Cartilage conduction efficiently generates airborne sound in the ear canal

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Abstract

Objective: By attaching a transducer to the aural cartilage, a relatively loud sound is audible even with a negligibly small fixation force. Previous study has identified several pathways for sound transmission by means of cartilage conduction. This investigation focused on the relative contribution of direct vibration of the aural cartilage to sound transmission in an open and in an occluded ear.

Methods: Thresholds with and without an earplug were compared for three experimental conditions; the transducer being placed on the tragus, pretragus, and mastoid. Eight volunteers with normal hearing participated.

Results: The thresholds increased with distance of the transducer from the ear canal (tragus, pretragus, mastoid, in that order). The differences were statistically significant for all conditions except for the occluded ear at 4 kHz. With the earplug inserted, the thresholds for the tragus condition were most sensitive below 2 kHz, indicating a significant contribution of direct vibration of the aural cartilage.

Conclusion: Direct vibration of the aural cartilage can enhance sound transmission. At low frequencies, cartilage conduction can deliver sound efficiently across a blockage in the ear canal. Stray airborne sound radiating from the transducer dominates cartilage conduction in the open ear at high frequencies.

Keywords

Air conduction; bone conduction; occlusion effect; aural cartilage; cartilage-air; cartilage-bone; direct-air; tragus

1. Introduction

The vibration of the cartilaginous portion of the ear canal generates sound in it, and the airborne sound is transmitted to the cochlea via the eardrum. In an open ear, this mechanism does not dominate sound transmission for air- and bone-conductions (AC and BC) [1]. By occluding the ear canal, the airborne sound is trapped in the ear canal, and amplified [2]. In this condition, the airborne sound influences BC thresholds at the frequency of 0.4-1.2 kHz [3]. When the transducer is directly placed on the aural cartilage, the airborne sound significantly influences the thresholds even in an open ear [4]. This form of sound transmission to the cochlea is referred to as cartilage conduction (CC) [5-7]. The transducer for CC is designed for vibrating the aural cartilage not the skull. It differs substantially from a BC transducer in that it is small, lightweight, and can be attached comfortably to the ear with a very small fixation force. Possible applications of CC include hearing aids [7-9], and efficiently delivery of sound to an ear with fibrotic aural atresia [10].

Figure 1 shows three possible sound transmission pathways when the transducer is attached to the aural cartilage. These pathways are referred to as Direct-AC, Cartilage-AC and Cartilage-BC [4, 8]. The Direct-AC, should not include the components of CC because its pathway does not involve the aural cartilage. The stray airborne sound radiated from the transducer also reaches the eardrum for BC [11, 12]. In actual fact, the airborne sound cannot completely be prevented for both conductions. The contribution of the other two pathways (Cartilage-AC, in particular) to the sound transmission is important to distinguish CC from AC and BC. In our previous study, the output levels at the threshold of audibility were compared among AC, BC, and CC using a Head and Torso Simulator and an artificial mastoid [4]. The results showed that the Direct-AC and Cartilage-AC were the dominant sound transmission paths. Although the Direct-AC pathway was blocked with an earplug, the CC thresholds were significantly lower than those for BC below 2 kHz. The previous study shows that CC is classified into neither AC nor BC.

With regard to the transducer location, the advantage of the aural cartilage to the other region has not been evaluated. There are several locations at which a transducer can be placed. If the transducer was attached to a region around the aural cartilage, the airborne sound would efficiently be generated to the same degree as CC. In this study, thresholds with and without an earplug were compared for the CC transducer placed on the tragus (aural cartilage), the pretragus (soft tissue), and the mastoid (bone). In an open ear, the stray sound (Direct-AC sound) radiated from the transducer can reach the ear canal. The amount of Direct-AC sound reaching the ear canal depends on the distance of the transducer from the entrance to the ear canal. To prevent the stray airborne sound from reaching the eardrum, an earplug was used for a matched set of experimental conditions. In an occluded ear canal, the intensity of the radiated airborne sound increases to decrease the thresholds in low frequency range [3]. Our previous study found the threshold decrease at 0.5 kHz for CC when the transducer was placed on the cavity of the ear canal [4]. The current results will reveal the difference in the contribution of Direct-AC and Cartilage-AC to the sound transmission among the locations. The purpose of this study is to clarify the characteristics of CC and the advantage of directly vibrating the aural cartilage to the sound transmission.

