1P5-8

Proceedings of Symposium on Ultrasonic Electronics, Vol. 35 (2014) pp. 139-140
3-5 December, 2014

Acoustic aspects of amplitude-modulated bone-conducted ultrasonic hearing

振幅変調された骨導超音波聴取の音響的側面について

Kazuhito Ito† and Seiji Nakagawa (Health Research Institute, National Institute of Advanced Industrial Science and Technology (AIST))
伊藤 一仁†，中川 誠司 (産総研 健康工学)

1. Introduction

Ultrasound, sound of frequencies greater than 20 kHz, is imperceptible by air conduction. But it actually becomes perceptible through bone conduction (BC). Several studies have reported that bone-conducted ultrasound (BCU) can be perceived by some of the profoundly deaf people with conductive and/or sensorineural hearing loss as well as those with normal hearing.[1)] Therefore, a novel hearing aid using BCU hearing (bone-conducted ultrasonic hearing aid: BCUHA) is being developed for profound deafness. However, the mechanisms of BCU hearing remain unclear and need to be clarified for better development of the BCUHA.

The most unique feature is that the subjective pitch of BCU sounds like a tone or harmonic sound of between ten and twenty kilohertz, independent of its own frequency. Moreover, the pitch is not masked well by air-conducted sound.[2)] In the BCUHA system, ultrasounds are amplitude-modulated by speech or environmental sounds and fed to listeners with a bone vibrator. The listeners can perceive the amplitude modulation signal component as speech or environmental sounds together with, but separately from the carrier signal component of BCU.

The acoustic and subjective characteristics of the hearing caused by a sinusoidal BCU tone as a carrier signal have been investigated so far. [3)] Then, BCU hearing is suggested to be a unique auditory sensation rather than a nonlinear self-demodulation effect generated in the signal propagation. On the other hand, for amplitude-modulated BCU hearing, the subjective aspects have been often reported, whereas its acoustic aspects have been disregard curiously in the past. However, such disregard is unacceptable because it is considered that the self-demodulation effect can be yielded more easily for the amplitude-modulated signal component than for the carrier signal component.[4)]

In this paper, acoustic fields in the ear canal under amplitude-modulated BCU stimulation were measured with respect to the self-demodulation effect of amplitude modulation signal generated at the ear. In addition, acoustic fields were compared between before and after the occlusion of the ear canal to identify the pathway of sound transmission of amplitude-modulated BCU.

2. Methods

Acoustic fields in the ear canal of a subject with normal hearing under BCU stimulation with amplitude modulation were measured. The bone vibrator (MA40E7S, Murata Manufacturing) was attached onto a mastoid portion of the subject’s temporal bone and held by the headset with a contact force of approximately 5 N. The acoustic fields were measured with a probe tube microphone (ER-7C, Etymotic Research), which was set into the ear canal. The tip of the probe was positioned at depths of approximately 30 mm from the tragus on the stimulated ear side. The microphone was calibrated with a sound level calibrator (type 4231, Brüel & Kjær).

The head of the subject was excited by a 30-kHz BCU with amplitude modulation of 500, 1000, and 2000 Hz. The subject was first asked to measure the subjective hearing threshold level for each amplitude modulation signal component by the method of adjustment. Then the excitation level was determined to be a sensation level (SL) of 20 dB. This level was loud enough for the subject with normal hearing to hear the amplitude modulation signal component separately from the carrier signal.

Acoustic fields were measured before and after the ear canal was occluded using a silicone ear plug (Insta-putty, Insta-Mold Products). The ear plug was introduced at most 10 mm into the tested ear canal. The subject again measured the subjective hearing threshold level for each amplitude modulation signal component after the occlusion. For comparison, acoustic fields under ordinary audible BC stimulation with the same frequencies as those of the amplitude modulation were measured in the same manner as mentioned above. All measurements were performed in an anechoic room.

3. Results and Discussions

The two frequency spectra of acoustic field in the ear canal under a 30-kHz BCU stimulation with 1-kHz amplitude modulation were superimposed in **Fig. 1**. The blue and green lines represent the spectra before and after the occlusion of the ear canal, respectively. In each spectrum, there was a remarkable signal peak with modulation sideband at 30 kHz corresponding to the BCU stimulation. However, there appears to be no obvious signal between 10 and 20 kHz related to the subjective pitch of BCU carrier. This suggests that the subjective pitch of BCU carrier cannot be generated by the self-demodulation effect.

