Natural Frequencies and Mode Shapes of Human Tympanic Membrane in Myringoplasty

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Abstract: The tympanic membrane of the human ear, sometimes called the eardrum, is a thin membrane that separates the outer and middle ears. Perforation of the tympanic membrane might result in longer-lasting hearing loss. This research aims to determine the natural frequencies and mode shape of the tympanic membrane by using the finite element method. The geometric model of the human tympanic membrane was created using CAD software (Solidworks) based on previously published physical parameters reported by other researchers. Then, Hypermesh was used to carry out eigenvalue analysis by imported the geometrical model. Two analysis models were used to compare the dynamic behavior, namely normal tympanic membrane and reconstruction of the membrane, using sliced cartilage myringoplasty. The thickness of the sliced cartilage was varied from 0.05 to 0.5 mm. Finally, the natural frequency and mode shape of reconstruction of the tympanic membrane is the same as normal tympanic membrane when cartilage thickness is 0.4 mm.

1 INTRODUCTION

Hearing loss is one of the most severe issues that people face in their daily lives. Numerous examples of conductive hearing loss have occurred due to issues with the tympanic membrane or ossicles. A perforated tympanic membrane or perforated eardrum, such as a holed tympanic membrane, is associated with liquid discharge from the middle ear through the ear canal. Tympanic membrane perforation refers to a hole in the thin membrane that divides the outer and middle ears.

Many researchers studying the human middle ear system used finite element analysis to replicate the tympanic membrane's dynamic behavior. The human hearing system's sensitivity to these qualities is determined. The characteristics that dictate the membrane's bending stiffness properties have been investigated, mainly two critical parameters: the tympanic membrane's Young's modulus and the eardrum thickness (Caminos, Garcia-Manrique, Lima-Rodriguez, & Gonzalez-Herrera, 2018). Another study calculates the viscous damping within the tympanic membrane, which may assist in smoothing the wideband response of a possibly highly resonant TM and Examine the role of an unusual element of human middle-ear anatomy: the narrow mucosal epithelial fold that connects the manubrium's midsection to the TM (De Greef et al., 2014). The next study calculates Young's modulus of a thin-shell model of the eardrum with subject-specific geometry that is numerically adjusted to match measured pressured forms (Ghadarghadar, Agrawal, Samani, & Ladak, 2013). Simulation of the dynamic behavior of tympanic membrane perforation had been done using the finite element method (Hidayat, Sudarsono, & Othman, 2020). The frequency responses of the human middle ear system with eardrum perforation using the finite element method were investigated by researchers (Hidayat, Sudarsono, Aviva, & Othman, 2019). The best graft thickness for cartilage myringoplasty was determined using finite element analysis in patients with varying diameters of tympanic membrane (TM) holes (Lee et al., 2007). A study predicted the conductive hearing loss would increase with increasing perforation size (Mehta, Rosowski, Voss, O'Neil, & Merchant, 2006). The simulation of the effect of perforation on the pressure difference across the TM by including a channel for sound coupling from the ear canal to the

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middle-ear cavity through the perforation (Voss, Rosowski, Merchant, & Peake, 2001). A study to determine the acoustic transmission properties of cartilage with various thicknesses and its mechanical deformation in response to air pressure changes (Zahnert, Hüttenbrink, Mürbe, & Bornitz, 2000).

However, there is no report on the tympanic membrane reconstruction using sliced cartilage performing eigenvalue analysis to determine the dynamic behavior. In the present study, the natural frequencies and mode shapes were determined to find out the proper thickness of sliced cartilage used for the reconstruction of tympanic membrane perforation. The three-dimensional model of the human tympanic membrane was created using CAD software. The human tympanic membrane was considered a flat elliptical shape. Then, the Hypermesh was used to generate the finite element model of the tympanic membrane. Two types of finite element model, namely model I and model II. Model I has the same material properties as the material used to close the hole at the center of the membrane then the model II used sliced cartilage myringoplasty. Finally, eigenvalue analysis was performed to determine the proper thickness of cartilage myringoplasty by comparing the natural frequencies and mode shapes of the model I and II.

