate model shows a better performance at the peak response area (600Hz-1kHz); 3) evaluating with the matching rate equation we proposed, 0.3mm cartilage plate model shows a better average performance at the recovery of hearing ability in total frequency range. To decide the specific dimension of optimal thickness, further investigation is required.

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