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# Perception Mechanisms of Bone-conducted Ultrasound assessed by Acoustic Characteristics in the External Auditory Meatus
# 外耳道内音響特性による骨導超音波知覚メカニズムの推定

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## 1. Introduction

Ultrasound is usually described as inaudible sound that has a frequency above 20 kHz. However, it actually becomes audible by bone conduction.[1)] Interestingly, several studies have reported that bone-conducted ultrasound was perceived by some of the profoundly deafs (with not only conductive but also sensorineural hearing loss) as well as normal hearing persons.[2,3)] Therefore, a bone-conducted ultrasonic hearing device is being developed as a novel hearing aid for profoundly deafness.[4)] However, the perception mechanisms remain unclear.

As for the perception mechanisms of ordinary bone conduction, three general routes of bone conduction hearing have been indicated: inertial, compressional, and osseotympanic routes. [5,6)] It is, however, generally accepted that bone conduction stimulates the cochlea by the same mechanisms as normal air conduction, which is referred to as “the traveling wave theory” by von Békésy (1953). [7,8)] Consequently, the issues of why ultrasound can be heard by bone conduction and how the profoundly deaf people hear it remain unresolved and need to be clarified for the better developments of the new hearing aid system. An important clue is that ultrasonic tones in bone conduction produce a sensation of pitch as a pure tone with an audible frequency of about 8 to 16 kHz.[1-4)] One possible explanation for this phenomenon is effects of non-linear distortions in the bone-conducted transmission path that consists of skull bones and soft tissues. In other words, one has suspected the possibility that ultrasounds in bone conduction are perceptible by the generation of subharmonics in the audible frequency range through nonlinearities and the use of the ordinary hearing route known as air conduction (the osseotympanic route with nonlinear distortions). [9)] Indeed, there were some reports that, when exposed to intense sound pressure levels in air conduction, the eardrum vibrates nonlinearly and can generate subharmonic vibrations.[10-12)] It cannot be denied that a similar phenomenon can arise in bone conduction.

In this study, to clarify the contributions of the occeotympanic and the inertial route to the bone-conducted ultrasonic perception, acoustic fields/vibrations in the external auditory meatus (ear canal) and the tympanic membrane under bone-conducted ultrasonic stimulation were measured. Then, evidence of nonlinear distortions, especially generations of subharmonics in the outer and middle ear were examined.

## 2. Methods

Acoustic fields in the external auditory meatus with bone-conducted ultrasonic stimuli were measured using a probe microphone (type 4182, Brüel & Kjær) inserted into four subjects’ ear canals. Bone-conducted ultrasonic tones were presented through a transducer (MA40E7S, Murata Manufacturing Co. Ltd.) that was attached at the mastoid on the measured ear side. In addition, tympanic membrane vibrations were also measured in one of the subjects by a laser Doppler vibrometer (LV1720, Ono Sokki Co. Ltd.).

The intensity of bone-conducted ultrasonic tones of 30 kHz was set to a level matching with 15 dB SL (sensation level) that is loud enough to hear because of the narrow dynamic range of the bone-conducted ultrasonic perception (13-23 dB in Nishimura et al. 2003). [13)] An equivalent sound pressure level corresponding to the loudness of a bone-conducted ultrasonic tone of 30 kHz was estimated by loudness matching with an air-conducted tone of 10 kHz using an insert earphone (ER-2, Etymotic Research Inc.) on the measured ear. In the current paper, we show data from a subject whose subjective pitch of a bone-conducted ultrasonic tone of 30 kHz is estimated at a frequency of 13–14 kHz.

## 3. Results and Discussion

A typical acoustic field in the external auditory meatus with a bone-conducted ultrasonic tone of 30 kHz is shown in **Fig.1**. The acoustic characteristic has a marked peak at the same frequency as that of

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the given stimulus. However, no signals appear in the frequency range corresponding to the subjective pitch (13–14 kHz) or the first subharmonic (15 kHz). According to the loudness matching, the loudness level of the bone-conducted ultrasonic tone of 30 kHz was equivalent to a sound pressure level of nearly 70 dB at 10 kHz. Therefore, if bone-conducted ultrasonic perception had resulted from audible subharmonics through nonlinear distortions in the transmission path, a signal with a level corresponding to the loudness level of the bone-conducted ultrasonic stimulus could have risen in the audible range of the acoustic field. This result suggests that there is no contribution of “the osseotympanic route with nonlinear distortions” to the bone-conducted ultrasonic perception. The other subjects had the same result.

Furthermore, as shown in **Fig. 2**, a tympanic membrane vibration with bone-conducted ultrasonic tone of 30 kHz also has a marked peak for that stimulus itself but no signal for the subharmonics within the audible frequency range of 10 to 20 kHz. Considering that tympanic membrane vibrations reflect the mechanical conductive characteristics of the middle ear and that the inertial bone conduction results from the relative translational motion between the middle ear ossicles and the temporal bone, this result suggests that there is no evidence for “the inertial route with nonlinear distortions” to produce subharmonics.

Consequently, it seems that the bone-conducted ultrasound is received as ultrasound itself, and specific properties of the perception should be related to the mechanisms in the cochlea or afferent neural pathway. This conclusion is consistent with the fact that bone-conducted ultrasound can perceived by subjects with the conductive hearing loss.

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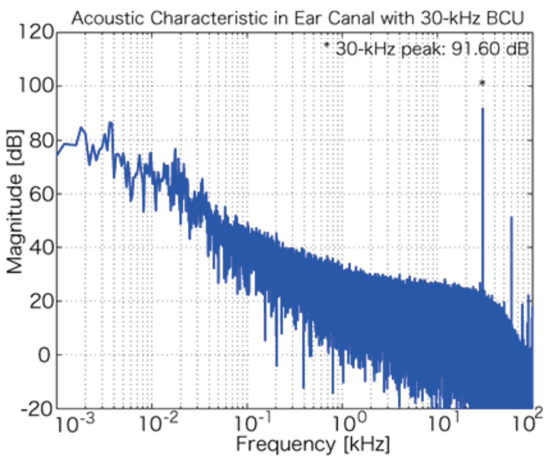


Fig. 1 An acoustic field in the external auditory meatus under a bone-conducted ultrasonic stimulus (30 kHz) measured by a probe microphone.

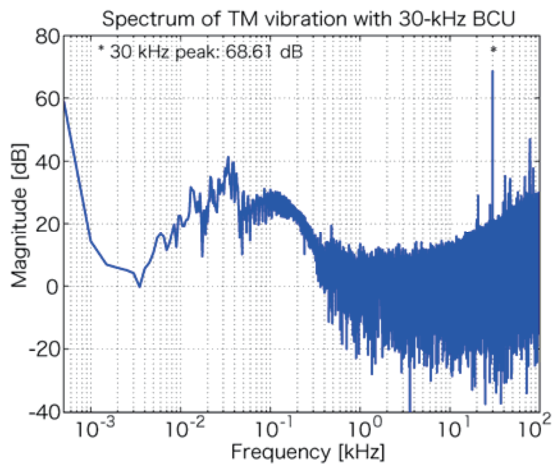


Fig. 2 A tympanic membrane vibration under a bone-conducted ultrasonic stimulus (30 kHz) measured by a laser Doppler vibrometer. (The small peak at 20.5 kHz is a system noise).