2 MATERIALS AND METHOD

2.1 Finite Element Model of Human Tympanic Membrane

Figure 1 shows the finite element model of the human tympanic membrane. The human tympanic membrane shown in Fig. 1 was considered a flat elliptic shape. The dimensions of flat elliptic shape are 10 mm and 9 mm for major and minor axis, respectively. This research used a tympanic membrane repaired by sliced cartilage at the center of the membrane. The value of 0.1 mm was used as the thickness of the membrane. Then, the thickness of cartilage was varied from 0.02 to 0.5 mm. In this study, two types of material properties were used to compare the natural frequencies and mode shapes of the human tympanic membrane, considered as Model I and Model II.

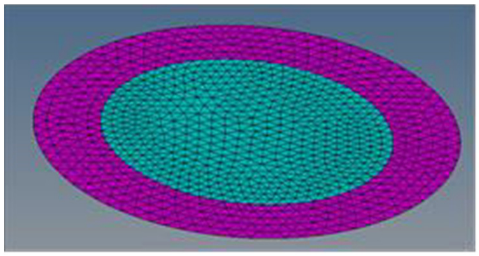

Figure 1: Finite Element Model of Human Tympanic Membrane.

Then, the fixed boundary condition was used around the shape of the tympanic membrane. The six-node triangular element was used to divide the tympanic membrane into 1155 pieces of finite elements.

2.2 Material Properties

Figure 2 shows the material properties of model I and model II. Firstly, the cartilage used in myringoplasty at the center of the tympanic membrane in the model I was defined the same as the material properties of the human tympanic membrane. Secondly, the sliced cartilage with the value of 2.8 N/mm^2 was used as Young's modulus at the center of the human tympanic membrane.

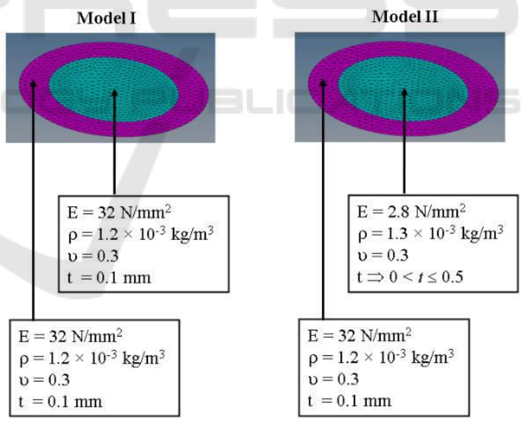

Figure 2: Material Properties of Model I and Model II.

As for the mass density, the value of 1.2×10^{-3} kg/mm^3 was used, which is the same value as the human tympanic membrane. Then, the mass density of sliced cartilage myringoplasty is 1.2×10^{-3} kg/mm^3. Both models used the value of 0.3 for Poisson's ratio.

Finally, the Optistruct of Hypermesh was used to carry out eigenvalue analysis of the model I and II. Eigenvalue analysis was used to obtain the natural frequencies and mode shapes of both models of the human tympanic membrane. In this research, the 1st and 2nd natural frequencies and mode shapes will be compared to each other in order to show the dynamic behavior of models I and II.

3 RESULT AND DISCUSSION

3.1 Result

Figure 3 shows the mode shape of the 1st natural frequency of the human tympanic membrane. The 1st natural frequency was obtained at 440 Hz. The model I and II have similar mode shapes for all-natural frequencies, which shows the fundamental shape for a vibrating circular membrane. The mode number is (0,1) due to the absence of nodal diameters but the presence of a circular node (the outside edge).

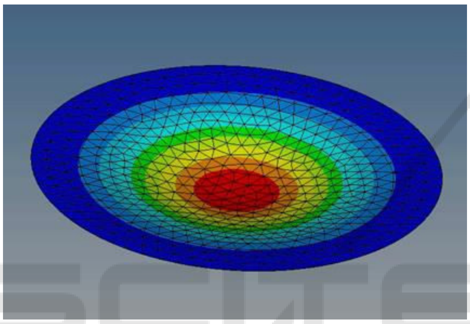

Figure 3: The Mode Shape of the 1st Natural Frequency.

