Effects of Stimulation Side on the Auditory Evoked Magnetic Fields: Objective Assessments of Sound Localization in Bone-conducted Ultrasonic Perception

Seiji Nakagawa*

Abstract Bone-conducted ultrasound (BCU) is perceived even by those who are profoundly sensorineural deaf. A novel hearing-aid using BCU perception, which transmits amplitude-modulated ultrasound by bone-conduction, has been developed for the profoundly deaf. To assess and optimize the bone-conducted ultrasonic hearing-aid (BCUHA), the characteristics of BCU perception need to be better specified. This study verified the discrimination capability of two-channel BCUs presented to the both left and right mastoids in the both normal-hearing and profoundly deaf subjects by evaluating the laterality of the auditory evoked cortical activities. In normal-hearing subjects, N1m responses, the most prominent deflections peaking about 100 ms after the sound onset, evoked by the contralateral stimuli were larger in amplitude and shorter in latency than those evoked by the ipsilateral stimuli for BCUs as well as audible sounds. The same phenomena were also observed for BCUs in profoundly deaf subjects. These results suggest that two-channel BCUs were separately localized and provide a rationale to develop a two-channel BCUHA.

Keywords: ultrasound, bone-conduction, MEG, N1m, laterality, auditory cortex.

1. Introduction

Although the upper frequency limit of human hearing is believed to be no higher than about 24,000 Hz[1], several studies have reported that bone-conducted ultrasounds (BCUs) are audible[2-5] (Fig. 1). Indeed, BCU hearing in humans has been demonstrated in various auditory pathological conditions, including sensorineural hearing loss and middle ear disorders[4]. BCUs are perceived even by profoundly deaf subjects who can hardly sense sounds even with conventional hearing-aids[5].

In 1991, Lenhardt et al. reported that BCU modulated by speech sounds were intelligible to some extent[6]; suggesting the possibility to develop a novel hearing-aid based on BCU perception. However, Dobie disputed Lenhardt’s results which was obtained from subjective psychological experiments[7]; and ever since there has been continuing controversy.

Lenhardt's argument was recently objectively supported by magnetoencephalography (MEG)[8, 9] and positron emission tomography (PET)[10]. Further, a bone-conducted ultrasonic hearing-aid (BCUHA) for the profoundly deaf has been developed[11]. In the BCUHA, ultrasounds are amplitude-modulated by speech or environmental sounds detected by microphones and presented to the mastoid or the sternocleidomastoid by a vibrator[11]. The basic parameters in the BCUHA were determined according to the results of previous studies into the physiological and psychoacoustical characteristics of BCU perception: subjective pitch[12], dynamic range of loudness[13], the optimal career frequency for perception[14], and frequency resolution[15]. However, to assess and optimize the BCUHA, the features of BCU perception need to be better specified.

A capability to discriminate multi-channel inputs is essential for sound-localization and is an important function in hearing-aids. For sound-localization in the horizontal plane, interaural time differences (ITDs) and interaural intensity differences (IIDs) play crucial roles[16]. Because

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there is little ITD, it is sometimes more difficult to localize bone-conducted sounds than air-conducted ones.

In this study, the capability to discriminate two-channel BCUs presented to the both left and right mastoids was verified in both normal-hearing and profoundly deaf subjects. We evaluated the laterality of auditory brain magnetic fields. For air-conducted audible sounds, it has been reported that N1m responses, the most prominent deflections peaking about 100 ms after the sound onset, evoked by the ipsilateral-ear stimuli are smaller in amplitude[17] and later in latency than those evoked by the contralateral-ear stimuli[17–19]. If two-channel BCUs presented to the right/left mastoids can be separately localized, the same phenomena should be observed.

2. Materials and Methods

2.1 An Overview of Bone-conducted Ultrasonic Perception

2.1.1 Dynamic range of loudness The psychoacoustical dynamic range is defined as the difference between an uncomfortable level (UCL) and the threshold. The dynamic range for BCU is about 20 dB, whereas that for 1,000 Hz air-conducted sound is more than 80 dB[13].

2.1.2 Pitch of sinusoids The subjective pitch of sinusoidal BCU does not depend on its frequency, and is almost constant around the pitch induced by pure tones of 10,000~14,000 Hz[12]. Sinusoidal BCU is perceived as a mono-tone sound[3, 9, 12, 20].

