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Instability of Bone-conducted Ultrasonic Perception: Assessments by Acoustic Field Analysis in the Inner Head and Intelligibility Test

骨導超音波知覚の不安定性の検証：頭部内伝搬解析と聴取試験による検証

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1. Introduction

Bone-conducted ultrasound (BCU) can be experienced as sound even by the severely hearing-impaired. We have developed a BCU hearing aid (BCUHA) for the profoundly deaf.[1-3] In the BCUHA, ultrasonic sinusoids with a frequency of about 30 kHz are amplitude-modulated by speech and presented to the mastoid by a vibrator. Remarkable results have already been achieved; enabling 42 percent of the profoundly deaf trial subjects to perceive some sort of sound, and 30% of them to recognize simple words. These results suggested its practicability, however, there is room for improvement, especially in terms of usability. One of important problems to be solved is instability of BCU hearing. Properties of BCU hearing, for instance, loudness, sound image of location, and articulation show relatively large chanes in each time, even though the vibrator is held to the identical mastoid process every time.

One of the causes of these instabilities can be explained by complicated distributions of sound fields in the inner head in BCU hearing. It is empirically known that BCU hearing is strongly affected even by slight changes of attachment condition of the vibrator (location, angle, and contact pressure) and users have to search the suitable conditions exploratorily in order to get better hearing. Sakaguchi et al. (2002) caluclated sound fields induced by bone-conduction stimuli and oserved considarable shifts of the sound field for each different stimulation location by ultrasonic frequency stimulation, whereas changes caused by audible frequency stimulation were negligible.[4]

Another candidate of the instability originate from the perceptual or cognitive features of hearing. BCU perception shows unique characteristics that differ substantially from that of air-conduction hearing in audible frequency range. For instance, sound sensation by BCUHA is accompanied by a shrill, sometimes unpleasant tone due to the ultrasonic carrier,[5] with a pitch corresponding to a 8–16 kHz air-conducted sinusoid. Additionally, the dynamic range of loudness, i.e., the difference between the threshold and the uncomfortable level, is extremely narrow at less than 20 dB.[6] Therefore, many users feel a sense of discomfort, in particular when they begin to use the BCUHA.

In this study, to assess the instability of BCU hearing, seemed to be caused by above reasons, numerical simulations of acoustic fields in the inner head were performed. Also, intelligibility tests were carried out repeatedly in the same subjects and transition of intelligibility associated with learning were evaluated.

2. Effects of Subtle Changes of Vibrator Location within the Mastoid Process Evaluated by Numerical Simulations

2.1 Method

Sound pressure distributions due to BCU stimulation, 30-kHz sinusoid, within a three-dimensional realistic head model were numerically estimated. A finite-difference time-domain (FDTD) method was used to calculate the wave propagation in the simulation model. 5 simulations were performed with changing the oscillator's location within the left mastoid process. The distances between adjacent oscillators were about 5 mm.

2.2 Results

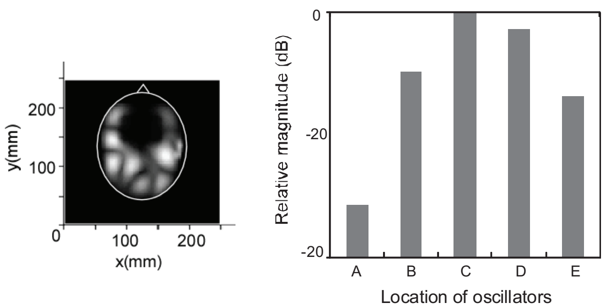

Fig. 1 Left: An example of distribution of maximum sound pressure at the xy-plane including the cochleae. Right: Maximum sound pressure at the left cochlea positions for 5 oscillator locations.

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Fig. 1 shows an example of distribution of maximum sound pressure at the xy-plane including the cochleae (left) and the maximum sound pressure at the left cochlea position for 5 oscillator locations. Although all oscillations were within the mastoid process, differences between locations reach more than 15 dB.

3. Assessment of Transition of Intelligibility Associated with Learning

3.1 Method

Word intelligibility of BCU speech for 4-mora Japanese words recorded with a male voice were investigated. Words with mid-range familiarity groups were selected to avoid ceiling and floor effects. As a method of amplitude modulation, double-sideband with transmitted carrier (DSB-TC) modulation was used for BCU speech. DSB-TC modulation is expressed as follow:

$$f(t) = A(1 + m \times s(t)) \times fc(t) \qquad (1)$$

The carrier signal $f_c(t)$ was a 30-kHz sinusoid, and the modulation depth m was adjusted for each word to avoid over-modulation. BCU speech were presented to one of the two mastoid processes of the subject's temporal bone by a piezoelectric ceramic vibrator.

12 Japanese normal-hearing adults (19-21 years, mean 19.9 ± 0.9, 7 females) who never experienced BCU hearing participated. After an explanation of an overview and unique characteristics of BCU hearing, subjects were instructed to set the vibrator carefully in the suitable condition while they heard a word "*doshaburi*" (heavy rain) repeatedly.

An experimental block consists of a learning part and a test part. In 4 subjects out of 8, 50 speech were presented with correct answers visually presented on a monitor first, and then intelligibility test was carried out using 50 speech (Learning-with-answer group). In other 4 subjects, 50 speech were presented without any answers first, and then intelligibility test was carried out using 50 speech (Learning-without-answer group). Subjects took part in 3 blocks serially a day. Totally, 12 blocks were carried out in 4 different days.

3.2 Results

Fig. 2 shows transitions of intelligibilities of each subject, and means of each subject group, respectively. No significant effects of presentation of answers, number of trial blocks, and their interaction were observed.

4. Discussions

Considering narrow dynamic range of loudness of BCU hearing,[6] differences of the sound energy at the cochlea positions between the oscillator locations seemed to have great effects on the perception.

In the intelligibility test, no significant increase of score was observed even though the number of trial increased. Further, the presence of answer had no significant effect. These results indicated that the learning effect on BCU speech hearing saturates at an early stage, at least in normal-hearing subjects.

On the other hand, variations of intelligibility score for each trial block was not small. Therefore, it is reasonable to think that changes of the sound energy received by the cochlea due to subtle changes of the attachment condition of the vibrator is a dominant cause of such variations of intelligibility.

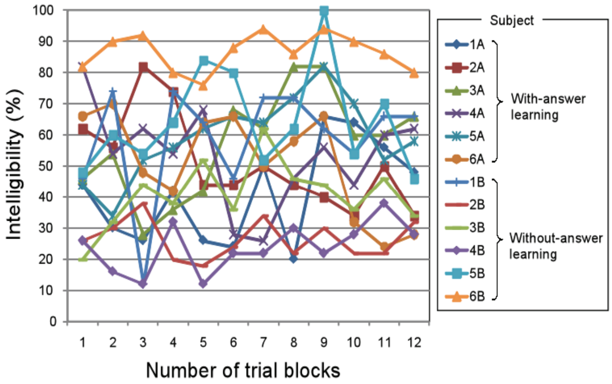

Fig. 2 Variations of intelligibility for each subject with increases of trials. 1A-6A: With-answer subjects, 1B-6B: Without-answer subjects.

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