Cartilage conduction efficiently generates airborne sound in the ear canal

Tadashi Nishimura^{a,*} MD, PhD, Hiroshi Hosoi^b MD, PhD, Osamu Saito^a, Ryosuke Miyamae^a MD,
Ryota Shimokura^a PhD, Toshie Matsui^c PhD, Toshiaki Yamanaka^a MD, PhD, Tadashi Kitahara^a MD,
PhD, Harry Levitt^d PhD

^a *Department of Otolaryngology-Head and Neck surgery, Nara Medical University, 840 Shijo-cho,
Kashihara, Nara 634-8522, Japan*

^b *Nara Medical University, 840 Shijo-cho, Kashihara, Nara 634-8522, Japan*

^c *Department of Life Science Center of Tsukuba Advanced Research Alliance, University of Tsukuba,
1-1-1 Tennodai, Tsukuba, Ibaragi 305-8577, Japan*

^d *Professor Emeritus, The City University of New York*

* Corresponding author.

Address: Department of Otolaryngology-Head and Neck surgery, Nara Medical University, 840
shijo-cho Kashihara, Nara 634-8522, Japan

Tel.: +81-744-22-3051; Fax: +81-744-24-6844; E-mail: t-nishim@naramed-u.ac.jp

1 **Cartilage conduction efficiently generates airborne sound in the ear canal**

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20 **Abstract**

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

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

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

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

39

40 **Keywords**

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

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44 **1. Introduction**

45

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

57 Figure 1 shows three possible sound transmission pathways when the transducer is attached
58 to the aural cartilage. These pathways are referred to as Direct-AC, Cartilage-AC and Cartilage-BC
59 [4, 8]. The Direct-AC, should not include the components of CC because its pathway does not
60 involve the aural cartilage. The stray airborne sound radiated from the transducer also reaches the
61 eardrum for BC [11, 12]. In actual fact, the airborne sound cannot completely be prevented for both
62 conductions. The contribution of the other two pathways (Cartilage-AC, in particular) to the sound

63 transmission is important to distinguish CC from AC and BC. In our previous study, the output levels
64 at the threshold of audibility were compared among AC, BC, and CC using a Head and Torso
65 Simulator and an artificial mastoid [4]. The results showed that the Direct-AC and Cartilage-AC
66 were the dominant sound transmission paths. Although the Direct-AC pathway was blocked with an
67 earplug, the CC thresholds were significantly lower than those for BC below 2 kHz. The previous
68 study shows that CC is classified into neither AC nor BC.

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

82 locations. The purpose of this study is to clarify the characteristics of CC and the advantage of
83 directly vibrating the aural cartilage to the sound transmission.

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85 **2. Materials and Methods**

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

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

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101 **2.1. Threshold measurement**

102

103 The thresholds were measured using a two-alternative forced-choice (2AFC) procedure. The
104 transformed up-down procedure was used to adjust stimulus levels adaptively to converge on that
105 stimulus level at which the probability of detecting the sound is 0.707 [13]. The details are described
106 in the previous study [4]. Thresholds were measured at frequencies of 0.5, 1, 2, and 4 kHz using a
107 2-dB step. The test stimuli consisted of tone bursts of 500 ms duration, including rise/fall ramps of
108 10 ms, Narrow band noise was presented at the opposite ear to mask any stray or cross-conducted
109 sound reaching the contralateral ear. The intensity of the masking noise was set at the AC threshold
110 level at the non-objective ear obtained in the preliminary measurement plus 30 dB. This masking
111 level was selected in order to prevent cross-hearing and over-masking. The testing procedure was
112 programed using RpvdsEX ver. 6.2 (Tucker-Davis Technologies, Gainesville, FL, USA). The
113 stimulus output and response input were processed using a real-time processor (RP2.1, Tucker-Davis
114 Technologies).

115

116 **2.2. Earplug**

117

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

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121 **2.3. Statistical analysis**

122

123 Thresholds for the open and occluded ear canal were compared for the three transducer locations.

124 The data were subjected to a three-way repeated-measures analysis of variance (ANOVA), with

125 transducer location, earplug, and frequency as within-subject factors. Bonferroni method was used

126 for post-hoc comparisons. In addition, the threshold shifts with insertion of the earplug were also

127 analyzed. A two-way ANOVA, with transducer location and frequency as within-subject factors was

128 used to analyze the threshold shifts. Bonferroni method was also used for post-hoc comparisons. The

129 significance level was set at $p < 0.05$.

130

131 **3. Results**

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133 The three-way ANOVA revealed statistically significant effects for transducer location ($F [2, 14] =$

134 $193.74, p < 0.001$), earplug ($F [1, 7] = 15.52, p < 0.01$), and frequency ($F [3, 21] = 19.10, p < 0.001$).

135 Interactions among these factors were also significant. The interactions with ear plug and frequency

136 are evident from Figures 3 and 4. Figure 3 shows the observed thresholds for the occluded ear canal

137 (earplug inserted). At 0.5 kHz, the threshold for the tragus condition was 22.1 dB lower than that for

138 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

158 tragus condition and 10.1 dB for the mastoid condition.

