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Estimation of relationships between transducer placements and peripheral propagation in cartilage conduction*

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***Abstract*— Bone-conduction (BC) has been applied to hearing aids for the conductive hearing loss, however, also has some disadvantage especially in wearability of a sound transducer. Therefore, as a solution, "cartilage conduction (CC)" has been proposed and applied to devices such as a hearing aid and smartphones. In CC, a sound transducer is placed on the cartilage of the pinna, and the air-conduction (AC) and osseotympanic BC components are dominantly transmitted. However, even in CC, the vibrating surface often contacts not only with the aural cartilage but also with the osseous parts of/around the pinna, and effects of such transducer placement on perception characteristics and propagation mechanisms remain unclear. In this study, we measured hearing thresholds and vibrations of the head when the transducer was placed on (1) the pinna, (2) the mastoid process of the temporal bone, and (3) the ear-front point (middle of between the tragus and the mandibular condyle). The results suggested that the ratios of the inertial and compressional BC components increases when the transducer is placed on the osseous parts, particularly in high frequency range. These findings provide useful information to optimize CC devices and develop a calibration method of CC.**

I. Introduction

Generally in bone-conduction (BC), the sound is said to be transmitted as 4 components (Fig. 1) : (1) the osseotympanic component, which involves sound radiated into the ear canal; (2) the inertial BC component, which is based on the relative motion between the middle ear ossicles and the temporal bone; (3) the compressional BC component, which results from compression and expansion and of the cochlear shell; and (4) the air-conduction component, which radiated from the transducer into the air and enters the ear canal [1].

However, in BC, a sound transducer needs to be pressed against to the mastoid process and this causes pain and discomfort its user. Thus, "cartilage conduction (CC)" has been proposed to solve these problems and actually applied to hearing aids for patients with atresia of the external auditory canal [2], and smartphones [3]. Since the cartilage is soft and elastic, it can reduce the pain associated with pressing.

On the other hand, in CC, sounds are transmitted via the aural cartilage that shows a strong non-linear characteristic and is easily deformed by pressing. Therefore, it is thought

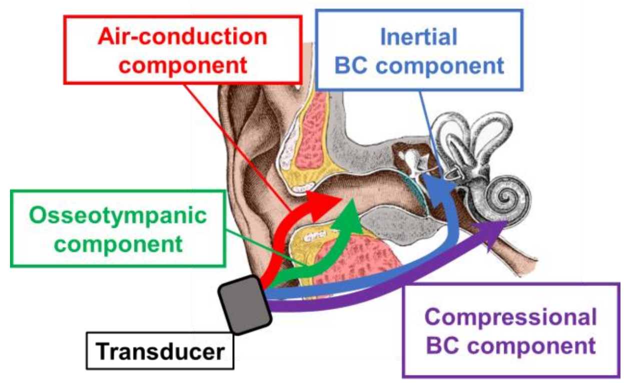

Fig 1. Sound components generated by bone-conduction.

that CC has unique perception characteristics different from ordinary BC, however, a limited number of studies have been conducted on CC and detailed mechanisms of perception and sound propagation in the auditory periphery remain unclear. Consequently, fundamental technology associated with CC have not been prepared. For example, a calibration method for the CC transducer has not been established.

It has been reported that the sound components were dominated by the AC and the osseotympanic BC components when a vibrator contacts only with a part of the concha [3] or the tragus [4]. However, even in CC, the vibrating surface often contacts not only with the aural cartilage but also with the osseous parts of the head around the ears. According to our previous report, significant amounts of the inertial and compressional BC components were generated depending on the vibrator placements and the pressing pressure [5]. In order to develop a calibration method for the CC transducer, it is necessary to clarify to what extent the aforementioned 4 propagation components contribute to the perception. The ratio of intensity of each sound component seems to be varied depending on the vibration placements, however, details of the sound transmission of CC in various conditions remains unclear.

