Aural cartilage vibration and sound measured in the external auditory canal for several transducer positions

Ryota Shimokura[a)], Hiroshi Hosoi[b)], Tadashi Nishimura and Toshiaki Yamanaka
Department of Otorhinolaryngology, Head and Neck Surgery, Nara Medical University, 840 Shijo-cho, Kashihara, Nara 634-8522, Japan
a) rshimo@naramed-u.ac.jp, b) hosoi@naramed-u.ac.jp

A clearly audible sound can be produced by delivering a vibration signal to the aural cartilage via a transducer. This type of conduction is called “cartilage conduction”. We developed a cartilage conduction hearing aid with a ring-shaped transducer that is gently placed around the entrance of the external auditory canal, without occluding the canal. The aim of this study was to consider several alternate contact positions for the transducer. To this end, we placed the transducer at the entrance of the auditory canal (i.e., current wearing style), behind the concha, on the ear lobe, and overtop of the temporal bone, and measured the transmitted vibrations at the aural cartilage and the generated sound in the external auditory canal. We found that the vibrations at positions with a cartilage component (i.e., entrance of the canal and behind the concha) were effectively transmitted to the entire aural cartilage, leading to larger sound generation in the external auditory canal. Thus, future cartilage conduction hearing aid models may feature transducers placed behind the concha.

Keywords: aural cartilage, external auditory canal, sound pressure level, vibration acceleration level

1. INTRODUCTION

Despite considerable advances in the development of hearing aids, several drawbacks to the traditional earplug design remain, especially for individuals with certain conditions. For example, earplugs may not easily fit in the closed external auditory canal of patients with atresia, and it may not be appropriate to stopple the external auditory canal with the earplug in patients with severe otorrhea. These individuals are thus encouraged to use a bone conduction hearing aid. The bone conduction transducer is fixed to a skull bone (mastoid), which transmits sound information, leaving the external auditory canal open. However, the pressure required to fix the bone conduction transducer to the skull (static force range: 1.7 – 4.0 N) can cause tenderness at the site of compression [1]. To avoid such discomfort, patients may opt for an implantable bone conduction hearing device (i.e., bone anchored hearing aid: BAHA), which relays vibrations to the temporal bone via an implanted titanium bolt [2-4]. However, the risks of surgery, combined with the high cost of the device and the potential for infection around the bolt, may discourage patients from choosing this option.

As an alternative to the bone conduction hearing aid, our research group has developed a hearing aid that employs aural cartilage conduction (cartilage conduction hearing aid) [5-16]. Hosoi described the potential of cartilage conduction for sound transmission in 2004 [5, 6]. Individuals reported hearing clear sounds when a certain type of transducer was gently placed on the aural cartilage. On the basis of this idea, a trial cartilage conduction hearing aid was constructed (**Fig. 1**). The transducer is a piezoelectric bimorph covered in elastic material. The transducer is attached to a ring-shaped component that is placed in the entrance of the external auditory canal, where it vibrates, transmitting sound information. Because the ring-shaped component does not occlude the external auditory canal open, it is suitable for patients with atresia of the external auditory canal or otorrhea. Additionally, as the transducer is placed on the aural cartilage with minimal pressure, it can be used comfortably for an extended period of time, unlike the bone conduction hearing aid, and does not require surgical implantation, unlike the BAHA. Previously, we found that in a patient with atresia of the external auditory canal, the cartilage conduction transducer produced an improvement in hearing thresholds of more than 25 dB for pure tones lower than 2 kHz [13, 15].