2. Materials and Methods

Eight volunteers (4 females and 4 males; 28–37 years old) with normal hearing participated in this experiment. The experimental procedure was approved by the ethics committee of Nara Medical University. Participants provided written informed consent before being enrolled. Before the experiment, AC and BC thresholds at frequencies of 0.5, 1, 2, and 4 kHz were measured. The ear with lower average BC thresholds was employed for this study in each subject.

Figure 2 shows the transducer whose property is described in the previous study (Nishimura et al, in press). The tragus (aural cartilage), pretragus (soft tissue), and mastoid (bone) locations for transducer placement are shown in Figure 2. The transducer was fixed in each location with adhesive tape to keep the plane of vibration in contact with the body. The threshold of audibility was measured at each of the three transducer locations without and with an earplug. Threshold measurements for the six experimental conditions were obtained in a randomized order. The thresholds were measured twice and averaged for each experimental condition. The experiment was performed in a sound proof room.

2.1. Threshold measurement

The thresholds were measured using a two-alternative forced-choice (2AFC) procedure. The transformed up-down procedure was used to adjust stimulus levels adaptively to converge on that stimulus level at which the probability of detecting the sound is 0.707 [13]. The details are described in the previous study [4]. Thresholds were measured at frequencies of 0.5, 1, 2, and 4 kHz using a 2-dB step. The test stimuli consisted of tone bursts of 500 ms duration, including rise/fall ramps of 10 ms, Narrow band noise was presented at the opposite ear to mask any stray or cross-conducted sound reaching the contralateral ear. The intensity of the masking noise was set at the AC threshold level at the non-objective ear obtained in the preliminary measurement plus 30 dB. This masking level was selected in order to prevent cross-hearing and over-masking. The testing procedure was programed using RPvdsEX ver. 6.2 (Tucker-Davis Technologies, Gainesville, FL, USA). The stimulus output and response input were processed using a real–time processor (RP2.1, Tucker-Davis Technologies).

2.2. Earplug

The earplug was made in the same manner as the previous study [4]. Based on the ear impression, an acrylic earplug was made to fit the ear canal tightly and to be sufficiently deep to the second bend.

2.3. Statistical analysis

Thresholds for the open and occluded ear canal were compared for the three transducer locations. The data were subjected to a three-way repeated-measures analysis of variance (ANOVA), with transducer location, earplug, and frequency as within-subject factors. Bonferroni method was used for post-hoc comparisons. In addition, the threshold shifts with insertion of the earplug were also analyzed. A two-way ANOVA, with transducer location and frequency as within-subject factors was used to analyze the threshold shifts. Bonferroni method was also used for post-hoc comparisons. The significance level was set at $p < 0.05$.

3. Results

The three–way ANOVA revealed statistically significant effects for transducer location (F [2, 14] = 193.74, p<0.001), earplug (F [1, 7] = 15.52, p<0.01), and frequency (F [3, 21] = 19.10, p<0.001). Interactions among these factors were also significant. The interactions with ear plug and frequency are evident from Figures 3 and 4. Figure 3 shows the observed thresholds for the occluded ear canal (earplug inserted). At 0.5 kHz, the threshold for the tragus condition was 22.1 dB lower than that for the pretragus condition and 29.1 dB lower than that for the mastoid condition. At 1 kHz, the threshold differences were smaller at 15.1 dB and 22.2 dB, respectively and at 2 kHz the differences were even smaller at 13.8 dB and 12.3 dB, respectively. At 4 kHz, the thresholds for the tragus, pretragus and mastoid conditions did not differ significantly. Figure 4 shows the observed thresholds for the open ear canal (no earplug). At each test frequency, the thresholds increased for the tragus, pretragus, and mastoid conditions in that order. The threshold for the pretragus condition was 18.5 dB to 21.1 dB higher than that for the tragus for frequencies below 4 kHz but only 9.4 dB higher at 4 kHz. The thresholds for the mastoid condition were consistently higher at all frequencies (by 26.4 to 29.8 dB) than the thresholds for the tragus condition.

