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Effects of stimulus placement on distantly-presented bone-conducted ultrasound transmission

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1. Introduction

Ultrasound, high-frequency sound above 20 kHz, cannot be heard by air-conduction. However, several studies have reported that high frequency sound up to at least 120,000 Hz can be heard clearly by bone-conduction (BC) [1-3]. This "bone-conducted ultrasound (BCU)" can be perceived even by the profoundly sensorineural hearing impaired, and can transmit speech by using amplitude-modulation [4].

BC stimuli are typically presented to the mastoid process of the temporal bone. However, BCU can be perceived even when presented to body parts distant from the head (distantly-presented BCU), e.g., the neck, trunk, and upper limbs [5]. Additionally, BCUs do not inherently generate perceptible sound leakage and vibration sensation. Therefore, distantly-presented BCU can be applied to a novel audio device that selectively transmits auditory information to a specific user who touches the vibrator at the chest, trunk, or upper limbs [5].

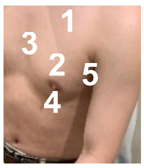
For the practical application of the distantly-presented BCU, it is crucial to improve speech intelligibility by optimizing the stimulus placement based on propagation mechanisms. Several studies have investigated the propagation mechanism of distantly-presented BCU. Nakagawa et al. (2018) reported that the hearing threshold of BCU increased with the distance from the head [5]. On the other hand, Ogino et al. (2019) measured the vibration of the upper limb when BCU was presented to the wrist [6]. The results showed a decrease in vibration amplitude with increasing propagation distance in the forearm, while the similar trend was not observed in the upper arm. This suggests that factors other than propagation distance, such as the anatomical structure of the stimulus site or coupling with the vibrator, may affect the perception of distantly-presented BCU.

In this study, to examine the effects of anatomical structure of stimulus placement on perception and propagation of the distantly-presented BCU, acceleration of vibration in the external auditory meatus and hearing threshold were measured for BCUs presented at several subdivided points within the chest, back, and upper limbs.

2. Methods

The experiments were conducted on eight males who had normal hearing (21–25 years). BCU stimuli were presented by a piezoelectric ceramic vibrator (Murata Manufacturing MA40E7S) at the following parts on the left side of the body (**Fig. 1**): (a) 5 points on the chest, (b) 5 points on the back, and (c) 7 points on the upper limbs. For the chest and the back, a waist supporter band (Bracco B009XTLSRS) was used, and for upper limbs, an elastic band (Asics TC8203) was used to keep the vibrator. The pressures were adjusted to 3.0 N using a load cell (Kyowa Electronic Instruments WGI-400A).

For the measurement of the vibration acceleration, a 30-kHz tone was used as the BCU stimulus. The voltage applied to the vibrator was set to 18.93 Vrms to achieve an SNR above a certain level at all locations. According to previous studies [7], the acceleration sensor (Ono Sokki NP-3211) was encased in urethane foam (diverted from Etymotic Research, Inc. ER1-14B) inserted into the left external auditory meatus. The acceleration of the external auditory meatus due to BCU stimulation placed at various parts of the body was measured for 5 seconds.

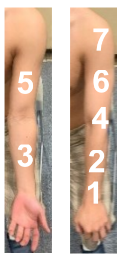


1. Midpoint of the clavicle
2. Center of pectoralis major muscle
3. Breastbone
4. Lower pectoralis major muscle
5. On the midaxillary line

(a) Chest

1. Trapezius muscle
2. Scapula
3. Spine
4. Latissimus dorsi
5. Triangle of auscultation

(b) Back



1. Wrist joint
2. Back of forearm muscles
3. Front of forearm muscles
4. Elbow joint
5. Biceps brachii
6. Triceps brachii
7. Deltoid muscle

(c) Upper limbs

Fig. 1 Placements of BCU stimuli.

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For the measurement of the hearing thresholds, a 30-kHz tone burst with a duration of 800 ms (including rise/fall times of 75 ms) was used as the BCU stimulus. Hearing thresholds were measured using a 1up-2down three-alternative forced-choice (3AFC) adaptive procedure with a decision rule that estimated the 70.7% correct point on the psychometric function [8].

