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Occlusion effects by bone-conducted sound to the facial parts assessed by hearing threshold and ear-canal sound pressure measurements

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1. Introduction

Bone conduction (BC) is a method of hearing sound through biological tissues, such as bones, skin, and muscles. BC sound has been applied to hearing aids for the conductive hearing loss, because one of components is transmitted directly to the inner ear [1]. In addition, it has been applied to various communication devices because it does not occlude the ear canal and is audible even when earplugs are worn. Devices that present stimuli to the mastoid process, such as hearing aids, and the condylar process, such as earphones, have been designed. Recently, novel audio devices using BC to the face, such as smart glasses, have been developed [2, 3]. However, the head is composed of many bones and has cavities such as the nasal cavity and paranasal sinuses, so strength of each bone-conduction component seems vary depending on placement within the face.

On the other hand, when the ear canal is occluded with earplugs, loudness of low-frequency sounds is enhanced [1]. This phenomenon is called the occlusion effect (OE). It is said that the OE is caused by a part of the osseotympanic component reflected by the earplugs [1]. The OE can efficiently enhance low-frequency sound of small audio devices that generally provide insufficient low-frequency output.

Some devices using BC stimulation to the facial parts are already designed, however, there have been no studies about the OE at each part of the face. In this study, we evaluated the OE by measuring the hearing thresholds and ear canal sound pressure (ECSP) at each part of the face. Amount of the OE is defined as a difference of hearing thresholds between unoccluded and occluded ear canals. The hearing threshold results from all the four components of the BC sound. In contrast, ECSP results from the sum of the osseotympanic component which once enters the biological tissue and radiates into the ear canal, and the air-conduction component which is radiated from the transducer [1]. Therefore, it is considered that it is possible to determine contribution of each component on the OE by comparing them.

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

2. Experiments

Eight participants (six males and two females, 21–25 years) who had no history of hearing function deficits participated in the experiment. All measurements were performed in an anechoic room. The BC transducer (B-81, RadioEar) was presented to the parts conventionally used with BC systems (hereafter referred to as conventional parts): mastoid process; condylar process; forehead, and other facial parts (hereafter referred to as facial parts): zygomatic bone; nasal bone; infraorbital region; jaw angle; chin (Fig. 1). Hearing thresholds and ECSPs of each participant were measured twice at 250, 500, 1000, 2000, 4000, and 8000 Hz with/without silicon earplugs (INSTAPUTTY, Insta-Mold Products). Hearing thresholds were measured using a 1up-2down transformed up-down with three alternative forced choices. ECSP was measured using a probe microphone (ER-7C, Etymotic) inserted into the ear canal on the same side of the stimuli, with its tip extending approximately 20 mm from the tragus (Fig. 2).

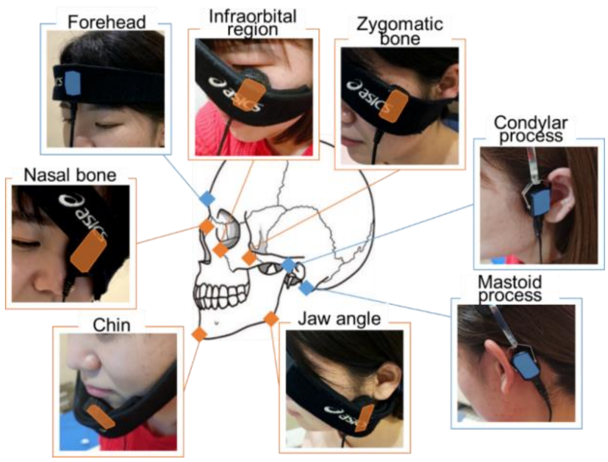

Fig. 1 Placements of the BC vibrator in the experiments.

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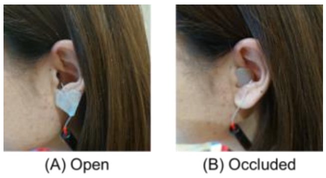

Fig. 2 Insertions of a probe microphone into the ear canal for the ECSP measurements.