Figure 5 shows the increase in threshold shift with the insertion of the earplug. A two–way ANOVA revealed statistically significant effects for transducer location (F [2, 14] = 10.90, $p<0.01$) and frequency (F [3, 21] = 257.06, $p<0.001$). An interaction between these factors was also recognized. The most striking aspect of the data is the change in the direction of threshold shift as a function of frequency. At 0.5 kHz, the thresholds are lower by just under 20 dB for all three transducer locations. At 1 kHz, insertion of the earplug has little effect on the observed thresholds. The thresholds are within +/- 4 dB of each other. Post hoc statistical tests did not show any significant differences among these thresholds. At 2 kHz, insertion of the earplug results in a significant increase in the thresholds for all three transducer locations. The tragus condition shows the largest increase (22.5 dB) while the mastoid condition shows the smallest increase (6.4 dB). The same pattern of increased thresholds is shown at 4 kHz. In this case, the increase is 32.7 dB for the tragus condition and 10.1 dB for the mastoid condition.

4. Discussion

For the occluded ear, the lowest threshold was observed when the CC transducer was placed on the tragus at the frequency of 0.5, 1, and 2 kHz. Except for the frequency of 4 kHz, the tragus condition was most effective for radiating the signal in the ear canal. The most typical findings were observed at the frequency of 0.5 kHz. For the tragus condition, the threshold at 0.5 kHz was 15.9 dB re a voltage of 0.1 mv applied to the transducer. When the CC transducer is placed on the pretragus, the sound transmission path is longer and the sound has to travel through both soft tissue and cartilage. The result at the frequency of 0.5 kHz was a relatively high threshold of 38.0 dB indicating that the signal was attenuated by 22.1 dB for the extra distance travelled. When the CC transducer is placed on the mastoid, the sound transmission path involves transduction across the skin and then bone conduction to the cartilaginous portion of the ear canal wall. The resulting threshold at 0.5 kHz was 45.0 dB indicating an attenuation of 29.1 dB for this pathway. Considering the fixation placements, the attenuation of the signal due to the extra distance for the pretragus condition was too large. The impedance mismatch between the cartilaginous portion of the ear canal and fibrotic tissue might attenuate the signal [14].

As for possible applications, CC is utilized for hearing aids for the ear with aural atresia

[7-9]. The previous study found a great benefit of CC hearing aids, particularly to the ear with fibrotic aural atresia. Fibrotic tissue connected to the ossicles provides an additional pathway, (termed fibrotic tissue pathway) for sound to reach the cochlea by means of CC [10]. Not the airborne sound but the vibration of the fibrotic tissue mediates the sound transmission in the ear with fibrotic aural atresia. Sound in the low to middle frequency range is transmitted more efficiently by CC than BC, although the CC transducer is placed with a negligibly small fixation pressure [10]. Direct vibration of the aural cartilage is very effective form to generate not only sound but also vibration in the ear canal, which may be responsible for effective sound transmission for an acquired aural atresia with fibrotic tissue pathway [8, 10].

The attenuation of the signals in the extra pathways from the tragus to the pretragus or mastoid decreased with increasing frequency. That is, the advantage of CC was decreased with increasing frequency. There is a problem at 4 kHz in that the thresholds were relatively high and are very similar for all three transducer locations (51.8 to 56.3 dB). The earplug used in this study was the same as that used in the previous study [4]. The attenuation of this earplug at 4 kHz is approximately 36 dB for conventional AC and it is likely that at 4 kHz there is substantial attenuation of cartilage conducted sound but no comparable attenuation of the Direct-AC sound radiated by transducer. If the intensity of the Direct-AC sound is more than 36 dB greater than the cartilage conducted sound, the earplug will not be effective in preventing Direct-AC sound from reaching the ear. That is, the observed thresholds at 4 kHz are unlikely to be representative of CC only and that the true CC thresholds would be much higher. Furthermore, the previous study showed no difference in the threshold at 4 kHz between BC and CC in the occluded ear canal [4]. The BC pathway was also important at 4 kHz. Just by the current results, it was not determined whether the Cartilage-AC sound dominated the transmission of 4 kHz sounds in the occluded ear canal.

