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Exploring the Impact of Pinna Hardness and Vibrator Placement on Bone Conduction Through the Pinna

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1. Introduction

Hearing is a process that enables the ear to detect sound through various pathways. Among them, air conduction and bone conduction have been extensively studied, forming the foundation for many hearing aids and auditory technologies. Recently, cartilage conduction, a bone conduction variant with stimuli on the ear's cartilage, has gained attention in medical and consumer fields[1)]. In cartilage conduction, sound is transmitted to the ear's cartilage using a vibrator placed in front of the ear canal[2)]. This method has led to the development of specialized hearing aids and consumer devices that can be placed on the earlobe or behind the ear[1,3)]. These advancements have highlighted the importance of the pinna in conducting sound, emphasizing the need for further exploration of its function and characteristics.

The field of cartilage conduction is still relatively new, with many unanswered questions about the impact of pinna's hardness and vibrator placement on sound transmission. As the market for cartilage conduction devices grows, the need to understand these factors in depth becomes increasingly important. Hearing researchers have begun to use silicone pinna models to simulate the human ear, allowing for controlled and replicable experiments[4)].

In this study, we build on existing research by employing custom-made silicone pinna models that mirror the structure of the human ear but vary in hardness levels. Differing from previous efforts[4)], we position the accelerometer in a location that aligns more closely with the actual site of the cochlea. This placement offers a more precise simulation of sound propagation through the ear. Through examining the interplay between pinna hardness, vibrator placement, and sound transmission, our research aims to better understand these factors, potentially aiding in enhancing the design of auditory devices relying on cartilage conduction.

2. Method

2.1 Pinna Models

For our study, we used silicone pinna models that were obtained online[5)]. By using various liquid silicones from SiliCreate[6)], we created models representing different Shore hardness levels: 0A, 15A, 30A, and 45A. Since the original lacked an ear canal, we designed one 8 mm in diameter and 13 mm long during the molding process. A video demonstration of the silicone pinna creation can be viewed here: https://youtu.be/KvZY5TiOy1I, omitting the ear canal creation. We placed an accelerometer 5 mm behind the new ear canal, resulting in replicated pinna models that weighed an average of 39±1 gram. It's essential to acknowledge certain constraints in our model: the chosen dimensions for the ear canal and the accelerometer's placement might not correspond precisely to an average human ear. While these factors may influence our study's results, our approach improves previous research by avoiding the problematic placement of the accelerometer on the cymba conchae[4)], near the vibrator in front of the ear canal.

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Fig. 1 *Top panel*: Vibrator in three different pinna locations. *Bottom panel*: Mounting base with accelerometer placement behind the ear canal.

2.2 Vibrator Design and Placement

In the experiment, a commercial bone conduction vibrator (SoundBone GD-SBM) from Golden Dance was utilized. The vibrator, housed within a case designed to resemble an earphone, was positioned in front of the ear canal, a configuration referred to as the "earphone type." The vibrator itself has a 10 mm diameter and an 8-ohm impedance. To facilitate the vibrator's placement on the earlobe and behind the cymba concha, two additional cases were custom-made using a 3D printer. The cases were specifically designed to resemble a clip and an earhook, and thus were named the "clip type" and "earhook type," respectively. The top panel of Fig. 1 illustrates