3. Results

Fig. 3 shows the OEs across all participants estimated as differences of the hearing thresholds between with and without the earplugs. A two-way ANOVA found main effects of the frequency ($p < 0.001$) and the presentation placement ($p < 0.001$), and a significant interaction between them ($p < 0.001$). The OEs were observed at 250–1000 Hz in all locations. In the nasal bone and infraorbital region, the OEs were observed also at 2000 Hz.

Fig. 4 shows the difference of the ECSP between with and without the earplug. The main effects of frequency ($p < 0.001$), presentation placement ($p < 0.01$), and a interaction ($p < 0.001$) were observed. The OEs were observed at 250–1000 Hz in all locations, and also at 2000 Hz in the infraorbital region.

4. Discussion

The OEs in facial parts except for the zygomatic bone were equal to or better than those of the conventional parts. These facial parts can be applied to audio devices that need to enhance low-frequency sounds.

The nasal bone, infraorbital region and jaw angle showed the larger OE than the conventional parts, however, they showed smaller ECSP differences. This suggests that the components directly transmitted to the middle and inner ear may affect the OE.

In the nasal bone and infraorbital region, the OE increased at 1000–2000 Hz. This range includes the resonance frequencies of the maxilla sinus (1000-2000 Hz [4]) and the ossicles (1500 Hz [5]). Moreover, the paranasal sinus including the maxilla sinus is connected to the middle ear via the nasal cavity and the auditory tube. Therefore, it can be considered that resonances in the cavities affect the components transmitted to the middle and inner ear.

In the jaw angle, the OE increased at 250–500 Hz. This ranges covers the resonance frequency of the jaw angle (400-500 Hz [6]). Additionally, the vibration direction of the jaw angle is same as that of the ossicles motion. So, it can be considered that the resonance of the jaw affects the motion of the middle ear.

5. Conclusion

In this study, to examine the OE when the BC stimuli were presented to the face, the hearing thresholds and ECSP were measured at each part of the face. We found that the facial parts showed equal to or larger OE than that of the mastoid and condylar processes, and can also be applied to audio devices that need to enhance low-frequency sounds. Further, it is possible that the components transmitted to the middle and inner ear affect the occlusion effect in the facial parts.

Acknowledgement

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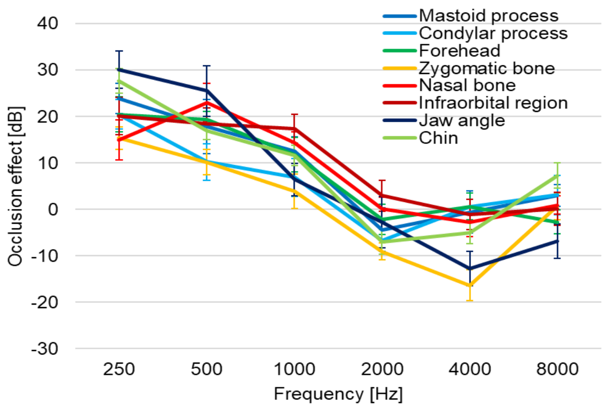

Fig. 3 The OE as differences of hearing thresholds between the occluded and open conditions (Mean ± SD).

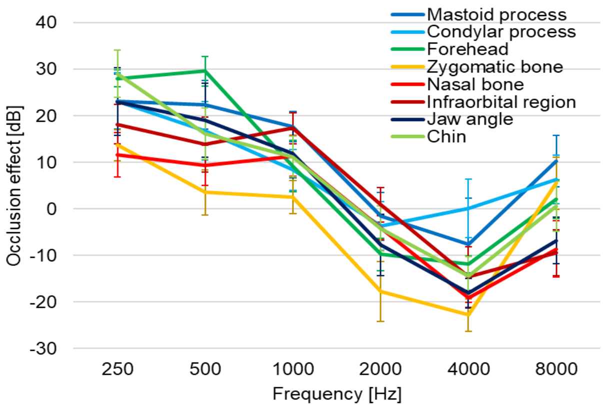

Fig. 4 Difference of the ECSP between the occluded and open conditions (Mean ± SD).