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EFFECTS OF CROSS-SECTIONAL AREA OF THE COCHLEAR FLUID DUCT ON COCHLEAR INPUT IMPEDANCE

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Abstract. *The effects of the cross-sectional area of the cochlear fluid duct on cochlear input impedance were studied using a three-dimensional finite-element model. The model consists of a middle ear and a cochlea. Two different types of cochlea were used in the model: 1) a tapered box cochlea and 2) a coiled cochlea. The cochlear input impedances of the two cochlear models were compared while varying several properties, such as fluid compressibility, round window density, and the cross-sectional area of the cochlear fluid duct. The results showed that the cross-sectional area of the cochlear fluid duct was the most significant factor in determining the cochlear input impedance. Moreover, change in area at the basal part was more important than at the mid-apical part.*
Keywords: Cochlear input impedance, Cross-sectional area of the cochlear fluid duct, Finite-element model

1. **Introduction.** It is difficult for a sound wave passing through air to be transferred into a fluid because the impedance of the fluid is much higher than that of air. Two mechanical theories can be used to describe the efficient transfer of a sound wave from air (ear canal) to fluid (cochlea) in the middle ear: 1) relationships among force, pressure, and area, and 2) level action [1]. Thus, understanding the cochlear input impedance (Z_c) is important in analyzing the mechanism of hearing. In this study, we sought to examine which component of the cochlea had the most significant effect on Z_c, so we developed a three-dimensional (3D) finite-element (FE) model. The model consists of two parts: the middle ear and the cochlea. We used two different types of cochlea in the model: 1) a tapered box cochlea and 2) a coiled cochlea. We varied several mechanical properties of the components of the cochlear model, and compared the Z_c values between the two types to clarify the most significant factor for Z_c.

2. **Finite-Element Model of the Middle Ear and Cochlea, and Cochlear Input Impedance (Z_c).** We developed an FE model of the middle ear and cochlea. We applied two shapes of cochlea in the model: 1) a tapered box shape (Figure 1) and 2) a coiled shape (Figure 2).

In the model, the input for the FE simulation was the sinusoidal pressure on the tympanic membrane. The dimensions of the tapered box cochlear model were obtained from Yoon et al. [2]. More detailed descriptions of the model and simulation can be found in previous papers [3-5].

The Z_c can be expressed as

$$Z_c = P_{SV}/U_{OW}, \tag{1}$$

where P_{SV} is the pressure at the scala vestibuli (SV) and U_{OW} is the volume velocity of the oval window (OW). P_{SV} was measured at the center of the stapes footplate contacting

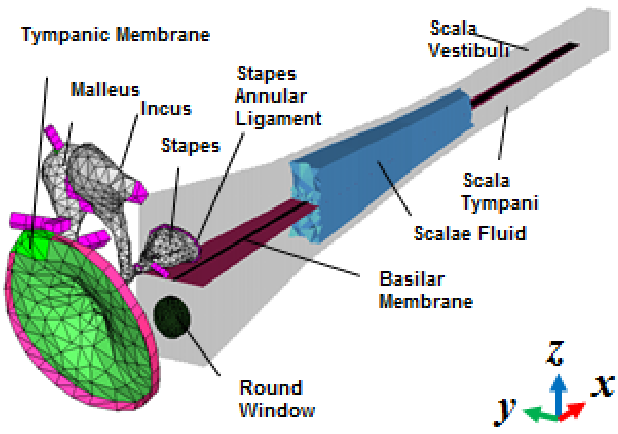

FIGURE 1. A 3D FE model of the tapered box cochlea and middle ear

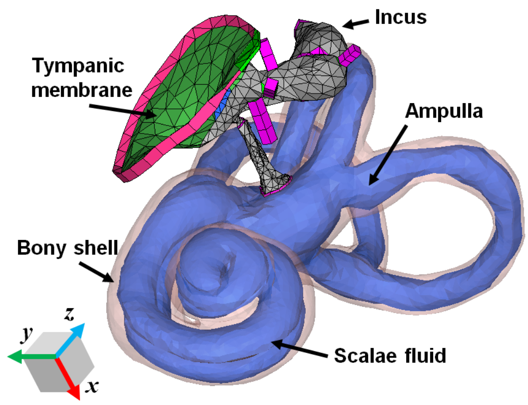

FIGURE 2. A 3D FE model of the coiled cochlea and middle ear

the cochlear fluid. U_{OW} was calculated by integrating the individual volume velocity of the triangular elements on the OW surface.

3. **Cross-Sectional Area of the Cochlear Fluid Duct and the Modified Box Model.** The cross-sectional area of the cochlear fluid duct was calculated along the basilar membrane (BM) length in both the tapered box cochlear model and the coiled cochlear model. The cross-sectional area was obtained every 1 mm from the base to the apex, to be orthogonal to the longitudinal direction of the BM. Figure 3 shows the area of SV and scala tympani (ST) of the two models, as well as physiological data obtained by Thorne et al. [6] for the area.