Figure 4 shows the thresholds for the open ear canal. In this case, both Direct-AC and Cartilage-AC sounds contribute to the observed thresholds [4]. A comparison of the thresholds in Figures 3 and 4 show that at 0.5 kHz the thresholds for the occluded ear canal are well below those obtained for the open ear canal. An airborne signal in the volume enclosed between the earplug and eardrum is amplified at a low frequency [2, 3]. This phenomenon is referred as to the occlusion effect. The threshold decrease at 0.5 kHz by the earplug indicated that the signal transmitted via the Cartilage-AC pathway was amplified by the occlusion effect. At this low frequency, the Cartilage-AC pathway is thus dominant. Similarly, at 4 kHz the threshold for the tragus in the open ear canal is much lower than that in the occluded ear canal. In the previous study, no difference in the threshold-shift by an earplug was observed between AC and CC [4]. Furthermore, as the above-mentioned, no significant effect of the transducer location was observed. At this high frequency, the Direct-AC pathway is dominant. The thresholds for the open and occluded ear canals at 1 kHz are not very different indicating that both Direct-AC and Cartilage-AC pathways are equally important at this frequency. At 2 kHz, the attenuation of this earplug at 4 kHz is approximately 34 dB for conventional AC in the previous study [4]. The thresholds for the open ear canal are lower than those for the occluded ear canal but not by a very large amount so that both Direct-AC and Cartilage-AC sounds are important at this frequency. The contribution of the Direct-AC pathway depends on the distance from the entrance of the ear canal. The current threshold-shifts by the earplug reflected the distance at the frequencies above 2 kHz. Stray airborne sound is also radiated by BC transducers [11, 12] and this is an issue that needs to be addressed in the design of both BC and CC transducers.

5. Conclusion

Direct vibration of the aural cartilage can enhance sound transmission. At low frequencies, cartilage conduction can deliver sound efficiently across a blockage in the ear canal. Stray airborne sound radiating from the transducer dominates cartilage conduction in the open ear at high frequencies.

Acknowledgements

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Figure legends

Figure 1 Scheme of the three main theoretical components of cartilage conduction

When the transducer is placed on the aural cartilage, sounds are transmitted to the cochlea via the three illustrated pathways. They are referred to as direct-air conduction, cartilage-air conduction, and cartilage-bone conduction [4].

Figure 2 Transducer and its fixation forms

Photo (a) shows the transducer. The photos (b, c, d) show the fixation of the transducer on the tragus (b), pretragus (c), and mastoid (d). The transducer was fixed on each location with an adhesive tape.

Figure 3 Thresholds for the occluded ear canal

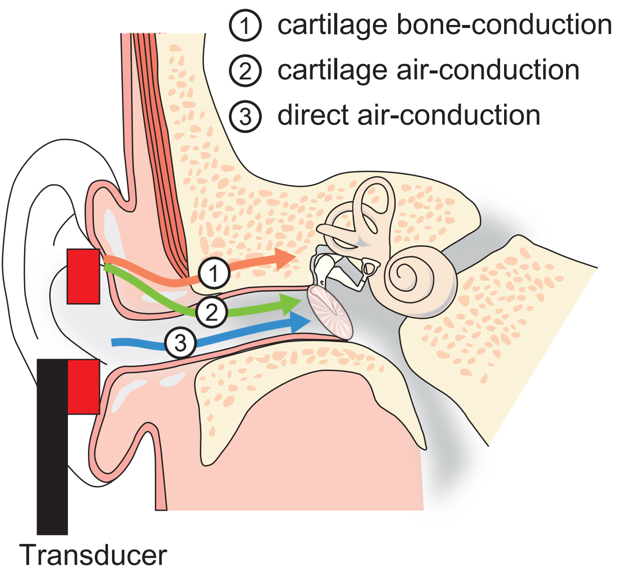
The thresholds are represented in dB scale referring to the input voltage of 0.1 mV. Vertical bars indicate standard deviations.

