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Basic properties of distantly-presented bone-conduction perception*

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Abstract— **Since a vibrator needs to be pressed onto the osseous parts of the head, bone-conduction (BC) is often accompanied by pain and esthetic problems. In order to solve these problems, "distant presentation" has been proposed. In the distant presentation, vibrators are presented to the neck, upper limb or trunk. Our previous studies focused on the perception and propagation characteristics of distantly-presented BC sound in the ultrasonic range and an application to a novel audio-interface. On the other hand, a limited number of studies have been conducted on distantly-presented BC in the audible-frequency range. In this study, to examine the basic properties of the distantly-presented BC perception in the audible-frequency range, hearing thresholds, difference limens for frequency (DLFs) and temporal modulation transfer functions (TMTFs) were measured under the condition that AC sounds were insulated sufficiently. The results obtained indicated that BC sounds can be clearly perceived at distal parts of the body even in the audible-frequency range and no significant degradation of frequency and temporal information occurs in the propagation process in the body.**

I. Introduction

Usually, we perceive sounds as a vibration of air. It is referred to as air-conduction (AC). On the other hand, we can perceive sound even as a vibration of biological tissues (bone, skin and muscle, etc.). It is called bone-conduction (BC).

Although the upper frequency limit of human hearing is believed to be approximately 20,000 Hz, several studies have reported that high-frequency sound up to at least 100,000 Hz can be perceived clearly by BC [1–3]. This "audible" ultrasound through BC is referred to as bone-conducted ultrasound (BCU). BCU can be perceived even by the profoundly sensorineural hearing-impaired, who can hardly sense sounds even with conventional hearing aids [4, 5]. Furthermore, BCU amplitude-modulated by speech sounds was intelligible to some extent, and thereby, BCU has been applied for a novel hearing aid by the profoundly hearing-impaired (bone-conducted ultrasonic hearing aid: BCUHA) [6-8].

Generally, in BC devices including BCUHA, it is necessary to press the vibrator onto osseous parts of the temporal bone, such as the mastoid process. Therefore, BC is often accompanied by pain and esthetic problems. Additionally, it is difficult to hold the vibrator steadily on the mastoid process's round surface. In order to solve these problems, "distant presentation" has been proposed [9]. In the distant presentation, vibrators are presented to the muscle of the neck, upper limb or trunk.

Our previous studies focused on the perception and propagation characteristics of distantly-presented BCU and an application to a novel audio-interface [9-11]. However, a limited number of studies have been conducted on distantly-presented BC in the audible-frequency range [12]. It is indispensable to investigate also in the audible-frequency range to elucidate the essential mechanisms of perception and propagation of BC sounds presented to distal parts of the body.

In the ultrasonic range, it is possible to evaluate only the BC-sound perception, because AC-sounds radiated from the vibrator are never perceived. On the contrary, in the audible-frequency range, not only BC-sounds but also AC-sounds radiated from the vibrator are perceived. AC-sounds need to be insulated sufficiently to evaluate only the BC-sounds perception.

In this study, as a first step to verify the basic perceptual characteristics of distantly-presented BC sound in the audible-frequency range, hearing thresholds were measured. Furthermore, to assess the characteristics of transferring frequency and temporal information, difference limens for frequency (DLFs), which reflect the frequency resolution, and temporal modulation transfer functions (TMTFs), which reflect the temporal resolution were measured. In all measurements, AC sounds were insulated sufficiently.

II. Insulation of Air-conducted sounds with ear-plug and ear-muff

In this study, AC sounds were insulated strongly by two kinds of ear-plugs and an ear-muff to evaluate only BC sounds. At first, urethane ear-plugs (DKSH Japan Silencia) were inserted into the subject's external auditory canals. After that, ear conchae were covered by silicone ear-plugs (Meiyu Insta-putty). Lastly, except for when the stimulus presented to the mastoid process, participants wore an ear-muff (3M PELTOR X5A) over the ear-plugs (Fig. 1). In order to examine the insulating effect, we measured the sound pressure level of the AC sounds radiated from the vibrator at the opening of the external auditory canal when the stimulus was presented under the same conditions as DLF and TMTF measurements (described later) and sound attenuation value based on ISO-

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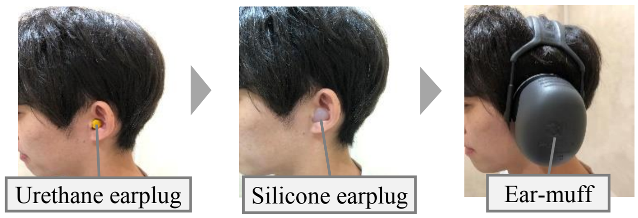

Figure 1. The method of insulation of air-conducted sounds used in the experiments.