We evaluated the amount of the AC and osseotympanic BC components quantitatively by estimating the ear-canal-

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sound pressure (ECSP) [6]. However, it has been difficult to evaluate only the inertial and compression BC components because the osseotympanic component cannot be blocked by earplugs. Nishimura et al. (2015) measured hearing thresholds of AC, BC, and CC when the auditory ear canal was filled with water [7]. They reported that the osseotympanic BC component was blocked by the injected water.

In this study, we investigated relationships between the transducer placements and the sound components when the AC and the osseotympanic components were blocked by earplugs and the injected water into the auditory canal respectively. Additionally, vibrations of the head surface were measured using a laser Doppler vibrometer. The inertial and compressional components were evaluated quantitatively from the result of these measurements.

All the experiments were approved by the Institutional Review Board on Life Science Research of Chiba University. Necessary information about the experiments was given to the participants and informed consent was obtained from each participant before the experiments.

II. Experiments

5 participants (male, 22-25 years) who has no history of deficits of hearing functions participated in the experiment. All the measurements were performed in an anechoic chamber.

A. *A sound transducer*

A sound transducer, assuming a smartphone, was newly developed for the experiments. The new transducer is composed of a piezoelectric device (R11-244018, TOKIN), used in existing smartphones, and a flat acrylic plate (5 cm^2) (Fig. 2). The piezoelectric vibrator is firmly glued to the flat acrylic plate.

B. *Presentation placement and method*

The vibrator was presented to following parts of subjects' head around the left ears (Fig. 3):

1) Pinna
2) Mastoid process of the temporal bone
3) Ear-front point (a part extended from the tragus to the mandibular condyle)

The transducer was fixed on the subjects' head with a rubber supporter band (Asics).

C. *Measurement of hearing threshold*

250, 500, 1000, 2000, 4000, 8000-Hz tone-bursts with duration of 800 ms including 150-ms rising/falling ramps were used as the stimuli. Hearing thresholds were measured using a 1-up/2-down transformed up-down with three-alternative forced-choice (3AFC), with a decision rule that estimated the 70.7% correct point on the psychometric function. In this procedure, three intervals were presented sequentially, and stimulus was presented in only one interval, and not presented in other two intervals. Participants were requested to respond one interval that stimulus was presented.

Fig 2. A sound transducer used in the experiments.

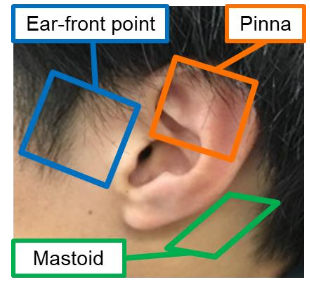

Fig 3. Placements of the transducer.

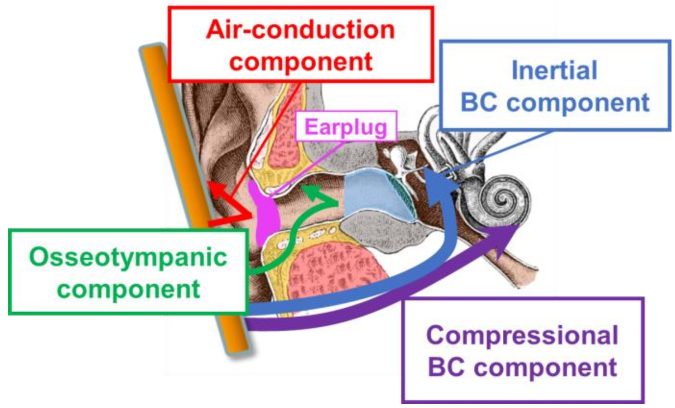

Fig 4. Sound transmission paths with earplugging and the water injected into the auditory canal.

Fig 5. Suction pillow to hold the head.

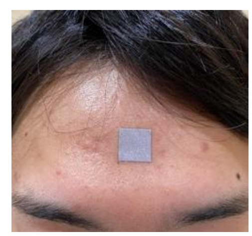

Fig 6. A reflective sticker at the head.

