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Basic perceptual characteristics of distantly-presented bone-conducted sounds: Threshold and frequency- and temporal resolutions in the audible-frequency range

遠位呈示骨伝導音の基礎知覚特性: 可聴周波数帯における検出閾及び周波数/時間分解能

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1. Introduction

Several studies have reported that high-frequency sound above 20 kHz can be perceived clearly via bone-conduction (BC). This audible ultrasound through BC is referred to as bone-conducted ultrasound (BCU).[1–3] Generally, BC sounds are presented to the osseous parts of the head. However, BC sounds can also be perceived even when presented to body parts distant from the head, such as the neck, trunk and upper limbs.[4] This "distant presentation" is expected to be applied to novel BC devices.

We have been focused on the perception and propagation characteristics of distantly-presented BCU.[4-6] On the other hand, it is indispensable to investigate also in the audible-frequency range to elucidate the essential mechanisms of distant presentation of BC. However, a limited number of studies have been conducted.[7]

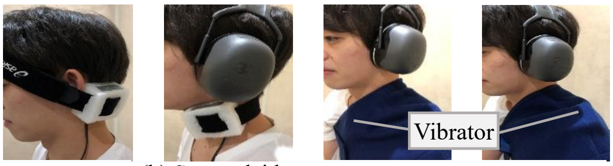
In this study, to examine the basic perceptual characteristics of distantly-presented BC sound in the audible-frequency range, hearing thresholds, difference limens for frequency (DLFs), which reflect the frequency resolution, and temporal modulation transfer functions (TMTFs), which reflect the temporal resolution, were estimated.

2. Methods

Seven males (21-26 years) with normal hearing participated. BC stimuli were presented to the following body parts by a BC vibrator (Radioear B-81): (a) Mastoid, (b) Sternocleidomastoid, (c) Clavicle, (d) Acromion (only for the hearing threshold measurement) (Fig. 1). In all experiments, to evaluate only BC sounds, air-conducted (AC) sounds radiated from the vibrator were insulated strongly by wearing urethane and silicone earplugs and an earmuff (except for the mastoid) together. All experiments were conducted in an anechoic room.

2.1 Experiment I: Measurement of hearing thresholds

As the stimuli, 250, 500, 750, 1000, 2000, 3000, and 4000-Hz tone bursts with a duration of 800 ms including 75 ms rising/falling ramps were used.



(a) Mastoid (b) Sternocleido mastoid (c) Clavicle (d) Acromion

Fig. 1 Stimulus placements used in the experiments.

Hearing thresholds were measured using a 1 up-2 down three-alternative forced-choice (3AFC) adaptive procedure with a decision rule that estimated the 70.7% correct point on the psychometric function.[8]

2.2 Experiment II: Measurement of DLFs

As the stimuli, tone bursts with the center frequencies (CFs) of 250, 500, 750, 1000, 2000, and 4000 Hz including 30-ms rising/falling ramps were used (duration: 400 ms).

DLFs were measured using a 1 up-2 down 2AFC adaptive procedure. Stimulus output levels were set to 10-15 dB SL. In each trial, two tone bursts that were equally spaced in linear frequency on either side of the CF were presented, and participants were requested to respond to the stimulus with higher frequency. The deviation from the CF (Δf) was varied adaptively.

2.3 Experiment III: Measurement of TMTFs

TMTF shows the threshold of sinusoidal amplitude-modulation (SAM) detection as a function of modulation frequency. The SAM detection threshold is determined systematically by measuring the detection of modulation depth. A double sideband amplitude modulation was applied to 1000 and 4000-Hz sinusoidal carriers. SAM stimuli are expressed as follows:

$$f(t) = \{1 + m \times \sin[2\pi f_m t]\} \times \sin(2\pi f_c t) \quad (1)$$

Here, m is the modulation depth, and f_m and f_c are the modulation and carrier frequency, respectively.

TMTFs were measured using a 1 up-2 down 3AFC adaptive procedure. Stimulus output levels were set to a level at which each participant could detect modulation sufficiently, based on 25 dB SL. In each trial, three BC stimuli (duration: 800 ms including 75 ms rising/falling ramps) were presented sequentially. One of the three stimuli was modulated, and the others were unmodulated. Participants were requested to respond to the modulation interval. The modulation

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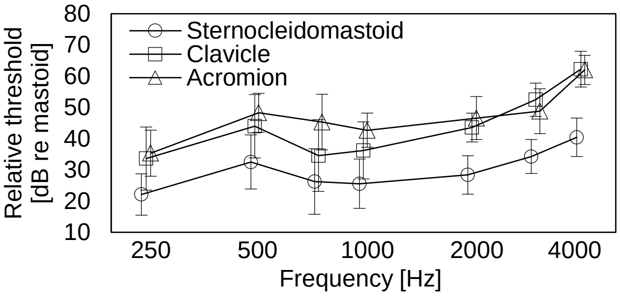

Fig. 2 Relative threshold of the distantly-presented bone-conducted sound. The threshold for the mastoid in each participant served as the reference (0 dB)

depth in the target intervals was varied adaptively.