2.1.3 Pitch of amplitude-modulated BCU Amplitude-modulated BCU has two pitches: One is induced by the BCU carrier, and the other by signal demodulations. The former corresponds to that induced by pure tones of about 10,000~14,000 Hz[12]. However, the mechanisms of demodulation have not been clarified.

2.2 Subjects

10 normal-hearing (3 females and 7 males; mean age 25.3 years, range 21–36, all right-handed) and 4 profoundly deaf volunteers (2 females and 2 males; mean age 56.3 years, range 45–62, all right-handed) took part in this experiment. Characteristics of the profoundly deaf subjects are summarized in Table 1: all were certified as sensing BCU sufficiently via the both left and right mastoids. During recordings, subjects sat on a chair in a magnetically shielded room, and were requested to watch self-selected silent movies with subtitles.

This study had prior approval from the Ethical Committee of the Kansai Center, National Institute of Advanced Industrial Science and Technology (AIST), Japan, and a written informed consent was obtained from each subject after an explanation of the nature and purpose of the investigation. No medication was given to the subjects before the experiments.

2.3 Stimuli

For the normal-hearing subjects, the following kinds of stimuli were presented in different sessions.

A. BCU: 30 kHz bone-conducted tone-burst amplitude-modulated by a 1,000-Hz tone-burst. Intensity: 10 dB SL.

B. Bone-conducted audible sound (BC): 1,000-Hz bone-conducted audible tone-burst. Intensity: 50 dB SL.

C. Air-conducted audible sound (AC): 1,000-Hz bone-conducted audible tone-burst. Intensity: 50 dB SL.

 Loudness of each stimulus was set to be almost constant through all the stimuli. The order of the sessions was counterbalanced between subjects. For the profoundly deaf subjects, only BCU was presented. To clarify the utility of the BCUHA in an actual environment, amplitude-modulated, not sinusoidal BCUs were used. For each session, two measurements were carried out with the stimulated side changed.

All stimuli were generated by a multifunction generator (WF1946, NF Corp., Yokohama, Japan). Bone-conducted sounds were amplified by a high-speed power amplifier (4020, NF Electric Instruments, Yokohama, Japan), and presented to the right/left mastoid by a newly devised ceramic vibrator. Air-conducted audible sounds were presented to the right-left ear via an inserted ear-phone (ER–2, Etymotic Research Inc., Elk Grove Village, IL, USA) and a plastic tube (29-cm length, 2-mm radius). Durations of all stimuli were 100 ms including linear rising and falling ramps of 10 ms each. Interstimulus intervals (ISIs) for all kinds of stimuli were varied randomly between 1,900 and 2,100 ms.

2.4 MEG Recordings

Recordings of event-related magnetic fields were carried out in a magnetically shielded room using a 122-channel whole-head neuromagnetometer (Neuromag-122TM; Neuromag Ltd., Helsinki, Finland). The vertical electrooculogram (EOG) was recorded by an amplifier (EEG-1100, Nihon Koden Corp., Tokyo, Japan) with infra- and supraorbital electrodes to monitor artifacts from eye blinks and eye movements. The magnetic data were sampled at 400 Hz after band-pass-filtering between 0.03 Hz and 100 Hz. Any epoch coinciding with magnetic signals exceeding 3,000 fT/cm and/or a vertical EOG deflection beyond 150 μV were rejected from further analysis. The average of more than 100 epochs was digitally band-pass-filtered between 0.1 and 30 Hz. The average of 200 ms pre-stimulus period served as the baseline.

2.5 Analyses

Neuromag-122TM has two pick-up coils in each position; these measure two tangential derivatives, ∂Bz/∂x and ∂Bz/∂y, of the field component Bz[21]. We determined:

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B' = \sqrt{(\partial Bz/\partial x)^2 + (\partial Bz/\partial y)^2}
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(1)
as the amplitude of the response. In each subject, we employed the N1m peak latency with a channel that showed the maximum amplitude placed over both temporal regions. N1m amplitudes and latencies were compared be-

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tween ipsi- and contralateral stimuli. Normalized N1m amplitudes were used in the comparisons: the maximum N1m amplitude among all channel positions in each subject was considered as 1.0. Analysis of variance (ANOVA) was performed on the normalized N1m amplitude and latency.

3. Results

Figure 2 shows an example of the averaged MEG wave forms for a normal-hearing and a profoundly deaf subject.