The intensity of stimulus in the one interval were varied adaptively, depending on responses of the participants.

The hearing thresholds were measured under two conditions, with/without putty earplugs and water. The earplugs were inserted in both ears and water was injected into the left ear. To measure the auditory thresholds of the inertial and compressional BC components, the AC component was blocked by earplugs and the osseotympanic component was blocked by the water (Fig. 4). The water was injected up to 40% of the volume of the auditory canal, which is considered the osseous part, because if the water was injected up to the cartilage part of the auditory canal, the osseotympanic component would reach the tympanic membrane through the water.

The water injection procedure was as follows;

1) The subject's head was fixed with a suction pillow (Fig. 5), the water was injected up to the entrance of the auditory canal, and the volume of the auditory canal was measured.
2) 40% of the measured volume of the water was injected into the auditory canal and measurements were started.

D. *Measurements of vibrations of the head surface*

Head surface vibrations using a laser Doppler vibrometer were measured when a total of six type of pure tones at 250, 500, 1000, 2000, 4000, 8000 Hz were presented.

The head and the presented transducer as a single rigid body, and the vibration generated in the head surface was assumed to be a synthesis of inertial and compressional BC components. The measurement position was set at the forehead (Fpz; in accordance with the international 10-20 method of EEG measurement), and a reflective sticker was attached to obtain a sufficient signal-to-noise ratios (Fig. 6). The subject's head was fixed with a suction pillow during the measurements. The voltage applied to the transducer was 3.0 V_{pp}.

III. RESULTS

A. *Measurement of hearing threshold*

Fig. 7 and 8 show averaged threshold across all participants, without and with earplugging and water injection, respectively. Fig. 9 shows the increase of hearing threshold with earplugging and water injection based on the hearing threshold of without earplugging and water injection. Table. 1 shows the estimated proportion of the inertial and compressional BC components in the perception of each presentation placement of the transducer. The main effect of the transducer placements was observed without and with earplugging and water injection and the increase of hearing threshold ($p < 0.05$). The hearing threshold increased in the order of the pinna, ear-front point, and the mastoid all over the frequency. In particular, there was a significant difference in the increase of hearing threshold between the pinna and mastoid process ($p < 0.05$). In the low frequency range, the hearing threshold decreased in the mastoid process and ear-front point. In contrast, a significant increase of hearing threshold between the mastoid process and ear-front point was observed only in the high frequency range above 1000 Hz. Especially in the high frequency range, the estimated ratios of the inertial and compressional BC components in the perception were also larger in the order of the mastoid, ear-

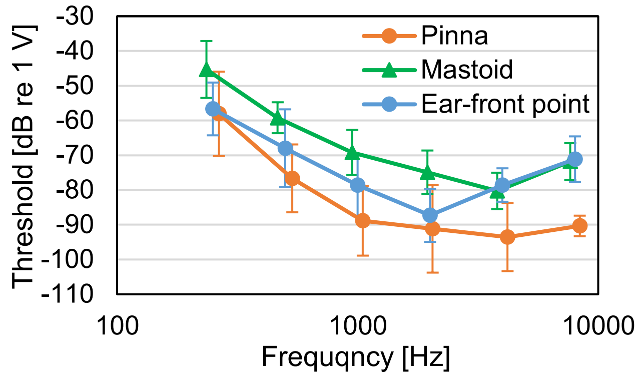

Fig 7. Threshold for each placement without earplugging and water injection.