3. Results

Fig. 2 shows the acceleration of vibration at the external auditory meatus and the average hearing threshold across all participants. When BCU stimuli were presented onto the back, higher acceleration and lower threshold were obtained than when presented onto the chest and upper limbs ($p < 0.05$). Similarly, when presented at the clavicle, the acceleration was higher, and the hearing threshold was lower compared to other stimulus placements on the chest ($p < 0.05$). Furthermore, when the stimuli were presented on the upper arm, flexion the elbow joint slightly decreased the hearing threshold and significantly increased the acceleration of vibration ($p < 0.05$) .

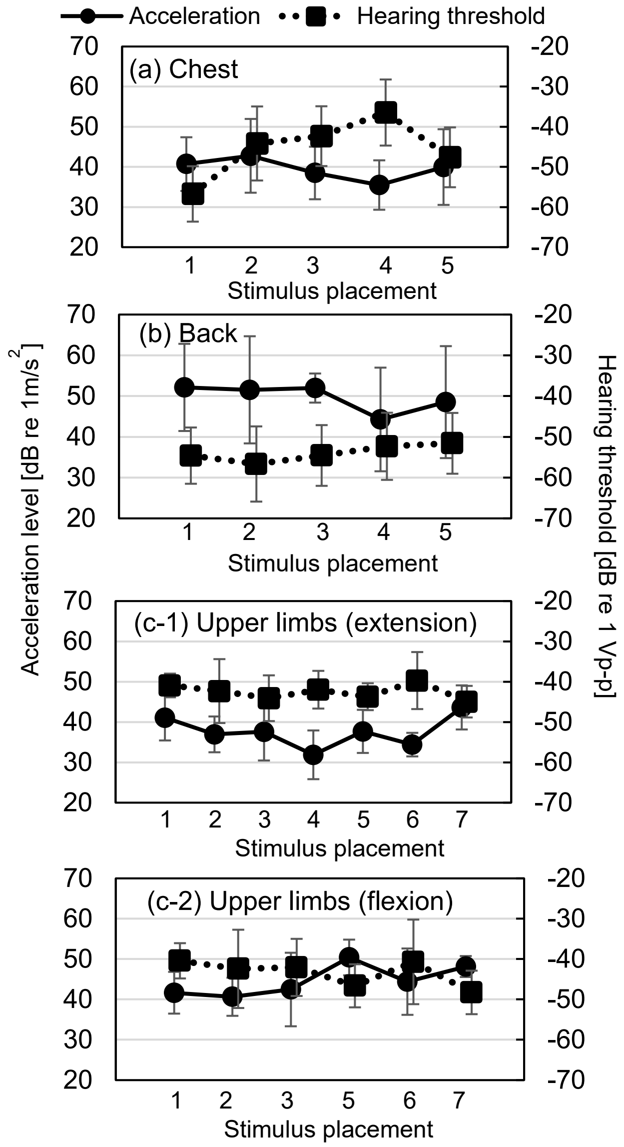

Fig. 2 The acceleration of vibration at the external auditory meatus and the hearing threshold for each stimulus placement.

4. Discussions

The highest vibration acceleration and the lowest hearing threshold were observed on the back. Previous studies have reported that the vibration acceleration of the carrier component decreases and the hearing threshold increases depending on the length of the propagation path [5, 9]. However, there appears to be no significant difference in the propagation distance between the back and chest. The current results may be attributed to the anatomical structure of the back. ewer muscles and muscle connections in the outer layers may have resulted in less loss during the propagation process, and the flatter shape of the back may have improved coupling with the vibrator. On the other hand, the better propagation performance observed at the clavicle could be attributed to the shorter propagation distance and simpler structure.

Furthermore, the flexion of the elbow joint significantly increased the acceleration in the upper arm. In this case, since flexion did not change the propagation distance to the receptors, it is possible that changes in the geometry of the stimulus placement and the elasticity of the muscles affected the propagation of BCU. More detailed research is needed to clarify the mechanism.

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