4869. The results obtained indicate the AC sound was successfully insulated.

III. Method

Seven males (21–26 years) who had no history of deficits in their hearing functions participated. Participants were given detailed information about the experiments, and informed consent was obtained from each participant before the experiments. All the experiments conducted in this paper were approved by the Institutional Review Board on Life Science Research of Chiba University.

BC stimuli were presented to the following parts of the body (Fig. 2).

(a) Mastoid process of the temporal bone

(b) Sternocleidomastoid muscle (muscle of the neck; middle point between the mastoid process and sternoclavicular joint)

(c) Sternal end of the clavicle

(d) Acromion (only for hearing threshold measurement)

BC stimuli were presented by a BC vibrator (Radioear B-81). Fig. 3 shows the frequency response for the B-81 used in this study between 100 and 10,000 Hz at a constant input voltage of 1 V_{RMS}.

The vibrator was pressed onto the mastoid process and sternocleidomastoid muscle using an elastic band with foam (Fig. 2 (a), (b)). An icing supporter was used to fix the vibrator to the clavicle and acromion (Fig. 2 (c), (d)). All measurements were conducted in an anechoic room.

A. *Measurement of hearing thresholds*

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

Prior to the experimental sessions, the stimulus was presented at the initial stimulus intensity (described later) in the hearing threshold measurement without pressing the vibrator onto the body surface, and it was confirmed that the AC sounds radiated from the vibrator were not perceived at any frequencies. Hearing thresholds were measured using a 1

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

Figure 2. Stimulus placements used in the experiments.

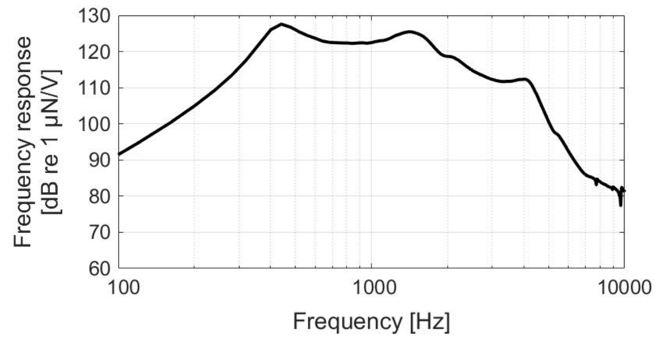

Figure 3. The frequency response for the B-81 used in the experiments measured at an input voltage of 1 V_{RMS} from 100 to 10,000 Hz. The magnitude is given in decibel relative to 1 µN/V

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 [13]. In this procedure, three intervals were presented sequentially, and the stimulus was presented only in one of the three intervals. Participants were requested to respond to the section in which the sound had been perceived. Hearing threshold measurements started from the stimulus intensity at which the sound could be perceived sufficiently by participants (initial stimulus intensity), and the intensity of stimulus in the target intervals was varied adaptively. The step size of the stimulus intensity corresponded initially to 4 dB and was reduced to 2 dB after two reversals and finally to 1 dB after four reversals. The mean of the last 8 reversals in a block of 11 reversals was used as the hearing thresholds.

B. *Measurement of difference limens for frequency (DLFs)*

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

The DLFs were measured using a 1 up-2 down two-alternative forced-choice (2AFC) adaptive procedure. Stimulus output levels were set to 15 dB SL for the mastoid process and sternocleidomastoid muscle and 10-15 dB SL for the clavicle. Prior to the experimental sessions, the stimulus was presented without pressing the vibrator onto the body surface, and it was confirmed that the AC sounds radiated from the vibrator were not perceived at any frequencies.

In each trial, two tone bursts that were equally spaced in linear frequency on either side of the CF were presented, and the participants were requested to respond to the stimulus with higher frequency. The DLF measurements started from the deviation from the CF (Δf) at which the participants could discriminate between two stimuli sufficiently, and Δf was varied adaptively. The measurements were conducted until 11 reversals of the change of the Δf were obtained, and the geometric mean of Δf/CF of the last 8 reversals was used as the discrimination values.

C. *Measurement of temporal modulation transfer functions (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 (DSB) amplitude modulation was applied to 1000 Hz and 4000 Hz sinusoidal carriers.

