Mechanisms of Bone-conducted Ultrasonic Perception Assessed by Psychoacoustical and Neurophysiological Measurements

Seiji Nakagawa, Mitsuo Tonoike

Life Electronics Laboratory
National Institute of Advanced Industrial Science and Technology (AIST), Osaka, Japan
s-nakagawa@aist.go.jp

Abstract
Mechanisms of bone-conducted ultrasound (BCU) were assessed by psychoacoustical and neurophysiological measurement. Dynamic range, and masking effects of BCU on air-conducted audible sound were investigated psychoacoustically. Also, auditory brainstem responses (ABRs) and activities of auditory cortices (N1m responses) were estimated by electro-encephalography (EEG) and magnetoencephalography (MEG), respectively. BCU showed narrower dynamic range than that for high-frequency air-conducted audible sound. High-frequency air-conducted audible sound, 10,000-14,000 Hz, were strongly masked by BCU. Further, substantial ABRs and N1m responses were elicited by BCU as well as air-conducted audible sound. These results indicate follows: (1) BCU perception depends on the inner hair cells activity induced by ultrasound, even without modulation being present, and does not depend on enhancement by the outer hair cells in the basal turn of the cochlea. (2) BCU has a same pathway as air-conducted audible sound between the cochlea nerve and the auditory cortex.

1. Introduction
Although several studies have reported that ultrasounds were perceived through bone conduction in the profoundly deaf as well as in normal-hearing subjects[1, 2], the perception mechanisms remain unclear. Several hypotheses were presented: Audible sound generation in the transmission path due to the non-linearity of biologocal tissues [3, 4], a contribution by vestibular hair cells[1, 5], or cochlear hair cells[6]. In this study, mechanisms of bone-conducted ultrasound (BCU) perception were assessed by psychoacoustical and neurophysiological measurement.

2. Experiments (Methods and Results)
2.1. Subjects
11 normal hearing volunteers (9 males, 21-52 years, righthanded) took part in these experiments.

2.2. Measurement of dynamic range
Method: For air-conducted sounds (500 ~ 16,000 Hz) and bone-conducted sounds (500 ~ 40,000 Hz), the thresholds and uncomfortable loudness levels (UCLs) were measured using an ascending method. The dynamic ranges were obtained by subtracting the thresholds from the UCLs. Result: No differences were observed between air-conducted and bone-conducted sounds under 8,000 Hz (Fig. 1). Over 8,000 Hz, dynamic ranges of bone-conducted sounds were narrower than that of air-conducted sounds. An average for BCU (20,000 ~ 40,000 Hz) was 22.7 ± 3.2 dB.

2.3. Measurement of masking
Method: For air-conducted sounds (500 ~ 16,000 Hz) and bone-conducted sounds (500 ~ 40,000 Hz), the thresholds and uncomfortable loudness levels (UCLs) were measured using an ascending method. The dynamic ranges were obtained by subtracting the thresholds from the UCLs. Result: High-frequency air-conducted audible sound, 10,000-14,000 Hz, were strongly masked by BCU (Fig. 2).

2.4. Measurement of auditory brainstem responses (ABR)
Method: 30,000 Hz tone pips (1 ms duration, 100 ms SOA, 5, 10, 15, and 20 dB SL) were presented by bone-conduction at each mastoid. Air-conducted clicks (rectangular wave, 0.1-ms duration, 100 ms SOA, 20, 40, 60, and 80 dB HL) were also presented to each ear. Result: Substantial ABRs, I ~ V waves, were observed by BCU as well as air-conducted sound.

2.5. Measurement of auditory evoked brain magnetic fields
Method: Following tone bursts (50 ms duration with 10 ms linear rising/falling ramps) were presented at subject’s ear/mastoid.
1. Air-conducted sounds (ACs; 1000, 2000, and 4000 Hz)
2. Low-frequency bone-conducted audible sounds (LBCs, 1000, 2000, and 4000 Hz)
3. High-frequency bone-conducted audible sounds (HBCs, 8000, 12000, 16000, and 20000 Hz)
4. Bone-conducted ultrasounds (BCUs, 22000, 27000, 32000, and 37000 Hz)
Recordings of magnetic fields were carried out in a magnetically shielded room using a 122-channel whole-head neuromagnetometer (Neuromag-122™, Neuromag Ltd., Helsinki, Finland). Two measurements were carried out with
Figure 1: Psychoacoustical dynamic ranges for air-conducted and bone-conducted sounds as a function of frequency.

Figure 2: Psychoacoustical dynamic ranges for air-conducted and bone-conducted sounds as a function of frequency.

changing stimulated side. For each kind of stimuli, N1m equivalent current dipoles (ECDs) were estimated in the Result: For all kinds of stimuli, substantial N1m were observed (Fig. 3), and ECDs were localized on the superior surface of the temporal lobe.

3. Discussions

In the current results, BCU showed narrow dynamic ranges. Narrow dynamic ranges are occasionally observed even in air-conducted sound perception: in the cochlea hearing impairment subject, for electrically evoked auditory perception, such as cochlea implants, since inner hair cells (IHCs) or the cochlea nerve are directly stimulated and outer hair cells (OHCs) don’t enhance their activity. The current study found large amount of masking for air-conducted sound in a broad frequency range, between 9,000 and 16,000 Hz. These frequency ranges correspond with the reported subjective pith [3, 4, 7] of BCU over 8,000-16,000 Hz. These results indicate a contribution by the cochlea partitions responding to high-frequency air-conducted audible sound. Non-linear hypothesis cannot explain unchanging pitch [3, 4, 7] and extremely narrower dynamic range of BCU. As conclusions, the current results indicate follows: (1) BCU perception depends on the inner hair cells activity induced by ultrasound, even without modulation being present, and does not depend on enhancement by the outer hair cells in the basal turn of the cochlea. (2) BCU has a same pathway as air-conducted audible sound between the cochlea nerve and the auditory cortex.

4. References