In the next step, we modified the tapered box model to make its cross-sectional area consistent with that of the coiled cochlea along the BM length. Figure 4 shows the Z_c of the modified cochlear model in comparison with that of the original one and experimental data [7-10]. The original tapered-box cochlea model shows about 6 dB differences in Z_c magnitude versus the original coiled cochlear model above 0.7 kHz. However, when the cross-sectional area of the tapered box cochlea is similar to that of the coiled cochlea, the Z_c of the tapered box cochlea becomes almost the same as that of the coiled cochlea.

Additionally, the cross-sectional area of the tapered-box cochlea was changed to be consistent with that of the coiled cochlea at some specific sections, such as basal part and the apical part, along the BM length, instead of along the entire BM length. Because the total length of the human BM is about 35 mm, 0-12 mm, 13-24 mm, and 25-36 mm sections from stapes along the BM length were considered to represent the basal, mid,

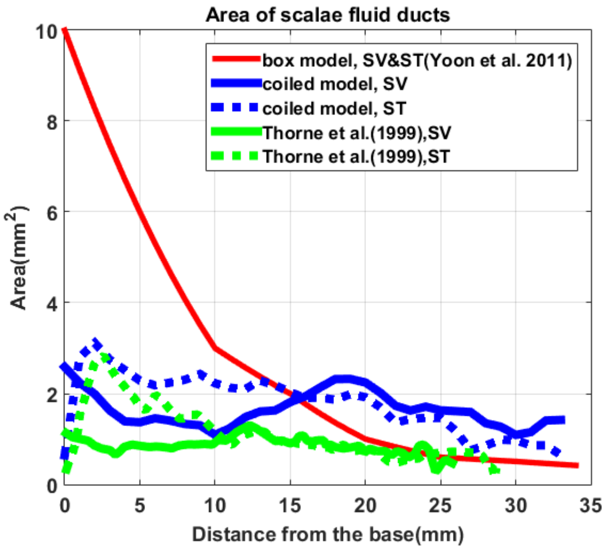

FIGURE 3. Cross-sectional area of the SV and ST along the BM length

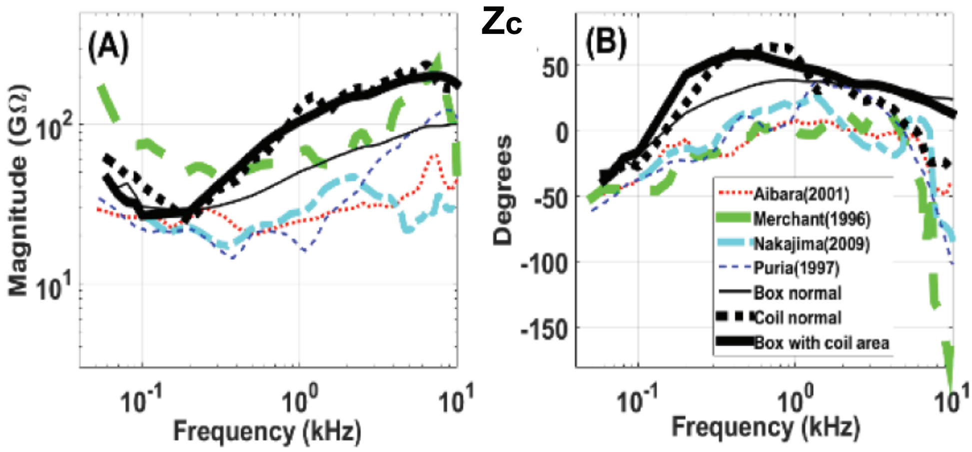

FIGURE 4. (A) Magnitude and (B) phase of Z_c of the tapered-box model, the coiled model, and the box model with the cross-sectional area of the coiled model

and apical sections, respectively. Figure 5 shows the magnitude of Z_c after modifying the cross-sectional area of the fluid duct in some specific sections. The modified tapered-box cochlea had a similar Z_c to the original box cochlea if the cross-sectional area at the basal section (0-12 mm) was not changed (blue-solid line vs. red-solid or cyan-solid lines in Figure 5). The cross-sectional area should not be changed in the whole basal section to keep the original Z_c. If the area changes within the basal section (green-solid, -dotted, and –dashed lines in Figure 5), then Z_c varies.

Furthermore, other potential factors that may affect Z_c were investigated. The following properties were varied to see the effect on Z_c: geometry of the cochlear duct, density of the round window (RW), and compressibility of the cochlear fluid. These modifications were performed with the coiled cochlear model instead of the tapered-box cochlear model. Figure 6 shows the results of the additional modifications.

