TEMPORARY THRESHOLD SHIFT IN AUDITION INDUCED BY EXPOSURE TO ULTRASOUND VIA BONE CONDUCTION

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Abstract

Vibrations with frequency above 20 kHz presented to the bones of skull are perceived as audible sound. This phenomenon is known as bone-conducted ultrasonic (BCU) perception, but its mechanism has been yet unclear. In the present study, we aimed at clarifying the difference between the processing mechanisms of BCU and ordinary bone-conducted sounds with frequency below 20 kHz (bone-conducted audible sounds: BCA) by measuring the auditory threshold of BCU and BCA sound before and after an exposure to tones or band noises with 1-min duration. In the results, the temporary threshold shift for BCU sounds showed similar characteristics to that for BCA sound, particularly when the same stimuli were presented as exposure. These results indicate that BCU and BCA shared some common auditory processing mechanisms.

Sounds with frequency above 20 kHz cannot be perceived in human audition, when presented as an air vibration through the ear canals. However, vibrations with such high frequencies are audible when presented through bone conduction (Bellucci, & Schneider, 1962; Corso, 1963; Gavreau, 1948; Pumphrey, 1962). This phenomenon is known as bone-conducted ultrasonic (BCU) perception. The BCU perception in humans has been reported in various auditory pathological conditions such as sensorineural hearing loss and middle-ear disorders (Bellucci & Schneider, 1962). The BCU is perceivable even for profoundly deaf subjects (Lenhardt, Skellett, Wang & Clarke, 1991). Interestingly, Lenhardt, Skellett, Wang and Clarke (1991) also reported that BCU modulated by speech sounds was recognizable as speech sound to some extent and suggested the possibility of development of a novel hearing aid by utilizing the BCU perception. The arguments of Lenhardt et al. were supported objectively by magnetoencephalography findings (Hosoi, Imaizumi, Sakaguchi, Tonoike & Murata, 1998; Nakagawa, 2007). Furthermore, a new hearing-aid for the profoundly deaf, the bone-conducted ultrasonic hearing-aid (BCUHA) has been developed (Nakagawa, Okamoto, and Fujisaka, 2006). Hearing tests on profoundly deaf subjects using this prototype show remarkable results: more than 40% of the profoundly deaf subjects were able to perceive some sounds, and 17% were able to recognize words (Nakagawa, Okamoto & Fujisaka, 2006). However, the mechanisms underlying BCU perception need to be better clarified to optimize the BCUHA.

Although the mechanisms of BCU perception remain unclear, recent electrophysiological measurements in humans have revealed that BCU evokes the same auditory pathway as audible-frequency sounds through the cochlear nerve, and there is no special organ for BCU perception (Nakagawa, 2009). Additionally, recent studies have shown several unique characteristics of BCU perception. For example, the pitch of sinusoidal BCU corresponds, irrespectively of its actual frequency, to a 10-odd kHz air-conducted sinusoid (Dieroff & Ertel, 1975; Nakagawa et. al, 1999; Nakagawa & Tonoike, 2005; Nishimura, Nakagawa, Sakguchi & Hosoi, 2003; Pumphrey, 1962). The dynamic range of BCU is extremely narrow at less than 20 dB and BCU strongly masks 10- to 15-kHz air-conducted sounds (Nishimura, Nakagawa, Sakguchi & Hosoi, 2003). Although various characteristics of BCU perception have been reported, its processing mechanism of the processing of BCU has not been fully uncovered.

In this study, we focused on investigation of the difference/commonality between the processing mechanisms of BCU and ordinary bone-conducted sounds with frequency below 20 kHz (hereafter in this article donated as bone-conducted audible sounds: BCA). A temporary shift or increase in auditory threshold, referred to as temporal threshold shift (TTS), as function of exposure to a prolonged intensive sounds. So far, TTS have been investigated mostly for air-conducted audible sounds. It is therefore expected that the present study would provide an unique cue for revealing what mechanism underlie the BCU perception.

Experiment I

The experiment I was designed to measure TTS induced by BCU after the exposure to BCU, and TTS induced by BCA after the exposure to BCA.

Subjects

Nine adult subjects with normal-hearing, ranged in age from 25 to 48 years ($M = 39.71$, $SD = 5.38$) participated in the experiment. Each subject performed in both of BCU and BCA sessions. A rest was provided for at least one hour between the two sessions to avoid influences of the exposure in the previous session, and the order of the two sessions was counterbalanced across the subjects.

Apparatuses

All types of BCU and BCA stimuli were presented to either one of the mastoid portions of the subject’s temporal bone by a newly devised ceramic vibrator. The vibrator was fixed by a headset with a clamping pressure of approximately 5 N (see Fig.1). The stimulation side was decided by subject's preference. BCU and BCA were generated by a personal computer at a sampling frequency of 96 kHz, and fed to the vibrator via a digital-to-analog converter (Audiofire 12, Echo Digital Audio Corp.), a power amplifier (M2629B, Mess-Tek) and a programmable attenuator (PA-5, Tucker-Davis Technologies, Inc.). The presentation of stimuli and the recording of the subjects’ responses were controlled by the PC operated by Windows XP. The experiment was carried out in a soundproof room.