Figure 4 Thresholds for the open ear canal

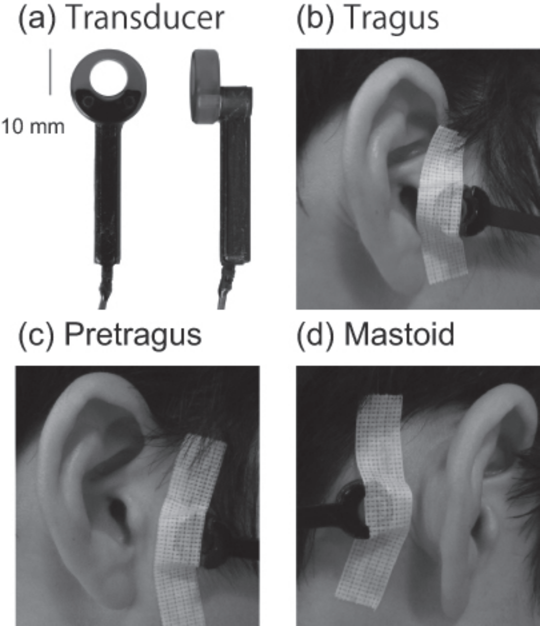
The thresholds are represented in dB scale referring to the input voltage of 0.1 mV. Vertical bars indicate standard deviations.

Figure 5 Threshold increase with the insertion of the earplug

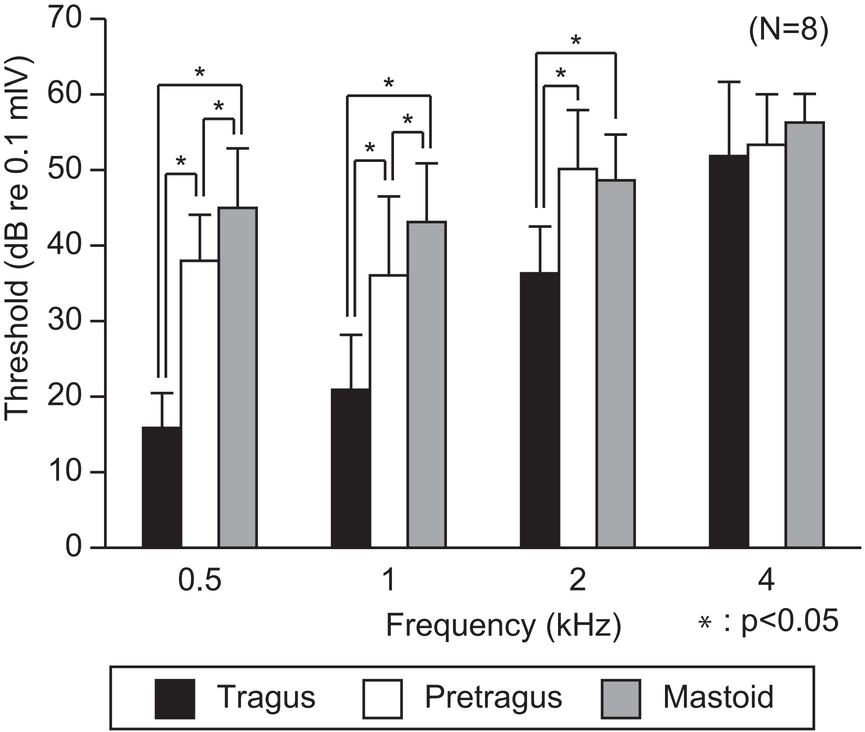
The threshold increases were calculated by subtracting the thresholds without the earplug from with it. Vertical bars indicate standard deviations.



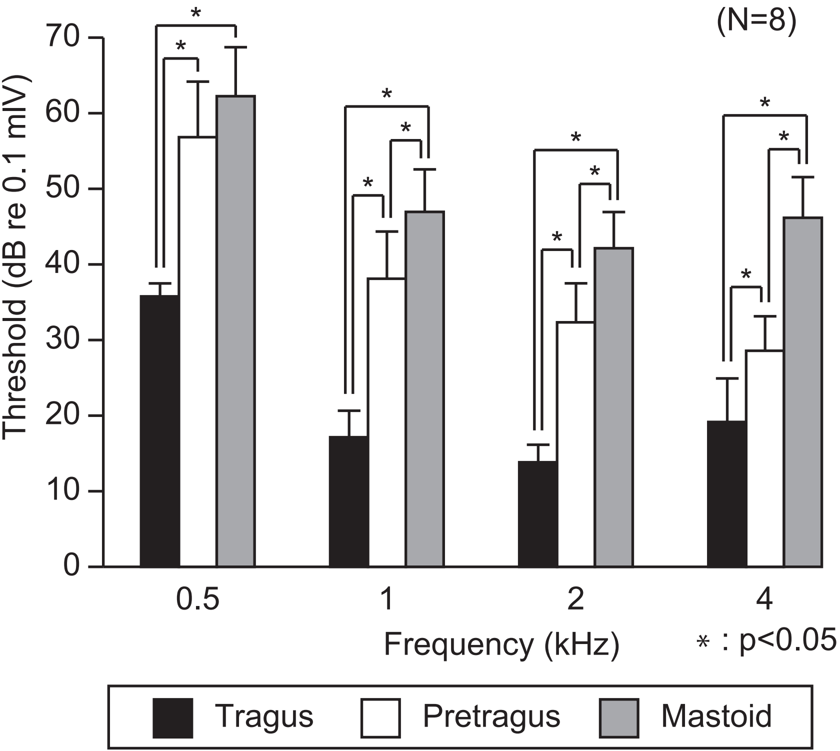
① cartilage bone-conduction
② cartilage air-conduction
③ direct air-conduction
1
2
3
Transducer