Changes to the SV area were implemented by modifying the geometry of the basal part. Originally, in the connection between SV and the vestibule, there was a concave section. By replacing the concave connection with a flat connection, we increased the SV area at the base. However, Z_c did not change significantly (red-dotted line in Figure 6). In the

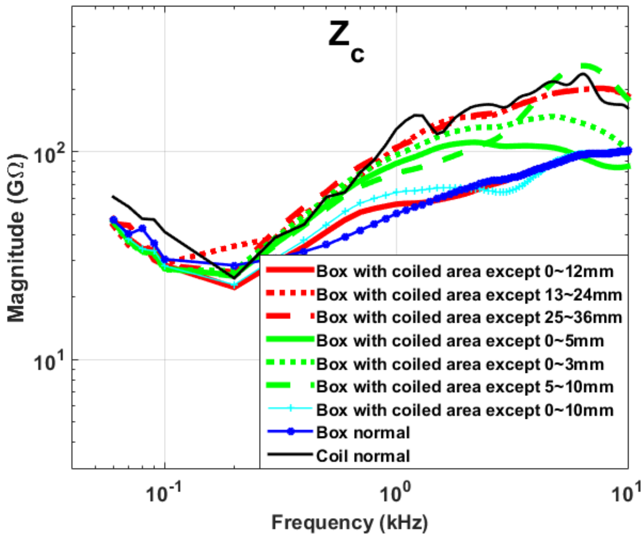

FIGURE 5. Magnitude of Z_c of the tapered-box model with varying the cross-sectional area in some specific ranges along the BM length

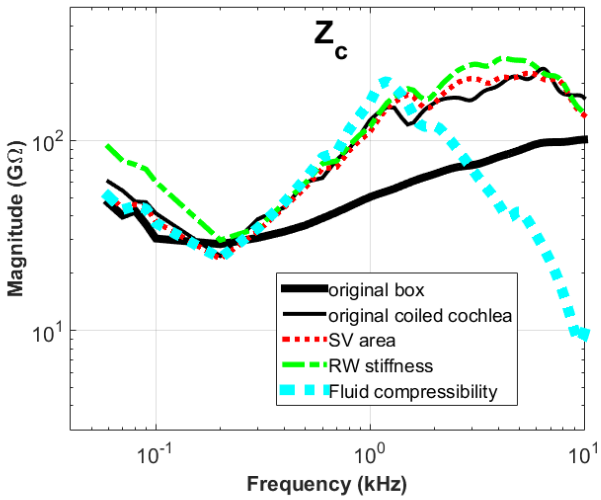

FIGURE 6. Magnitude of Z_c with varying the SV area, RW density, and cochlea fluid compressibility

model, the relationship for Z_c between SV and ST was similar to the parallel resistances in the RLC circuit. Thus, a smaller cross-sectional area can be a more dominant factor affecting Z_c. While the box model had a symmetric cross-sectional area between SV and ST, the coiled model had an asymmetric area: the area of the ST was smaller than that of the SV. Thus, the effect of area change on Z_c was more clearly observed in the box model than in the coiled model. Also, change in ST area was more significant in determining Z_c in the coiled cochlear model.

We decreased the RW density by one order of magnitude from the original case. The decrease in RW density caused a Z_c increase only at low frequencies (below 0.2 kHz; green-dash-dotted line in Figure 6). Because the RW is located in the furthest place from the OW along the BM length, and cochlear fluid is continuous and almost incompressible, the change in RW density affects the Z_c only at low frequencies.

Changes in cochlear fluid compressibility were implemented by decreasing the speed of sound in the fluid to one-third of the original value. In the coiled cochlear model, a decrease in incompressibility did not affect Z_c up to 1 kHz, whereas there was a significant drop in Z_c above 1 kHz. However, the tendency in the Z_c change due to the sound speed (i.e., fluid compressibility) differed significantly in terms of patterns between the box model and the coiled model. Thus, it was difficult to extract a general relationship between fluid compressibility and Z_c for both the box cochlea and the coiled cochlea.

4. **Conclusions.** To clarify the most significant factor for Z_c, we varied several components and mechanical properties with a tapered-box cochlear model and a coiled cochlear model. The FE simulation results revealed that the cross-sectional area of the cochlear duct was the most significant factor tested in determining Z_c. Furthermore, between the two cochlear fluid ducts (i.e., SV and ST), the duct with the smaller cross-sectional area had the more significant effect on Z_c. For the future, we plan to measure the Z_c with varying the cross-sectional area of the cochlear fluid duct. The experiment will be helpful to understand the Z_c as well as to develop a new operation skill for patients who have difficulty in hearing by changing the Z_c.

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