Stimuli

The exposure stimuli were a tone burst of 60 s in duration with 30-kHz frequency and presented at 15 dB SL in the BCU session, and with 12-kHz frequency at 75 dB SL in BCA

Fig. 1. Illustration of providing a vibration to bones of skull.

session, respectively. The test stimuli to measure the threshold were tones of 200 ms in duration with 25 ms of rising and falling ramps, with an identical frequency to that of the exposure stimulus in each session.

Procedures

Prior to each session, the approximate threshold was measured for each subject by using the method of adjustment. Tone bursts of 200 ms in duration were repeatedly presented at SOA of 400 ms. Subjects were instructed to adjust the sound level by pressing a key labeled ‘up’ when the tones were too weak and not audible, or a key labeled ‘down’ if when they were too intensive, and then a key labeled ‘decide’ when they were just above audible level. The obtained threshold was used as a reference threshold in the following experimental sessions for measuring threshold shifts.

In the experimental session, threshold was measured for fifteen trials before and after the exposure, by using the method of limit. In each trial, test stimulus of 200 ms in duration started from a level smaller than the provisionally obtained reference threshold, and repeated at SOA of 400 ms with the sound level increasing by a certain step. The subjects were instructed to press ‘0’ key at the instant of perceiving the sound. The test stimulus was stopped immediately after the subjects’ key press. The next trial started 10 seconds after the previous trial started.

The trials were grouped into five blocks by three trials each. In each block, the threshold measured in the first trial was used to define the range of intensity in the second and the third trials. In the first trial in BCU session, the sound level of the test tone burst started from 10 dB below the provisionally obtained reference threshold and increased in 1.0-dB step. In the second and the third trials, the sound level started from 5 dB below the threshold measured in the first trial and increased in 0.5 dB step. In the first trial of the BCA session, the sound levels started from 20 dB below the provisionally obtained reference threshold and increased in 2 dB step. In the second and the third trials, the sound level started from 10 dB below the threshold measured in the first trial and increased in 1.0-dB step.

Additionally, all subjects performed a loudness matching test for BCU and BCA by using the method of adjustment. A 30-kHz tone burst and a 12-kHz tone burst with 200 ms in duration were presented alternately with SOA of 400 ms. The intensity of 30-kHz tone burst was fixed to 15 dB SL whereas that of 12 kHz tone burst was varied according to the subjects’ response. The subjects were required to adjust the level of 12 kHz tone burst until the perceived loudness of the 12 kHz tone burst matched with that of the 30 kHz tone burst.

Results

The second and the third trials of each block were averaged per subject and this value was defined as the threshold on each temporal position. Fig. 2 illustrates the threshold shifts calculated by averaging data from all subjects. The result shows that the exposure to BCU increased the threshold for approximately 3 dB. This effect was decreased gradually and back to about the pre-exposure level 110-s after the end of exposure. In contrast, threshold shift in BCA was not as explicit.

The result of loudness matching test showed that the sound levels of BCA tone burst perceived as equivalent to that BCU tone burst of 15 dB SL ranged from 54 to 68 dB SL (M = 57.44). These values are smaller than 75 dB SL of the BCA exposure, implying that the BCA exposure stimulus was perceived to be louder than BCU exposure stimulus.

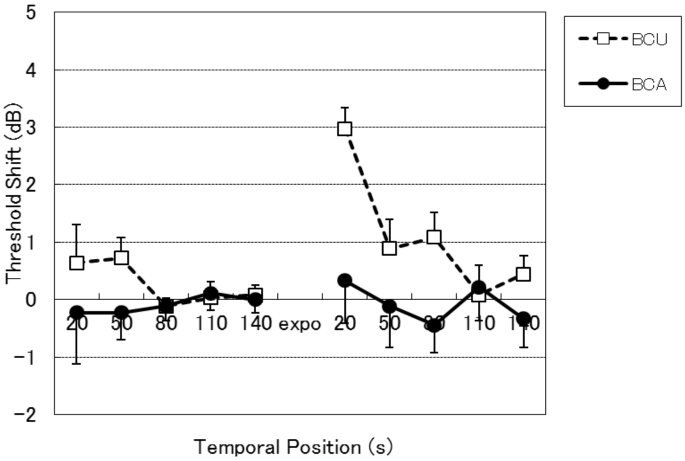

Fig. 2. Temporary threshold shift for BCU and BCA exposures. In the figure, ‘temporal position’ means the time from the beginning of threshold measurement, and ‘expo’ means the presentation of exposure stimuli. Error bars indicate the standard errors.

Experiment II

The experiment II was designed to examine the interaction between BCU and BCA, by measuring TTS induced by BCU and BCA after the exposure to a band noise with sonic frequency.

Method

Eight adult subjects with normal-hearing, ranged in age from 34 to 48 years (*M* = 36.50, *SD* = 6.68), participated in the experiment. Each subject performed in both of BCU and BCA sessions. A rest was provided for at least one hour between the two sessions to avoid influences of the exposure in the previous session, and the order of the two sessions was counterbalanced across the subjects.