To explain how a cartilage conduction transducer amplifies sound, three separate sound transmission pathways may be considered (**Fig. 2**). First, the air conduction pathway between the transducer and the eardrum encompasses the resonance effects in the auditory canal (air pathway). Second, in the indirect air conduction pathway vibrations in the aural cartilage radiate sound to the external auditory canal (cartilage-air pathway). Third, in the bone conduction pathway, vibrations are transmitted to the skull and reach the inner ear in this way (cartilage-bone pathway). Considering the gap in acoustic impedance between the cartilage and skull bone, it is unlikely that the cartilage–bone pathway significantly contributes to hearing compared with the other pathways, as the subjective loudness induced by cartilage conduction is fundamentally caused by the sound arriving at the eardrum [11]. Sound arriving at the eardrum is the result of both the air and cartilage-air pathways, as shown in **Fig. 2**.

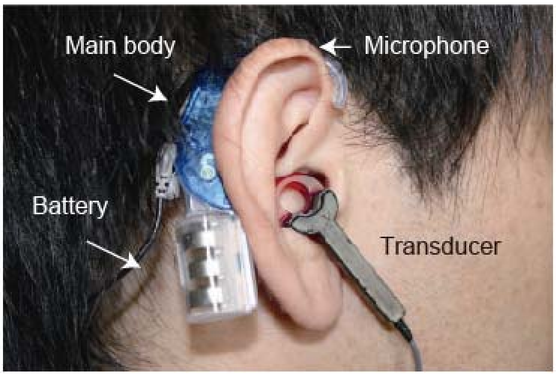

Fig. 1. Trial model of a cartilage conduction hearing aid (behind-the-ear type).

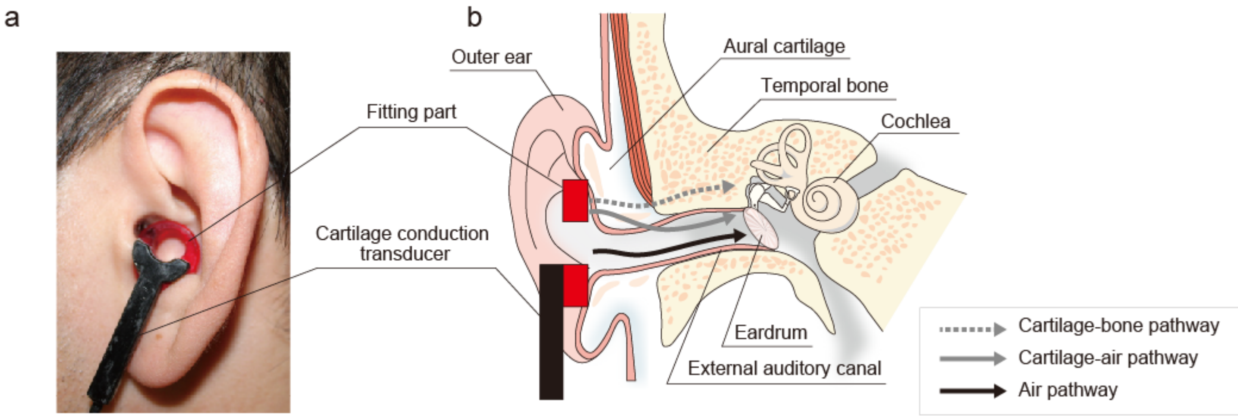

Fig. 2. Possible sound transmission pathways from the transducer.

The current trial model of the cartilage conduction hearing aid features a ring-shaped transducer placed at the entrance of the external auditory canal, as shown in **Figs. 1 and 2**. It was designed with an emphasis on 1) open-fitting and 2) efficient transmission of vibration, using trial and error, without any objective assessments in the development stage. Thus, we have yet to determine whether our design is optimal for our two main factors. In this study, we compare various contact positions of the transducer by measuring the vibration acceleration level (VAL) at the aural cartilage and the sound pressure level (SPL) in the external auditory canal. Aural cartilage comprises the outer ear and is distributed around the exterior half of the external auditory canal (**Fig. 2**). The aim of this study was to identify the most effective vibration center in and around the outer ear. The findings of this study are applicable to the development of new transducer models and therefore new cartilage conduction hearing aids.

