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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.

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 efficient delivery of sound to an ear with fibrotic aural atresia [10].

Fig. 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 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

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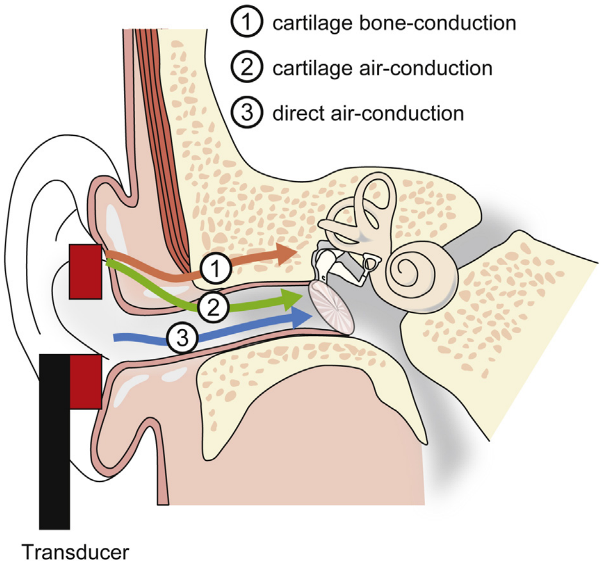

Fig. 1. Scheme of the three main theoretical components of cartilage conduction. When the transducer is placed on the aural cartilage, sounds are transmitted to the cochlea via the three illustrated pathways. They are referred to as direct-air conduction, cartilage-air conduction, and cartilage-bone conduction [4].

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.

Fig. 2 shows the transducer whose property is described in the previous study [4]. The tragus (aural cartilage), pretragus (soft tissue), and mastoid (bone) locations for transducer placement are shown in Fig. 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 nonobjective 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 programmed 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).

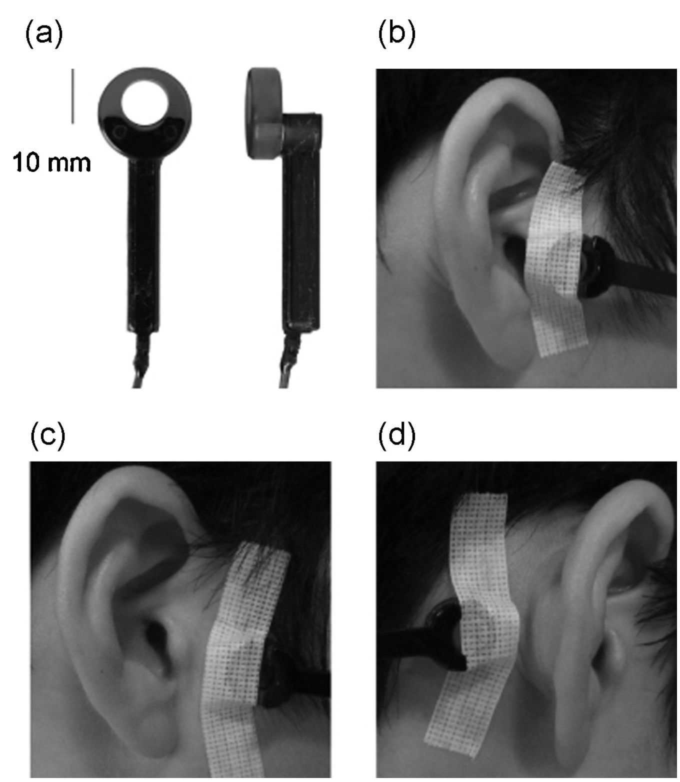

Fig. 2. Transducer and its fixation forms. Photo (a) shows the transducer. The photos show the fixation of the transducer on the tragus (b), pretragus (c), and mastoid (d). The transducer was fixed on each location with an adhesive tape.