3. Results

3.1 Hearing thresholds

Fig. 2 shows relative thresholds when the hearing threshold for the mastoid served as the reference. The hearing thresholds increased as the stimulus placements got further from the head. Additionally, in the distal parts, the relative thresholds increased as the stimulus frequency increased.

3.2 DLFs

Fig. 3 shows DLFs in each stimulus placement. In the mastoid, the DLF was about 0.3% at all CFs, and no significant differences were observed between the mastoid and distal parts at 500-3000 Hz. However, the DLF was increased at 250 and 4000 Hz in the clavicle.

3.2 TMTFs

Fig. 4 (a) and (b) show modulation thresholds in each stimulus placement using the 1000 and 4000-Hz sinusoidal carriers, respectively. In the case of the 1000-Hz carrier, no significant variations depending on increasing modulation frequency were observed in all stimulus placements. Additionally, no significant increases as the stimulus placements got further from the head were observed. In the case of 4000-Hz carrier, the modulation thresholds increased at a modulation frequency of 100 Hz or higher, however, no significant differences were observed among the stimulus placements.

4. Discussion

In our previous study on the hearing threshold of distantly-presented BCU,[4] the increase in the hearing threshold from the mastoid was only about 5 dB in the sternocleidomastoid, 20 dB in the upper arm. On the other hand, in this study, the increase in the hearing threshold was about 20-40 dB in the sternocleidomastoid, 35-65 dB in the clavicle and acromion. These results indicated that distance attenuation is much larger in the audible-frequency range compared to the ultrasonic range.

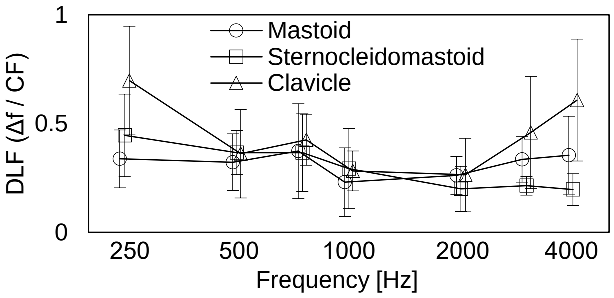

Fig. 3 Frequency difference limens (DLF) for each stimulus placement

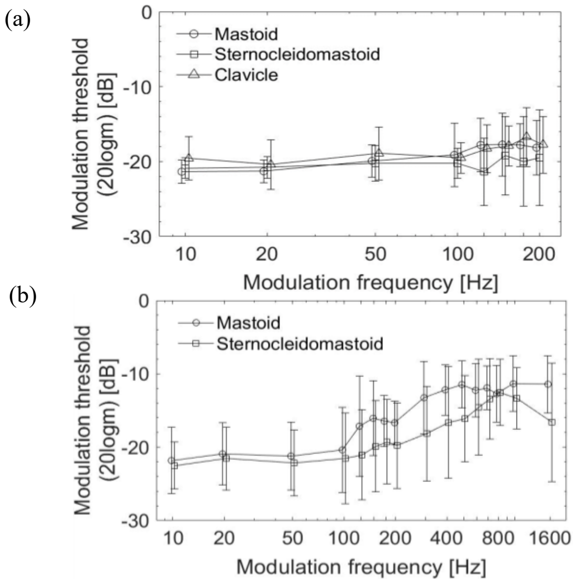

Fig. 4 Modulation-detection threshold at carrier frequencies of (a) 1000 Hz and (b) 4000 Hz

At the mastoid and sternocleidomastoid, the DLF was the same as that of AC sound at all CFs.[9] In addition, no significant differences in DLF were observed among stimulus placements at almost all CFs. These results indicated that degradation of frequency information occurred in the propagation process of BC sounds is sufficiently small.

No significant differences of TMTF were observed among stimulus placements at all modulation frequencies regardless of the carrier frequencies. This result indicated that no degradation of temporal information of BC sounds occurred in the propagation process in the human body.

Acknowledgment

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