2. METODS

2.1. Contact positions and general method

One individual (37 year, male) without disorders of the outer ear or external auditory canal participated in our study. We tested the efficacy of the ring-shaped transducer in four different positions: the entrance of the auditory canal, behind the concha, on the ear lobe, and overtop of the temporal bone, as shown in **Fig. 3**. In the latter three positions, we used double-sided tape to fix the transducer in place. The input signal for the transducer was a pure-tone train ranging from 125 Hz to 16 kHz in 1/12 octave steps. The tones were 1 s in duration and were each followed by a silent interval of 0.5 s. The signal levels were used to drive the cartilage-conduction transducer, which had a 2.0 volt power source. We used a notebook computer (X60; Lenovo, Beijing, China) to generate the input signal.

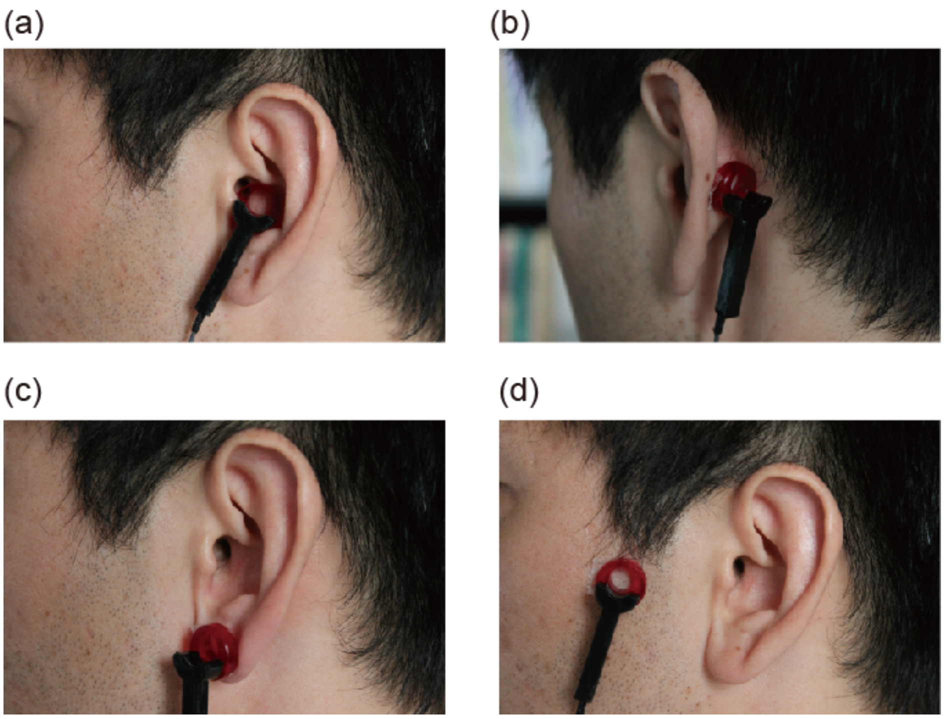

Fig. 3. Contact positions of the transducer: (a) entrance of the auditory canal, (b) behind the concha, (c) on the ear lobe, and (d) overtop of the temporal bone. The dots indicate the three vibration measurement positions (ear tragus, scaphoid fossa, and concha). There was limited space for the subminiature charge accelerometer on the concha for the contact point at the entrance of the canal (a), so we placed it behind the concha.

2.2. Measurement of vibration at the aural cartilage

To examine the vibrations transmitted through the aural cartilage, we measured the VAL at three points (ear tragus, scaphoid fossa, and concha) in the outer ear, as shown in **Fig. 3**. The VAL is a logarithmic scale that relates effective acceleration to a reference value (10^{-6} m/s^2) [17]. We used double-sided adhesive tape to attach a subminiature charge accelerometer (type 4374; Brüel & Kjaer, Naerum, Denmark) to the three measurement points in series. The accelerometer was connected to a conditioning amplifier (NEXUS; Brüel & Kjaer, Naerum, Denmark). The obtained signal was digitized for subsequent analysis with a sampling rate of 44.1 kHz and a 16-bit resolution (UA-101 analogue-to-digital converter, Roland, Japan).