Figure 4 shows the 1st natural frequency of the human tympanic membrane. In the eigenvalue analysis, the thickness of sliced cartilage was varied from 0.02 mm to 0.5 mm. Furthermore, the natural frequencies of model II were increased due to the effect of thickness of sliced cartilage. Thus, model I and model II have the same natural frequency when the thickness of sliced cartilage is 0.42 mm.

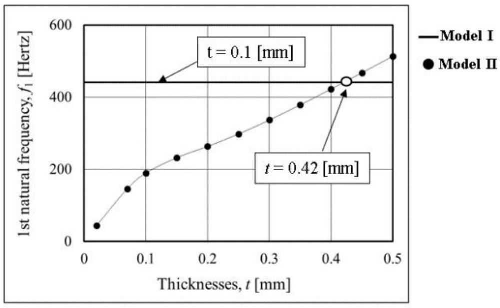

Figure 4: The 1st Natural Frequency of Tym Membrane.

Figure 5 shows the mode shape of the 2nd natural frequency. The mode shape of model I and II are similar mode for the 2nd natural frequency at the 809 Hz. In this case, the mode shape of the tympanic membrane is (1,1), which has a single nodal diameter and a single circular node (the outside edge).

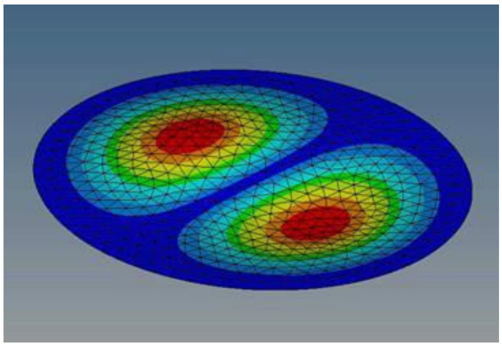

Figure 5: The Mode Shape of the 2nd Natural Frequency.

Figure 6 shows the 2nd natural frequency of the tympanic membrane. The 2nd natural frequency of model II was increased when the thickness of the cartilage myringoplasty become larger. Finally, the 2nd natural frequency for both models has the same value when the thickness of cartilage myringoplasty is 0.398 mm.

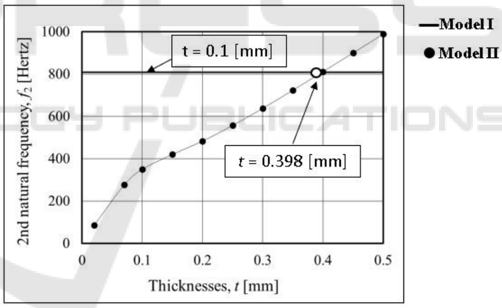

Figure 6: The 2nd Natural Frequency of Tympanic Membrane.

3.2 Discussion

The use of cartilage in TM restoration has been established, most notably in situations of chronic tubal dysfunction, adhesion processes, and complete or recurrent TM abnormalities. This work uses eigenvalue analysis to determine the natural frequency of the human ear system with a healed tympanic membrane following myringoplasty with various cartilage thicknesses. The first and second natural frequencies of the normal tympanic membrane and different thicknesses of reconstruction membrane with cartilage myringoplasty were compared. The study estimated the optimum cartilage thickness for myringoplasty using frequency response analysis but did not include dynamic behavior, such as natural frequency and mode shape. In order to clarify this result, the natural frequency and mode shape of the human tympanic membrane using the actual shape to define the optimum thickness of sliced cartilage myringoplasty.

4 CONCLUSIONS

The effect of various thicknesses on the natural frequency of the human middle ear system during myringoplasty was examined in this study. Eigenvalue analysis of the tympanic membrane with a flat elliptic shape had been carried out to obtain the natural frequencies and mode shapes. The first and second natural frequencies and modes shapes for each model had been compared. The value of around 0.4 mm was defined as the thickness of sliced cartilage in myringoplasty.

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