Meanwhile, there was a single signal peak at 1 kHz beyond the noise floor. This signal peak seems to be a sound radiated in the ear canal and probably generated by the self-demodulation effect of the amplitude modulation signal of the BCU stimulation. In addition, as shown by a difference in magnitude between the spectra, the signal peak grew up after the occlusion of the ear canal. This attributes to the occlusion effect of BC as is well known. It should be noted that both the signal peaks before and after the occlusion have audible sound pressure levels for normal hearing: 19.1 dB SPL with the open ear canal and 38.6 dB SPL with the occluded ear canal. Therefore, this result suggests that when applying amplitude-modulated BCU stimulation to listeners with normal hearing, they can perceive the amplitude-modulation signal demodulated into the audible frequency range rather than that in the ultrasonic range.

Two types of the occlusion effect were plotted in **Fig. 2**. The solid lines denote the effect as sound pressure in the ear canal and the dotted lines the effect as subjective hearing threshold. Moreover, the green lines represent for the self-demodulated signals and the blue lines for the signals derived from audible BC stimuli with the same frequencies as those of the amplitude modulation for comparison. The occlusion effect as sound pressure in the ear canal showed typical characteristics for both the signals.[5] Consequently, it is suggested that the self-demodulated signals were transmitted through the skin and soft tissues into the ear canal in the same way as audible BC sound.

On the other hand, the subjective occlusion effect on the self-demodulated signals was little as opposed to that on the signals derived from audible BC stimuli. Interestingly, this result leads to a discrepancy between the acoustic and subjective occlusion effects on the self-demodulated signals. An explanation is the possibility that the sound pressure of the self-demodulated signal in the ear canal is not the main contributor to the perception of the amplitude modulation signal of BCU due to the presence of other or special modes of BC perception. However, this issue remains unresolved and further empirical studies are needed.

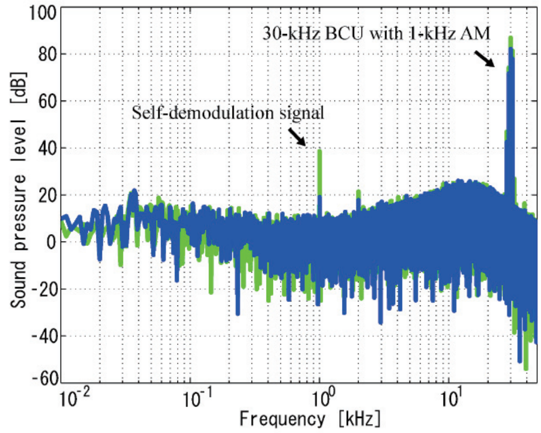

Fig. 1. Acoustic fields in the ear canal under a 30-kHz BCU stimulation with 1-kHz amplitude modulation before and after the occlusion of the ear canal.

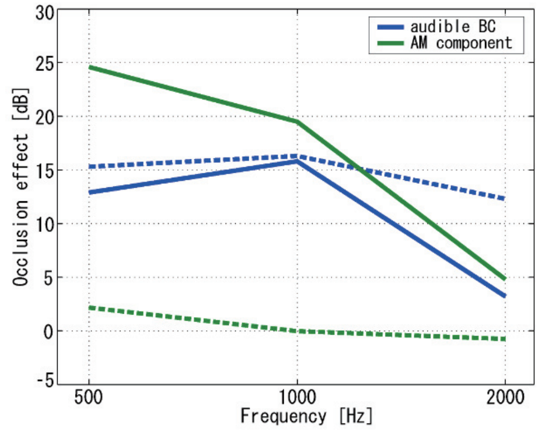

Fig. 2. The occlusion effects as sound pressure in the ear canal (solid lines) and subjective hearing threshold (dotted lines). The green lines represent for the self-demodulated signals and the blue lines for the signals derived from audible BC stimuli.

Acknowledgment

A part of this work was supported by the Funding Program for Next-Generation World-Leading Researchers provided by the Cabinet Office, Government of Japan, and the Grants-in-Aid for Scientific Research (26282130, 26560320, 25280063) of Japan Society for the Promotion of Science.

References

1. M. L. Lenhardt, R. Skellett, P. Wang, A.M. Clarke: Science, **253** (1991) pp.82-85.
2. T. Nishimura, S. Nakagawa, T. Sakaguchi, and H. Hosoi: Hearing Res. **175** (2003) 171
3. K. Ito and S. Nakagawa: Jpn. J. Appl. Phys. **49** (2010) 07HF31.
4. M. Yoneyama, J. Fujimoto, J.A.S.A., **75**(5), (1983) pp. 1532-1536.
5. S. Stenfelt, S. Reinfeldt, Int. J. Audiol., 46, (2007), pp. 595-608.