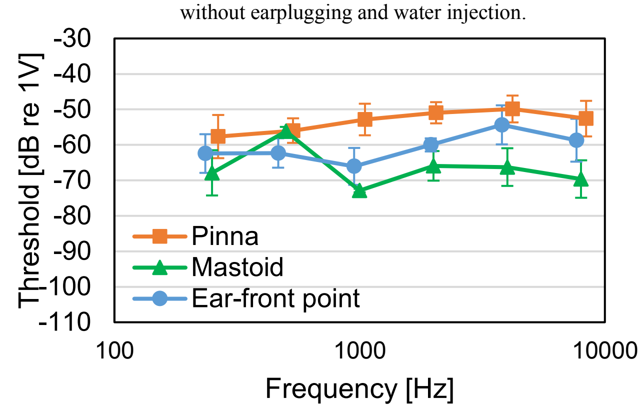

Fig 8. Threshold for each placement with earplugging and water injection.

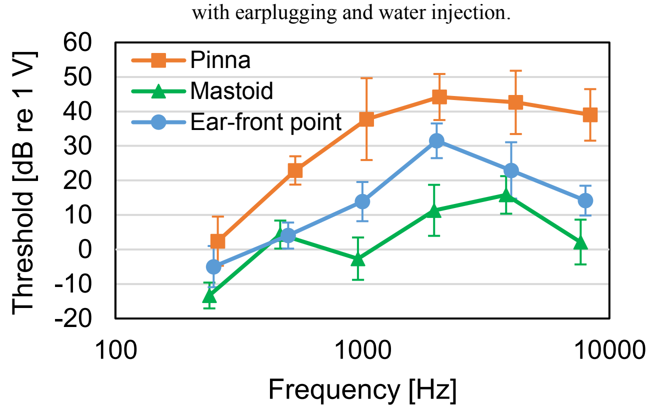

Fig 9. Increase of the hearing threshold for each placement.

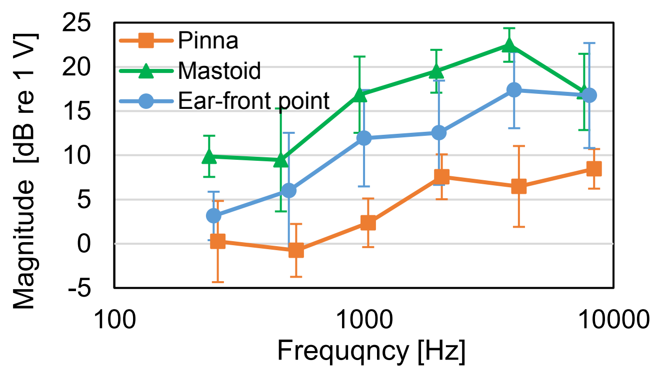

Fig 10. Vibrations of the head surface for each placement.

Table 1. The estimated ratios of the inertial and compressional BC components.

Frequency (Hz)	The estimated ratios of the inertial and compressional BC components (%)		
	Pinna	**Mastoid**	**Ear-front point**
250	75.80	254.83	177.19
500	7.16	60.87	62.87
1000	1.29	135.77	20.24
2000	0.62	27.09	2.66
4000	0.74	16.19	7.16
8000	1.12	78.02	19.60

front point, and the pinna. However, the estimated ratios of the inertial and compressional BC components in the mastoid and ear-front point exceeded 100%.

B. *Measurement of vibrations of the head surface*

Fig. 10 shows vibrations of the head surface at each placement of the transducer. The main effect was observed of the transducer placements on the vibrations of the head surface ($p < 0.05$). Vibrations of the head surface increased in the order of the mastoid process, ear-front point, the pinna all over the frequency. In particular, a significant difference was observed between the pinna and the mastoid processes ($p < 0.05$).

IV. DISCUSSIONS

Regardless of the frequency, the increase of hearing threshold was greater in the pinna than in the mastoid process. Because the pinna is close to the auditory canal, the air-conduction and the osseotympanic components have a large proportion of its perception [8]. However, a large increase of the hearing threshold may have been caused, because the components that propagate through the auditory canal were blocked by water injection. This is consistent with the results of the vibrations of the head surface measurements, which showed that it was small when the transducer was attached to the pinna and large when to the mastoid process.