2.3. Measurement of sound via the cartilage-air pathway

To examine the sound arriving in the external auditory canal, we measured the SPL using a probe microphone (type 4182; Brüel & Kjaer, Naerum, Denmark), which had a metallic probe tube (length: 100 mm, diameter: 1.24 mm) that allowed sound pressure to be measured in a closed or narrow space. The conditioning amplifier and measurement condition were same as for the vibration measurements.

In this study, we wanted to compare sound transmitted via the cartilage-air pathway with sound transmitted via vibrations in aural cartilage. Thus, we wanted to isolate the sounds arriving through each pathway (**Fig. 2**). However, the sound measured in the canal includes sound energy also from the air pathway (i.e., which does not need the cartilage vibration), because the transducer also generates a low level air-born signal. This is especially the case for the contact position at the entrance of canal (**Fig. 3a**), which receives a large contribution from the air pathway compared with the other positions. Therefore, we measured SPLs in both touching and non-touching conditions. In the touching condition, the transducer was touching the contact positions, as shown in **Fig. 3**, while in the non-touching condition, the transducer was as close as possible to the contact positions without touching the aural cartilage. In the non-touching condition, we used an experimental stand to position the transducer close to the contact positions such that the distance between the transducer and each position was less than 3 mm. The difference in SPL between the touching and non-touching conditions was expected to be the sum of the sound conducted through cartilage.

3. RESULTS

Fig. 4 shows the VAL as a function of frequency for the four contact positions. The VAL was calculated using the mean values among the three measurement points (ear tragus, scaphoid fossa, and concha). The aural cartilage vibrated easily at frequencies lower than 1 kHz and decayed quickly for higher frequencies. The vibration was the largest at the entrance of the auditory canal, and decreased in the following order: behind the concha, at the ear lobe, and overtop of the temporal bone.

Fig.5 shows the difference in SPL between the touching and non-touching conditions for the four contact positions. A larger SPL was observed for frequencies lower than 1 kHz. The sound pressure was the largest at the entrance of the canal, and decreased in the following order: behind the concha, at the ear lobe, and overtop of the temporal bone. For the temporal bone contact point, we found a negative difference in SPL for values greater than 1 kHz.

4. DISCUSSION

We found that the transducer effectively transmitted vibrations to the aural cartilage. This was especially the case for frequencies lower than 1 kHz, which is consistent with our previous report [14]. The vibration was stronger at the contact points at the entrance of the auditory canal and behind the concha, and weaker at the ear lobe and temporal bone. This is likely because the former positions contain aural cartilage, while the latter positions do not. For instance, while the ear lobe comprises the outer ear, it is predominantly composed of fat. Therefore, it appears that vibration transmission efficiency is low for positions without a cartilage component. Another factor is the distance of the ear lobe from the ear canal. The transmission efficiency was highest for the contact point at the entrance of the canal. This may partially be due to the way in which the transducer was worn. For instance, we did not use double-sided adhesive tape to fix the transducer in place at the entrance of canal, and so the ring component may have pushed out the surrounding cartilage, despite the low pressure used to insert the ring.

The SPL difference between the touching and non-touching conditions increased as the vibration of the aural cartilage increased. For the contact point at the temporal bone, the SPL difference had a negative value for frequencies higher than 1 kHz. This indicates that the SPL in the canal was larger in the non-touching than in the touching condition, and that cartilage conduction was nearly absent at the temporal bone. In the touching condition, the sound pathway to the canal was blocked by the tragus when measuring the signal at the temporal bone contact, while in the non-touching condition, the transducer was located in a higher position, maintaining a direct sound pathway. This may explain why we observed negative SPL values for the temporal bone contact point.

