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Technical Note

Development of monaural and binaural behind-the-ear cartilage conduction hearing aids

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ABSTRACT

Hosoi (2004) found a pathway for clear sound transmission via aural cartilage. Our research group is developing a new hearing aid using this mechanism. The cartilage conduction hearing aid can be used in patients who cannot insert the earplugs of conventional hearing aids. The cartilage conduction hearing aid (model HD-GX) is composed of a main unit, a transducer, and a fitting part. The ring-shaped fitting part is placed in the entrance of the ear canal, and the vibration at the cartilage then generates sound in the external auditory canal. The cartilage conduction sound remains in the canal and reduces the risk of acoustical feedback. Considering this advantage, we designed it to wear behind the ear (BTE) (model HD-GX2). As binaural cartilage conduction can present sound directivity equivalent to that of air conduction, we then developed a binaural cartilage conduction hearing aid (model HD-GX3) by combining two BTE hearing aids.

1. Introduction

Our research group is developing a new hearing aid using aural cartilage conduction. This study has its origin in the finding by Hosoi (Nara Medical University) that there was clear transmission of sound when a transducer was fit on the ear tragus [1]. The transmission route is quite different from that of the two previous known types of conduction – i.e., air and bone conduction (for details, see Section 2) – and it is termed "cartilage conduction" [1]. We created a test model of a cartilage conduction hearing aid (model HD-GX) in 2008 and evaluated its performance [2–8]. The HD-GX is composed of a main unit, a transducer, and a fitting part (Fig. 1). The ring-shaped fitting part, attached to the cartilage piezoelectric transducer, is placed in the entrance of the external auditory canal, where it transmits vibration to the ear cartilage and sound to the external auditory canal simultaneously.

Which patients would benefit from a cartilage conduction hearing aid? Although the air conduction hearing aid is commonly worn worldwide, some patients with hearing loss are unable to use it. For example, because the air conduction hearing aid earplug must be inserted in the ear canal, patients with atresia of the external auditory canal do not have space for the earplug, and patients with severe otorrhea cannot block their external auditory canal with the earplug for sanitary reasons. Such patients have had no choice but to use a bone conduction hearing aid. Bone conduction hearing aids, however, cause tenderness at the site of compression when the transducer is fixed to skull bone for a prolonged interval. To avoid this problem, the patients can choose an implanted bone conduction (bone-anchored) hearing aid [9–11], although the surgery and possible infection around the attaching part may be deterrents to patients choosing it. The cartilage conduction hearing aid was developed to address these problems.

The major advantages of this hearing aid are that the transducer is placed gently at the entrance of the external auditory canal, and the ring-shaped fitting part does not occlude the external auditory canal. We have noted that patients who have problems with other hearing aids are doing well with the cartilage conduction hearing aid [8]. These patients show a functional gain of 40–60 dB in the frequency range from 500 Hz to 2 kHz [8]. Other patients often have significantly improved hearing in the frequency range lower than 2 kHz.

2. Mechanism of cartilage conduction

How is amplified sound perceived using cartilage conduction? There are three transmission pathways of cartilage conduction

Abbreviations: BTE, behind the ear; IID, interaural intensity difference; ITD, interaural time difference; SPL, sound pressure level; USB, universal serial bus; VAL, vibration acceleration level.

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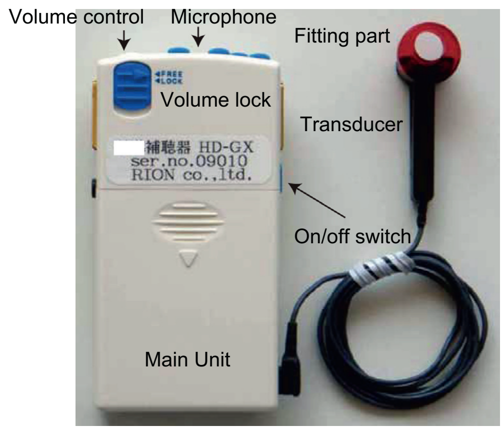

Fig. 1. Cartilage conduction hearing aid model HD-GX (body-worn type).

(Fig. 2). The first is a direct air conduction pathway, from the fitting part to the eardrum (direct air pathway). Here, the transducer produces not only vibration but also sound. The second is an indirect air conduction pathway whereby vibration at the aural cartilage and surrounding tissue generates and radiates sound in the external auditory canal (cartilage–air pathway). The third is a bone conduction pathway wherein vibration is transmitted to the skull bone (cartilage–bone pathway). The air and bone pathways are common routes that operate based on the same principles that pertain to regular air and bone conduction hearing, respectively. In contrast, the cartilage–air pathway is not a common sound conduction route. It is a new idea that human tissue generates sound in the external auditory canal, like a speaker cone. We are therefore examining the contribution of the cartilage–air pathway to hearing [5,7].