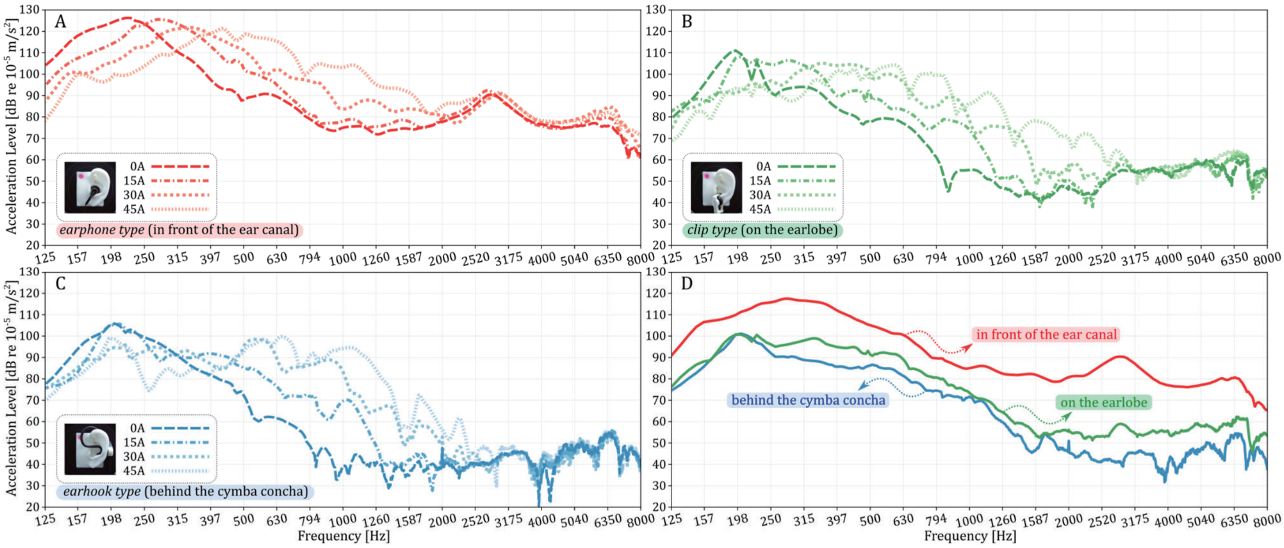

Fig. 2 Acceleration level by frequency for various vibrator placements and pinna hardness. (A-C) depict earphone, clip, and earhook types at four hardness levels; (D) shows average acceleration for each type, averaged across hardness levels.

the original vibrator (earphone type) alongside these two new configurations in their respective locations.

2.3 Experiment Procedure

The experiment was designed to measure the frequency response of sound traveling from the vibrator through the pinna to the accelerometer's location. Silicone pinna models were fixed to a mounting base, and accelerometer model PCB 352A24 was positioned behind the ear canal, as shown in Fig. 1 (bottom panel). A time-stretched pulse (TSP) signal was sent to the vibrator at 1 V_{RMS}, and the propagated sound was recorded by the accelerometer. The recorded TSP signal was convolved with the inverse of the original TSP to extract the impulse response. A Fast Fourier Transform (FFT) was applied to this impulse response to derive the frequency response.

The methodology remained consistent across various pinna hardness levels and vibrator placements. The measurement process was repeated five times per configuration, with the vibrator detached and reinstalled each time. The experimental design recognized that the obtained frequency response would contain the vibrator's characteristics. Since the same vibrator was used in all measurements, its non-flat transfer function remained consistent. This consistency allowed observed changes in frequency response to reflect variations in pinna hardness and vibrator placement, rather than the vibrator itself.

4. Results Interpretation and Conclusion

The frequency response, displayed in Figs. 2A-C, highlights the relationship between acceleration levels and different variables such as vibrator placements and pinna hardness. Observations reveal a consistent response above 3175 Hz, with minimal deviation across pinna hardness. Within the 397 Hz to 3175 Hz range, there is a discernible pattern, as softer pinnas demonstrate more substantial sound attenuation, reflected by a decrease in acceleration level. Interestingly, this trend reverses for frequencies below 397 Hz, likely due to the flexible nature of soft materials and their ability to transmit low-frequency vibrations efficiently.

In Fig. 2D, acceleration levels are averaged across hardness levels, assuming minimal impact on overall response. The earphone type, positioned closest to the accelerometer, shows higher levels, underlining the distance's influence on sound transmission. For the clip and earhook types, results align below 250 Hz. Above this frequency, the earlobe's acceleration level surpasses that behind the cymba concha, an expected outcome given the clip type's closer proximity to the accelerometer.

In conclusion, this study explores how pinna hardness and vibrator placement affect sound transmission. Specifically, the findings show that softer pinnas transmit low-frequency vibrations better, and vibrators closer to the cochlea's representative location have higher sound transmissibility.

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