On the other hand, a significant increase of the hearing threshold between the mastoid process and ear-front point was observed only in the high frequency range above 1000 Hz. In addition, especially in the high frequency range, the estimated ratios of the inertial and compressional BC components in the perception were also larger in the order of the mastoid, ear-front point, and the pinna. Since the presented area of the transducer to the osseous parts is larger in the order of the mastoid, ear-front point, and the pinna, it is thought that the mastoid is more likely to generate the inertial and compressional BC components than the ear-front point or the pinna [8]. In addition to, the osseotympanic component is significant in the low frequency range, which is known as the occlusion effect [9], so the difference in the estimated ratios of the inertial and compressional BC components among the transducer placements is larger in the high frequency range than in the low frequency range.

It is thought that the reason why the estimated ratios of the inertial and compressional BC components in the mastoid and ear-front point exceeded 100% is the insufficiency of the injected water into the auditory canal, and the osseotympanic component which amplified in the low frequency reaches the tympanic membrane. In addition to, since the mastoid process and ear-front point were the conditions for attaching the vibrator to the osseous parts, it was also thought that the osseous parts in the auditory canal were vibrated. It is thought that the impedance of the water and the wall of the auditory canal is lower than that of the air and the wall of the auditory canal, and the vibration of the osseous parts the auditory canal reached the tympanic membrane through the water.

Regarding the placements of the transducer, when the transducer only attached to the cartilage part, AC and osseotympanic components generated in the auditory canal increased, and when it attached to the osseous part, the inertial and compressional BC components increased. On the other hand, when focusing on the frequency, it was observed that the ratio of AC and the osseotympanic components increased in the low frequency range, while the ratio of the inertial and compressional BC components increased in the high frequency range. While these results are useful for quantification of the cartilage conduction, more detailed studies are needed.

REFERENCES

[1] S. Stenfelt, N. Hato, and R. Goode, “Factors contributing to bone conduction: The middle ear” The Journal of the Acoustical Society of America, vol. 111, 947-959, 2002.

[2] T. Sakaguchi, Y. Hosoi , *A basic study of cartilage conduction hearing*., Audiology Japan, vol. 51, 375-376, 2008.

[3] T. Nishimura, H. Hosoi, O. Saito, R. Miyamae, R. Shimokura, T. Matsui, and T. Iwakura, “Benefit of a new hearing device utilizing cartilage conduction”, Auris Nasus Larynx, vol. 40(5):440-446, 2013.

[4] S. Nakagawa, T. Hotehama, K. Ito, “Hearing characteristics by a pinna-conduction: Detection threshold and acoustical properties in the outer ear”, Proc. Life Engineering Symposium, 431-432, 2013.

[5] T. Jitsukawa, S. Otsuka, and S. Nakagawa, “Effects of cartilage conduction vibrator placement in the pinna on the detection threshold and the ear canal sound pressure”, Proc. Spring Meet. Acoustical Society of Japan., pp. 521-522, 2019.

[6] Y. Sugawara, S. Otsuka, and S. Nakagawa, “Relationships between transducer placements and ear-canal-sound pressure at the threshold of the cartilage conduction”, Proc. Autumn Meet. Acoustical Society of Japan., pp.587-588, 2020.

[7] T. Nishimura, H. Hosoi, O. Saito, R. Miyamae, R. Shimokura. T. Yamanaka, T. Kitahara, and H. Levitt, “Cartilage Conduction Is Characterized by Vibration of the Cartilaginous Portion of the Ear Canal”, PLOS ONE, 10(3): e0120135, 2015.

[8] Y. Sugawara, S. Otsuka, and S. Nakagawa, ”Estimation of hearing threshold and propagation process in the head for the development of an output calibration method for a bone-conduction smartphone”, Proc. Spring Meet. Acoustical Society of Japan., pp.81-482, 2020.

[9] S. Stenfelt, and S. Reinfelt, “A model of the occlusion effect with bone-conducted stimulation”, International Journal of Audiology, 46(10):595-608, 2007.