In this experiment, the same exposure stimulus was presented in BCU and BCA sessions. The exposure stimulus was a band noise of 60 s in duration with frequency distributed equally between 8 and 16 kHz and presented at 45 dB SL. The test stimuli to measure the threshold were tone bursts of 200 ms in duration, with 25 ms rising and falling ramps. The test stimulus was a 30-kHz tone burst in BCU session and a 12-kHz in the BCA session, respectively.

The procedures of the experiment II were completely identical to those of the experiment I. That is, the reference threshold was provisionally obtained before the experimental session by using the method of adjustment, 15 trials of the threshold measurement were carried out both before and after the exposure by using the ascending series of the method of limit.

Results

The second and the third trials of each block were averaged per subject and this value was defined as the threshold on each temporal position. Fig. 3 illustrates the threshold shifts calculated by averaging data from all subjects. In the results, 3-dB or slightly smallerthreshold shifts were obtained in both BCU and BCA session. Similar results were obtained in the BCU and BCA sessions.

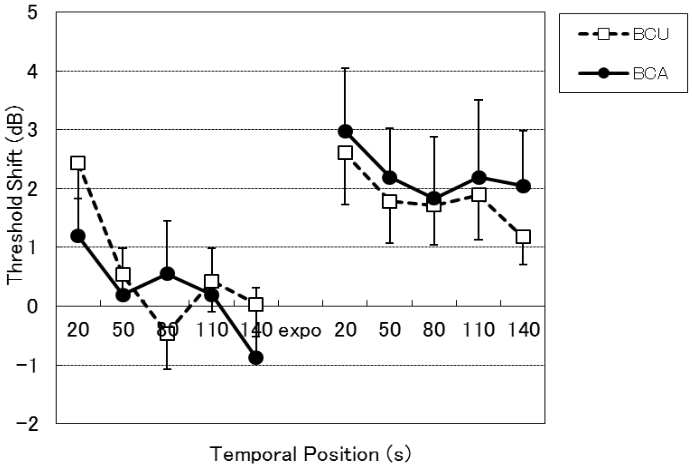

Fig. 3. Temporary threshold shift induced by band noise at audible frequency. In the figure, ‘temporal position’ means the time from the beginning of threshold measurement, and ‘expo’ means the presentation of exposure stimuli. Error bars indicate the standard errors.

Discussion

In the experiment I, the exposure to BCU induced approximately 3-dB increase of threshold, while the amount of threshold shift in BCA was much smaller. To discuss the implication of this result, the loudness and physical energy of the exposure stimuli must be taken account for. From the results of loudness matching test, the loudness of the exposure stimulus of BCA was larger than that of BCU. However, in terms of physical energy provided to bones, the intensity of the exposure stimulus of BCA was 5 to 15 dB smaller than that of BCU, which values were estimated from the measurement of the amplitude of the vibration of induced by the vibrator (Ito & Nakagawa,2011). In short, BCA exposure was larger in terms of loudness than BCU exposure, while BCU exposure was larger in terms of physical intensity. These facts lead to the conclusion that TTS depends more on physical energy than on loudness. They also implies that TTS relates to the processing not of the auditory center, in which stimulation is coded as sounds, but of peripheral organs, in which stimulation is not yet coded as sounds.

In the experiment II, the characteristics of TTS in BCA were very similar to those in BCU. The exposure stimulus that is band noise with sonic frequency was the same between in the BCU and BCA sessions. The fact that the exposure stimuli of sonic frequency induced TTS in BCU implies that BCU perception depends on the same mechanism as the sound with sonic range does. In other words, BCU perception and BCA perception uses some common processing mechanism in the periphery where stimulation is not yet coded as sound. This notion can be supported by the previous masking effect study (Nishimura, Nakagawa, Sakauchi & Hosi, 2003).

The result of the experiment II shows that the same exposure stimulus induced the similar amount of TTS in BCU and BCA. This fact validates the hypothesis that the physical intensity of exposure stimulus determines the amount of TTS, which is derived from the results of the experiment I.

Several hypotheses have been proposed for explaining why ultrasounds can be perceived when they are presented by bone-conduction. One of them is that sounds with sonic frequency are generated by non-linear transfer characteristics of human body. Another one is that humans perceive not sounds but vibration itself when ultrasounds are provided. However, these hypotheses cannot explain activities of the auditory cortices in the profoundly deaf subjects (Hosoi et al., 1998; Nakagawa, 2007), because they have little sensitivity to audible sound below 20 kHz. Further, no audible-frequency components were observed by physioacoustical measurements on/around the human head during BCU perception (Ito, & Nakagawa, 2010, 2011). . The most dominant explanation of BCU perception for the present is that cochlea directly perceives ultrasound to be sounds. An electrophysiological study showed an strong evidence for this explanation (Nakagawa 2009). The proposed explanation for the results in this article seems to be accordance with this hypothesis that cochlea can perceive ultrasounds as audible sounds.

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