Channels that show maximum amplitudes in both temporal regions are enlarged. In the normal-hearing subject, substantial N1m components were elicited at latencies of 80–140 ms in each wave form. Also, N1m can be observed in the profoundly deaf subject for BCUs.

Figures 3 and 4 show N1m peak amplitude and latency (mean ± S.D.) respectively, for each kind of stimuli. In normal-hearing subjects, significant effects of the stimuli (AC/BC/BCU, p < 0.001), the stimulation side (ipsi-/contralateral, p < 0.001), the hemisphere (left/right, p < 0.01)
were observed for both amplitude and latency. N1m for BCU was significantly smaller in amplitude (vs AC: p < 0.01, vs BC: p < 0.01) and larger in latency (vs AC: p < 0.01, vs BC: p < 0.01) than AC and BC. Significant differences were observed between AC and BC in amplitude (p < 0.05), whereas no difference was observed in latency. In terms of the stimulation side, amplitudes were significantly larger (AC: p < 0.001, BC: p < 0.001, BCU: p < 0.005) and latencies were shorter (AC: p < 0.01, Δ = 8.1 ± 4.1 ms, BC: p < 0.01, Δ = 6.0 ± 3.4 ms, BCU: p < 0.01, Δ = 7.0 ± 3.8, Δ indicates a difference of latency between ipsi- and contra-lateral stimuli) for the contralateral rather than the ipsilateral stimuli.

In profoundly deaf subjects, the effects of the stimulation side (p < 0.01) were observed in both amplitude and latency, whereas the effect of the hemisphere was observed only in amplitude. Amplitudes were significantly larger (BCU: p < 0.05) and latencies were shorter (BCU: p < 0.05, Δ = 9.5 ± 4.8) for the contralateral compared to ipsilateral stimuli.

4. Discussion

Hari and Mäkäälä have reported that N1m evoked by contralateral air-conducted stimuli was larger in amplitude than that evoked by ipsilateral stimuli [13]. In our study, the amplitudes evoked by BCUs as well as by audible sounds were significantly larger for contralateral than for ipsilateral stimuli. In terms of latency, it is well-known that the N1m evoked by the ipsilateral is later than that of the contralateral by approximately 10 ms [13–15]. In our results, as well as for audible stimuli, differences were also observed between the contra- and ipsilateral BCU. These results suggest that two-BCU channels presented to the left and right mastoid were separately localized, i.e., each BCU channel entered the ipsilateral auditory pathway before the superior olivary nucleus. This finding also provides a rationale to develop a two-channel BCUHA.

In this study, as well as the normal-hearing, these same phenomena were shown even in profoundly deaf subjects. Among several hypotheses about the mechanism BCU perception, one proposes a transformation into low-frequency audible sound due to certain bio-mechanical non-linearity [7]. However, it was thought that detection of audible low-frequency sounds would be impossible for the profoundly deaf subjects who participated in the experiment because they had little sound sensitivity below 20 kHz. Also, no audible frequency components were observed by physioacoustical measurements on/around the human head during BCU presentation [22]. The current results suggest that BCU is perceived by a special mechanism which is different from that of audible-sound perception, and that BCU enter the auditory pathway before the superior olivary nucleus.

5. Conclusion

The ability to discriminate two-channel BCUs presented to both left and right mastoids was verified in both normal-hearing and profoundly deaf subjects by evaluating the laterality of the auditory evoked cortical activities. The results showed that N1m responses evoked by contralateral stimuli were larger in amplitude and shorter in latency than those evoked by ipsilateral stimuli for BCUs as well as audible sounds. As well as in the normal-hearing subjects, these phenomena were observed even in profoundly deaf subjects. The finding provides the rationale to develop a two-channel BCUHA.

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References

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Seiji Nakagawa received a Ph.D. degree in electronic engineering from the University of Tokyo in 1999. He joined the Electrotechnical Laboratory (ETL) in 1999. Since 2003, he has been a senior research scientist at the National Institute of Advanced Industrial Science and Technology (AIST). His current research interests are in the imaging of auditory function in humans and developments of medical and welfare equipments. He was awarded the Ogino Award from JSMBE and the Docomo Mobile Science Prize in 2003, the Second Prize in the Japan Biotechnology Business Competition in 2004, and the Ichimura Award and the Nature medicine- Anges MG Biomedical Award in 2006.

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