159

160 **4. Discussion**

161

162 For the occluded ear, the lowest threshold was observed when the CC transducer was placed on the
163 tragus at the frequency of 0.5, 1, and 2 kHz. Except for the frequency of 4 kHz, the tragus condition
164 was most effective for radiating the signal in the ear canal. The most typical findings were observed
165 at the frequency of 0.5 kHz. For the tragus condition, the threshold at 0.5 kHz was 15.9 dB re a
166 voltage of 0.1 mv applied to the transducer. When the CC transducer is placed on the pretragus, the
167 sound transmission path is longer and the sound has to travel through both soft tissue and cartilage.
168 The result at the frequency of 0.5 kHz was a relatively high threshold of 38.0 dB indicating that the
169 signal was attenuated by 22.1 dB for the extra distance travelled. When the CC transducer is placed
170 on the mastoid, the sound transmission path involves transduction across the skin and then bone
171 conduction to the cartilaginous portion of the ear canal wall. The resulting threshold at 0.5 kHz was
172 45.0 dB indicating an attenuation of 29.1 dB for this pathway. Considering the fixation placements,
173 the attenuation of the signal due to the extra distance for the pretragus condition was too large. The
174 impedance mismatch between the cartilaginous portion of the ear canal and fibrotic tissue might
175 attenuate the signal [14].

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

177 [7-9]. The previous study found a great benefit of CC hearing aids, particularly to the ear with
178 fibrotic aural atresia. Fibrotic tissue connected to the ossicles provides an additional pathway,
179 (termed fibrotic tissue pathway) for sound to reach the cochlea by means of CC [10]. Not the
180 airborne sound but the vibration of the fibrotic tissue mediates the sound transmission in the ear with
181 fibrotic aural atresia. Sound in the low to middle frequency range is transmitted more efficiently by
182 CC than BC, although the CC transducer is placed with a negligibly small fixation pressure [10].
183 Direct vibration of the aural cartilage is very effective form to generate not only sound but also
184 vibration in the ear canal, which may be responsible for effective sound transmission for an acquired
185 aural atresia with fibrotic tissue pathway [8, 10].

186 The attenuation of the signals in the extra pathways from the tragus to the pretragus or
187 mastoid decreased with increasing frequency. That is, the advantage of CC was decreased with
188 increasing frequency. There is a problem at 4 kHz in that the thresholds were relatively high and are
189 very similar for all three transducer locations (51.8 to 56.3 dB). The earplug used in this study was
190 the same as that used in the previous study [4]. The attenuation of this earplug at 4 kHz is
191 approximately 36 dB for conventional AC and it is likely that at 4 kHz there is substantial attenuation
192 of cartilage conducted sound but no comparable attenuation of the Direct-AC sound radiated by
193 transducer. If the intensity of the Direct-AC sound is more than 36 dB greater than the cartilage
194 conducted sound, the earplug will not be effective in preventing Direct-AC sound from reaching the
195 ear. That is, the observed thresholds at 4 kHz are unlikely to be representative of CC only and that

196 the true CC thresholds would be much higher. Furthermore, the previous study showed no difference
197 in the threshold at 4 kHz between BC and CC in the occluded ear canal [4]. The BC pathway was
198 also important at 4 kHz. Just by the current results, it was not determined whether the Cartilage-AC
199 sound dominated the transmission of 4 kHz sounds in the occluded ear canal.

200 Figure 4 shows the thresholds for the open ear canal. In this case, both Direct-AC and
201 Cartilage-AC sounds contribute to the observed thresholds [4]. A comparison of the thresholds in
202 Figures 3 and 4 show that at 0.5 kHz the thresholds for the occluded ear canal are well below those
203 obtained for the open ear canal. An airborne signal in the volume enclosed between the earplug and
204 eardrum is amplified at a low frequency [2, 3]. This phenomenon is referred as to the occlusion effect.
205 The threshold decrease at 0.5 kHz by the earplug indicated that the signal transmitted via the
206 Cartilage-AC pathway was amplified by the occlusion effect. At this low frequency, the
207 Cartilage-AC pathway is thus dominant. Similarly, at 4 kHz the threshold for the tragus in the open
208 ear canal is much lower than that in the occluded ear canal. In the previous study, no difference in the
209 threshold-shift by an earplug was observed between AC and CC [4]. Furthermore, as the
210 above-mentioned, no significant effect of the transducer location was observed. At this high
211 frequency, the Direct-AC pathway is dominant. The thresholds for the open and occluded ear canals
212 at 1 kHz are not very different indicating that both Direct-AC and Cartilage-AC pathways are equally
213 important at this frequency. At 2 kHz, the attenuation of this earplug at 4 kHz is approximately 34 dB
214 for conventional AC in the previous study [4]. The thresholds for the open ear canal are lower than

215 those for the occluded ear canal but not by a very large amount so that both Direct-AC and
216 Cartilage-AC sounds are important at this frequency. The contribution of the Direct-AC pathway
217 depends on the distance from the entrance of the ear canal. The current threshold-shifts by the
218 earplug reflected the distance at the frequencies above 2 kHz. Stray airborne sound is also radiated
219 by BC transducers [11, 12] and this is an issue that needs to be addressed in the design of both BC
220 and CC transducers.

221

222 **5. Conclusion**

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

227

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229

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237

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289 **Figure legends**

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

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

295

296 **Figure 2 Transducer and its fixation forms**

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

299

300 **Figure 3 Thresholds for the occluded ear canal**

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

303

304 **Figure 4 Thresholds for the open ear canal**

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

307

308

309 **Figure 5 Threshold increase with the insertion of the earplug**

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

312

313

Figure 1

Figure 2

(a) Transducer

(b) Tragus

(c) Pretragus

(d) Mastoid

Figure 3

Figure 4

Figure 5