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Propagation Characteristics of the Bone-conducted Ultrasound in the Living Human Head: Individuality of the Propagation Delay

骨導超音波の頭部内伝搬特性 - 伝搬遅延特性の個人性の検討

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1. Introduction

An ultrasound with frequency above 20 kHz (up to about 100 kHz) can be heard via bone-conduction (BC)[1)]. This "audible" ultrasound through BC is referred to as the bone-conducted ultrasound (BCU). Since BCU can be perceived not only by normal hearing but also by severe hearing impaired[2)], a novel hearing aid (bone-conducted ultrasonic hearing aid, BCUHA) is being developed for profoundly hearing impaired[3)].

The perception mechanisms of BCU, however, have still unclear. For the better understanding of the perception mechanisms of BCU, various approach have been made: estimation of the propagation process of BCU in the head by using computer simulations or actual measurements is one of these approaches. In the previous studies, we estimated the propagation velocity of BCU in a living human head as approximately 300 m/s by using the pattern of acoustic interference of simultaneous bilateral excitation[4)].

Further, we estimated the characteristics of the propagation delay of ultrasonic sinusoidal pulse by using across-frequency phase disturbance of the acceleration responses[5)]. We also estimated the propagation delay by using an instantaneous frequency (IF) analysis for higher accurate detection of the delay[6)] and showed presence of frequency dependence of transient delay characteristics. However, since the methods used in the previous study[6)] was very time consuming to measure responses for ultrasonic sinusoidal pulses and the burden for subjects was large, it was difficult to conduct measurements for many subjects.

Therefore, in this study, we modify the methods in order to reduce the time associated with the measurements of responses for ultrasonic sinusoidal pulses, and we conducted the measurements with new method for four subjects. As a modified method, we just measured responses for a swept-sine signal. From the obtained swept-sine signal, the impulse responses were calculated, then the distributions of simulated responses for ultrasonic sinusoidal pulse were obtained by convolving ultrasonic pulses with the measured impulse response.

2. Measurements

2.1 Methods

The experimental setup is shown in **Fig.1**. Vibrators (Murata Manufacturing MA40E7S) were attached onto the subjects' mastoid processes and accelerometers (Ono Sokki NP3211) were placed at the left and right ear canal entrances.

A swept-sine signal with frequency from 20,000 to 40,000 Hz with sweep duration of 1 s was used as an excitation signal for impulse response measurements. The excitation signals were presented unilaterally and the acceleration responses at ipsi- and contra-lateral ears were recorded simultaneously.

Measurements were performed four times for each side. On each measurements the vibrators and the accelerometers were reinstalled. In order to improve the SN ratio of the response signals, 100 times averaging was performed for each measurement. Impulse responses were calculated by convolving the inverse filter of the original swept-sine signal with the swept-sine responses.

The excitation signals were synthesized digitally with a sampling frequency of 800 kHz, generated through a 16-bit AD/DA converter (National Instruments, PXI-6120). The analog signals from the accelerometers were converted to digital signals by the AD/DA converter with a 16-bit and 800-kHz sampling and stored in a PC. PyDAQmx[7)] that operates on Python 2.7 was used for controlling the AD/DA converter.

2.2 Instantaneous Frequency Analysis

Simulated transient responses of sinusoidal ultrasonic pulses were obtained by convolving sinusoidal signals which were 100-wave with frequency from 25 kHz to 35 kHz in 200-Hz steps with the impulse responses which were obtained in the former section.

The IF analyses were applied on the

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simulated transient responses. The instantaneous phase as a function of time is represented as:

$$\phi_f(t) = \tan^{-1}\frac{x_{hf}(t)}{x_f(t)}, \qquad (1)$$

where $x_f(t)$ is the response signal for the excitation frequency, f, and $x_{hf}(t)$ is the Hilbert transform signal of $x_{hf}(t)$. The IF signal as a function of time for f, $IF_f(t)$, is obtained as the time derivative of $\phi_f(t)$ as :

$$IF_f(t) = \frac{1}{2\pi}\frac{d\phi_f(t)}{dt}. \qquad (2)$$

Then, the normalized IF is obtained as time-frequency function normalized by the excitation frequency f:

$$nIF(t,f) = \frac{IF_f(t)}{f}. \qquad (3)$$

3. Results and discussion

As examples for the results, the normalized IF maps of the subjects A, B and C were shown in **Figs. 2A, 2B** and **2C** respectively. The left and the right columns show ipsi- and contra-lateral responses respectively. In these IF maps, arrivals of the first wave were illegible. For indication of the first arrival time, waveforms of the acceleration responses of the swept-sine signals were plotted on the upper side of each of the IF map with corresponding time.

In these examples of results, the IF maps show that after reaching the first wave with low frequency dependence there was early arrival wave(s) with low frequency dependence. At the subsequent delay, there were subsequent waves with strong frequency dependence.

In other results that are not shown here, although there were differences in the delay time and the number of the early arrival waves and in the strength of the frequency dependence in the subsequent waves, which were derived from mounting state and subjects' head shapes, characteristics were generally similar.

4. Conclusions

For multiple subjects, the propagation delay characteristics were examined. In the results, the temporal structure of arriving waves that are common among the subjects was shown. The individuality of the propagation delay is reflected in the delay time and the frequency dependencies.

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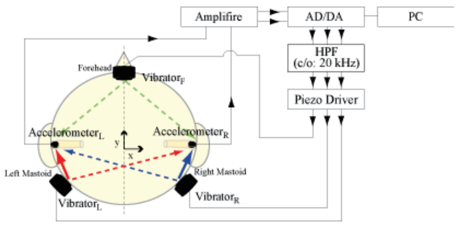

Fig. 1. Experimental set-up for the measurement of the propagation characteristics of BCU in a human head.

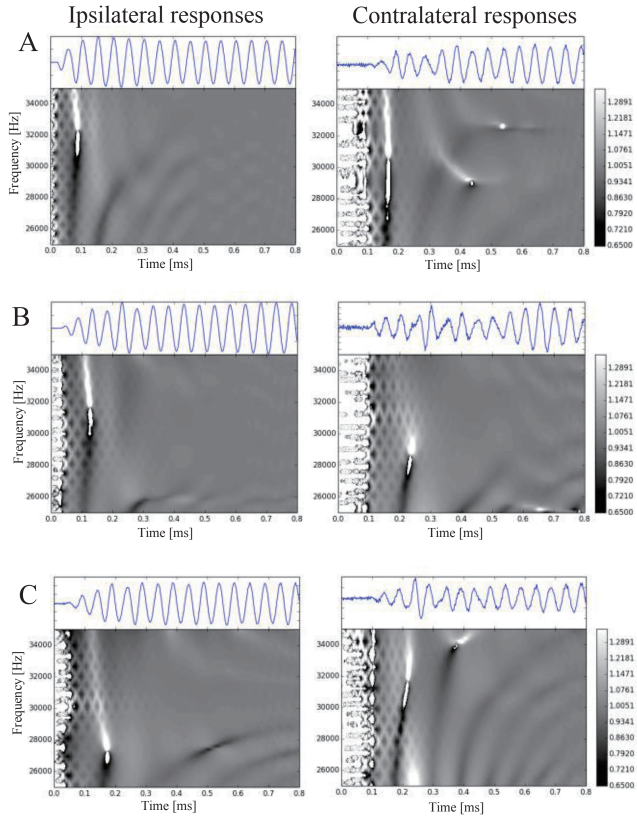

Fig. 2. Normalized IF maps for the subject A, B and C (row A, B and C). The left and the right columns show ipsi- and contra-lateral responses respectively.

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