To examine the routes of cartilage conduction, the transmitted vibration at the auricle is measured when the transducer is placed at the entrance of the external auditory canal. A subminiature charge accelerometer (type 4374; Brüel & Kjaer, Naerum, Denmark) was attached with double-sided adhesive tape, and the vibration acceleration levels (VALs) were measured at six points in and around the auricle (ear tragus, scaphoid fossa, ear lobe, temporal bone, behind the concha, mastoid), as shown in Fig. 3a [12]. The subject shown, a 36-year-old man, had no disorders of the outer ear. The input signals of the transducer were pure tones (duration 1 s) covering the range from 125 Hz to 16 kHz in steps of 1/12 octave (input voltage 2 V). The ethics committee of Nara Medical University approved the use of this procedure.

Fig. 3b shows the VAL at each point of measurement. The transmitted vibration was strong in the low-frequency range (<3 kHz) in the aural cartilage and surrounding tissue. The spectral characteristics of the transmitted vibration correlated well with the clinical evaluations by the patients [8]. The hearing improvement is thus

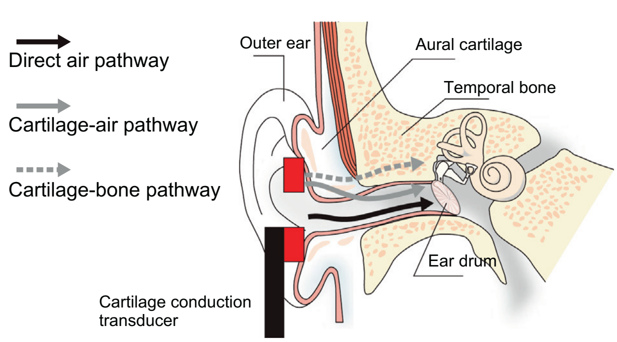

Fig. 2. Direct air, cartilage–air, and cartilage–bone conduction pathways for the cartilage conduction transducer.

likely to be caused by the vibration at the auricle. Also, the ear tragus, scaphoid fossa, and behind the concha, each of which contains cartilage, vibrated more strongly than did any other tissues at the other measurement points. The ear lobe comprises the auricle, but it is composed predominantly of fat. The ring-shaped fitting part effectively delivers the vibration to the various regions of the aural cartilage, which is why the device is called a "cartilage conduction hearing aid".

3. Sound in and out of the external auditory canal

In recent years, the "open-fitting" earplug, which has significant leak venting, has become a popular alternative to the conventional occluding (closed-fitting) earplug in hearing aids (Fig. 4b) [13]. The open-fitting design reduces the feeling of fullness in the ear of the user and can be worn more comfortably for an extended period of time. Furthermore, the distortion of the user's own voice and the sound of mastication during a meal are reduced because the occlusion effect is eliminated. However, the open-fitting earplug has some acoustical drawbacks, such as poor low-frequency performance and increased risk of acoustical feedback. Therefore, the open-fitting earplug can be applied only in patients with mild or moderate hearing impairment [14]. The open-fitting and cartilage conduction hearing aids are similar in terms of the external auditory canal opening. In this experiment, the output sound in the external auditory canal and the sound leaking from behind the outer ear were measured. The experiment was performed on a subject who wore a closed-fitting earplug, an open-fitting earplug, and a cartilage conduction transducer, respectively (Fig. 4).

3.1. Measurement setup

Sound in the external auditory canal was measured by inserting a probe microphone (type 4182; Brüel & Kjaer, Naerum, Denmark) while the subject wore a closed-fitting earplug, an open-fitting earplug, and a cartilage conduction transducer, respectively. The probe microphone had a metallic probe tube (length 100 mm, diameter 1.24 mm) that allowed sound pressure to be measured in a confined, narrow space. A rubber tube was placed on the distal end of the probe for safety. The tip of the probe was inserted to a point 20 mm from the entrance of the external auditory canal. The earplugs were connected to an ear-insert microphone (Eartone 3A; 3M Company E-A-R, Indianapolis, India) to deliver the sound (Fig. 4a and b). For the open-fitting earplug and cartilage conduction transducer, the probe was inserted through their respective openings. For the closed-fitting earplug, the sound pressure was obtained by adding the occlusion gain to the measured value of the open-fitting earplug. The occlusion gain was measured with an ear simulator (type 4128C; Brüel & Kjaer), attaching the closed and open-fitting earplugs. Subsequently, the subject was positioned lying down on his side, and the sound behind the outer ear was measured by locating the probe microphone, as shown in Fig. 4c. The probe microphone was fixed in place with an experimental stand. The inputsignals were pure tones covering the range from 125 Hz to 16 kHz in steps of 1/12 of an octave. Three signal levels were used to drive the inserted earphone (0.05, 0.1, 0.2 V) and for the cartilage conduction transducer (0.5, 1.0, 2.0 V). These input voltages were adjusted to equal the maximum sound pressure levels in the external auditory canal. Accordingly, the grades of the input voltages in this study are termed "low input," "middle input," and "high input." The measured sounds were digitized for subsequent analysis with a sampling rate of 44.1 kHz and 16-bit resolution (UA-101 analog-to-digital converter; Roland, Hamamatsu, Japan).