A previous report demonstrated that sound can be effectively generated via cartilage conduction for frequencies below 1 kHz [12]. When we compared the averaged values of VAL and SPL below 1 kHz, we obtained the following relationship:

$$SPL = 0.94VAL - 22.84 \qquad (1)$$

with a high correlation (R^2 = 0.97). This equation suggests the existence of a linear relationship between the aural cartilage vibration and the associated sound in the external auditory canal. As the sound conveyed via cartilage conduction comprises the dominant hearing sensation [11], the phenomenon is termed “cartilage conduction hearing.”

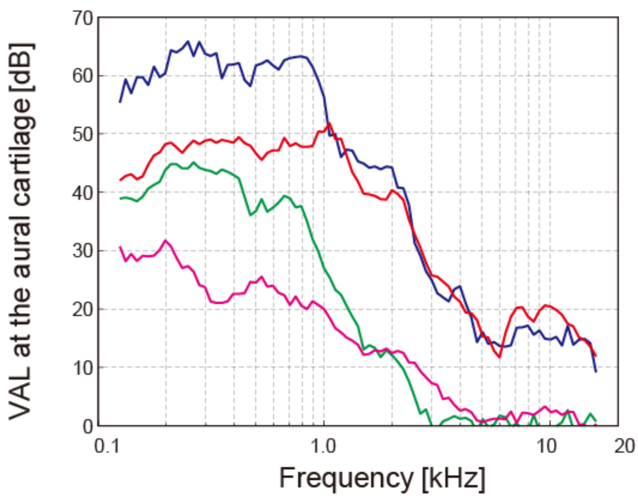

Fig. 4. VAL at the aural cartilage for the four contact points: entrance of canal (–), behind concha (–), ear lobe (–), and temporal bone (–).

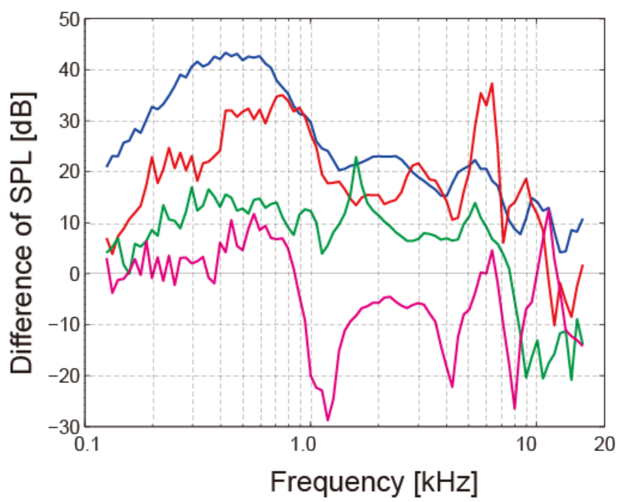

Fig. 5. SPL difference between the touching and non-touching conditions in the external auditory canal for the four contacts points: entrance of canal (–), behind concha (–), ear lobe (–), and temporal bone (–).

As we are in the initial stages of developing cartilage conduction hearing aids, several wearing styles for the transducer have been proposed. For example, the transducer could be embedded behind the ear (**Fig. 1**), and thus vibrate the cartilage behind the concha. This wearing style is relatively effective because there is sufficient contact with the cartilage. Another proposed model is an earring type transducer, which would be attached to the ear lobe. We hypothesized that a hearing aid that simulated an accessory might attract female users. However, vibrations at the ear lobe are not easily transmitted to the aural cartilage, so this wearing style may not be realistic.

5. CONCLUSIONS

A specific type of transducer, gently placed on the aural cartilage, can be used to create clear audible sound (cartilage conduction). When a transducer is placed at the entrance of the auditory canal, behind the concha, on the ear lobe, and overtop of the temporal bone, the amount of aural cartilage at these sites (i.e., entrance of the canal and behind the concha) modulates the efficacy of vibrational aural cartilage transmission, such that sites with more cartilage will produce a louder sound in the external auditory canal. Below 1 kHz, the transmitted vibration and generated sound have a linear relationship.

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