SAM stimuli are expressed as follows:

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

Here, A is the amplitude of the entire stimulus, m is the modulation depth, and f_m and f_c are the modulation and carrier frequency, respectively. The duration of the stimuli was 800 ms including 75 ms rising/falling ramps.

TMTFs were measured using a 1 up-2 down three-alternative forced-choice (3AFC) adaptive procedure. Stimulus output levels were set to a level at which each participant could detect modulation sufficiently, based on 25 dB SL. Prior to the experimental sessions, the stimuli were presented without pressing the vibrator onto the body surface, and it was confirmed that the AC sounds radiated from the vibrator were not perceived at any frequencies.

In each trial, three BC stimuli were presented sequentially. One of the three BC stimuli was modulated, and the others were unmodulated. The participants were requested to respond to the modulation interval. TMTF measurements started from the modulation depth (m) at which the modulation could be detected sufficiently by the participants, and the modulation depth in the modulation intervals was varied adaptively in the same manner as in Experiment I. The step size of the modulation depth corresponded initially to 4 dB (in units of 20 log) and was reduced to 2 dB after two reversals and finally to 1 dB after four reversals. The mean of the last 8 reversals in a block of 11 reversals was used as the modulation threshold.

IV. RESULTS

A. *Hearing thresholds*

Fig. 4 shows relative thresholds of the distantly-presented BC sound when the threshold for the mastoid process in each participant served as the reference (0 dB). Although the hearing thresholds increased as the stimulus placements got further from the head, all of the participants could perceive BC sounds in the audible-frequency range even in the distal parts of the body. In the distal parts, although the peak (about 5-10 dB) was observed at 500 Hz, the relative thresholds increased as the stimulus frequency increased, especially at 1000-4000 Hz in the clavicle and acromion.

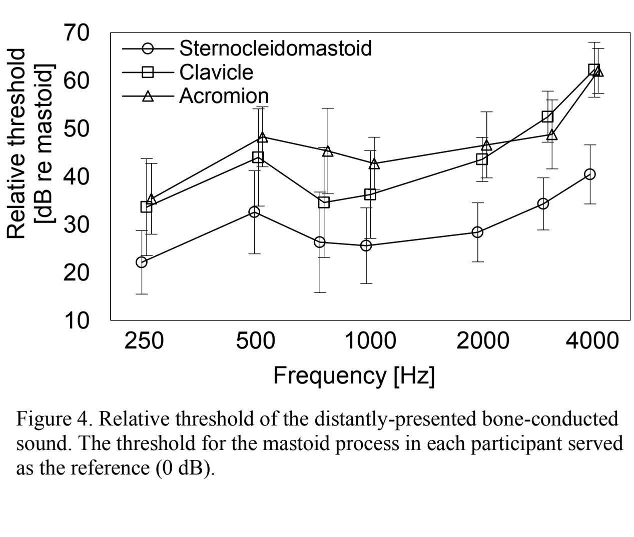

Figure 4. Relative threshold of the distantly-presented bone-conducted sound. The threshold for the mastoid process in each participant served as the reference (0 dB).

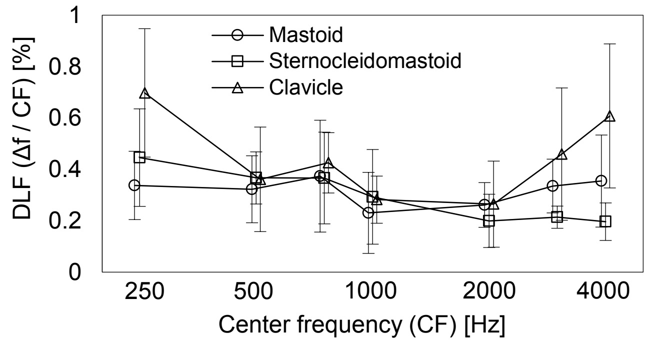

Figure 5. Frequency difference limens (DLF) for each stimulus placement

B. *Difference limens for frequency (DLFs)*

Fig. 5 shows DLFs in each stimulus placement. In the mastoid process, the DLF was about 0.3% at all CFs, and no significant differences were observed between the mastoid process and distal parts at 500-3000 Hz. However, the DLF was increased at 250 Hz and 4000 Hz in the clavicle.

C. *Temporal modulation transfer functions (TMTFs)*

Fig. 6 (a) and (b) show modulation thresholds in each stimulus placement using the 1000-Hz 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 the 4000-Hz carrier, the modulation thresholds were increased at a modulation frequency of 100 Hz or higher. In the said modulation frequency range, although the modulation threshold of the mastoid process was larger than that of the sternocleidomastoid muscle, no significant differences were observed.