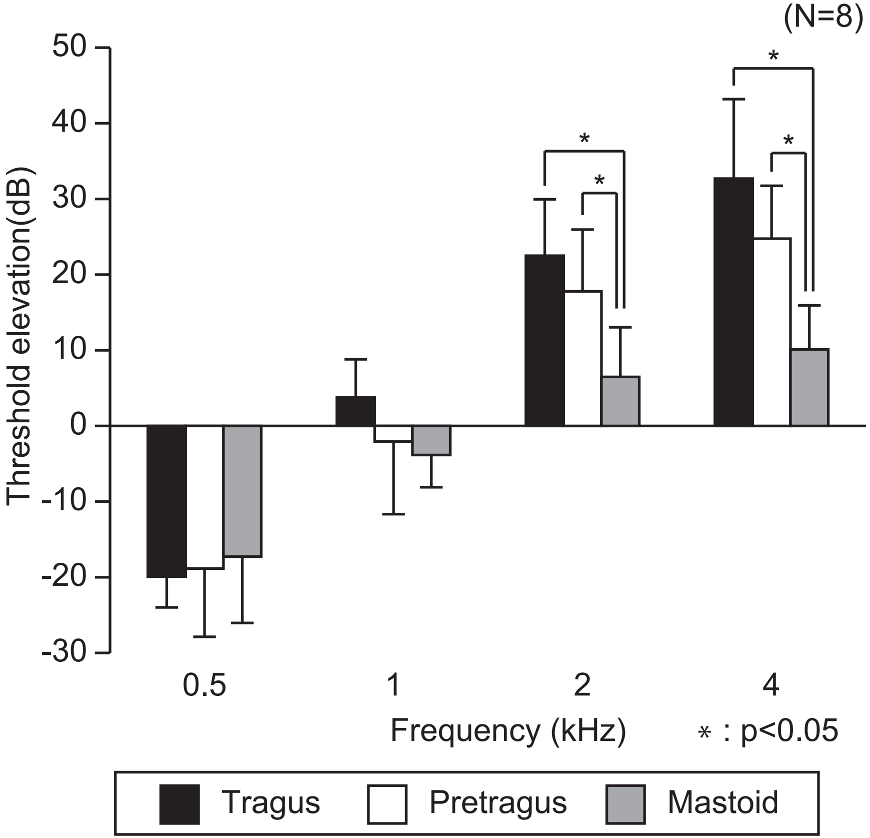
(a) Transducer
10 mm
(b) Tragus
(c) Pretragus
(d) Mastoid



70
60
50
40
30
20
10
0
Threshold (dB re 0.1 mlV)
(N=8)
*
0.5
1
2
4
Frequency (kHz)
* : p<0.05
Tragus
Pretragus
Mastoid



(N=8)
Threshold (dB re 0.1 mlV)
70
60
50
40
30
20
10
0
0.5
1
2
4
Frequency (kHz)
* : p<0.05
Tragus
Pretragus
Mastoid


(N=8)
50
40
30
20
10
0
-10
-20
-30
Threshold elevation(dB)
*
*
*
*
0.5
1
2
4
Frequency (kHz)
* : p<0.05
Tragus
Pretragus
Mastoid