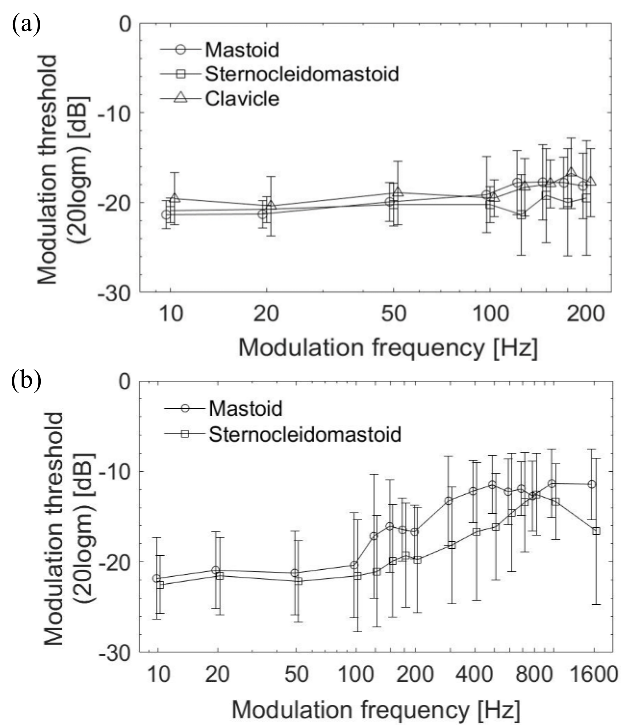

Figure 6. Modulation-detection threshold at carrier frequencies of (a) 1000 Hz and (b) 4000 Hz

V. Discussion

A. Hearing thresholds

Hearing thresholds were increased as the stimulus placements got further from the head as with our previous study [12]. On the other hand, a dip of the hearing threshold about 5-10 dB at 1000 Hz, shown in the previous study, was not observed. This discrepancy of the threshold might be caused by a difference of the vibrator (previous study: Radioear B-71) or the method of holding the vibrator, however, further studies are required to elucidate the detailed mechanism. In our previous study on the hearing threshold of distantly-presented BCU [9], an increase in hearing threshold from the mastoid process was only about 5 dB in the sternocleidomastoid muscle, 20 dB in the upper arm, 27 dB in the lower arm. On the other hand, in this study, an increase in hearing threshold from the mastoid process was about 20-40 dB in the sternocleidomastoid muscle, 35-65 dB in the clavicle and acromion. These results indicated that distance attenuation in the human body is much larger in the audible-frequency range compared to the ultrasonic range.

B. Difference limens for frequency (DLFs)

At the mastoid process and sternocleidomastoid muscle, the DLF was the same as that of AC sound at all CFs [14]. In addition, no significant differences were observed in DLF among stimulus placements at almost all CFs, whereas the hearing thresholds increased as the stimulus placements got further from the head. These results indicated that the degradation of frequency information occurred in the propagation process of BC sounds is sufficiently small.

C. Temporal modulation transfer functions (TMTFs)

No significant differences among stimulus placements were observed 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.

According to a former study on the TMTF of AC sound, the sidebands caused by amplitude modulation were perceived as another pitch above a certain modulation frequency, and the modulation threshold subsequently decreased [15]. On the other hand, in this study, no significant decreases in the modulation thresholds were observed as the modulation frequency increased. It is thought that the reason for this is that no significant sidebands exceeding the level of the noise floor were caused because the stimulus intensity was set to a smaller level (25 dB SL) to prevent the perception of the AC sounds radiated from the vibrator. Therefore, it is necessary to consider a more effective insulation method of the AC sounds and a method to eliminate the effect of vibratory sensation to elucidate the detailed perceptual mechanisms of distantly-presented BC sound in the audible-frequency range.

VI. Conclusion

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) and temporal modulation transfer functions (TMTFs) were measured under the condition that AC sounds were insulated sufficiently. The results obtained indicate that BC sound can be clearly perceived at distal parts of the body even in the audible-frequency range, whereas distance attenuation is occurred largely as compared to BCU. Additionally, it is also indicated that no significant degradation of frequency and temporal information occurs in the propagation process of BC sound in the body. These results provide useful information not only for elucidating the mechanisms of perception and propagation of distantly-presented BC sound, but also the development of novel BC devices using "distant presentation" that can transmit the sound information selectivity to users who touch the device.

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