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Transient Acceleration Response of a Bone-Conducted Ultrasonic Pulse in Living Human Head*

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Abstract— **Ultrasonic hearing through bone-conduction is referred to as bone-conducted ultrasound (BCU). Because the perceptual mechanisms of ultrasonic hearing are still unclear, it is necessary to approach the subject from various aspects to clarify such mechanisms; the propagation process of ultrasonic vibration in the head is one of them.**

To estimate propagation pathways and modes of BCU in living human head, we measured the transient acceleration responses for ultrasonic pulses. The acceleration responses were obtained at the left and right ears simultaneously for left-side, right-side and forehead excitations. Transient responses show that there are several transmission pathways or modes, and the dominant pathways of BCU were identified.

I. Introduction

Ultrasound with frequencies above 20 kHz and up to at least 100 kHz can be heard via bone-conduction (BC) [1-4]. Such audibility of ultrasound is known as ultrasonic hearing and the audible ultrasound in this case as bone-conducted ultrasound (BCU). The characteristics of ultrasonic hearing show some interesting features: A sinusoidal BCU stimulus induces perception of a simple high-pitched tone independent of frequency [1-7]. The perceptive dynamic ranges for BCUs are much narrower than those in the sonic range and almost constant with frequency [8,9]. In addition, it has been reported that profoundly hearing-impaired people as well as normal-hearing people can hear BCU [6,7,10] and recognize phonetic information from a voice-modulated BCU [11,12]. Although the perceptual mechanisms of ultrasonic hearing are still unclear, we have been developing a new hearing-aid system for profoundly hearing-impaired people called bone-conducted ultrasonic hearing aids (BCUHA) [13,14]. The BCUHA usually use 30 kHz as the carrier frequency, since audibility of BCU is empirically higher at about 30 kHz when using a Piezoelectric vibrator with the resonance frequency of 40 kHz.

To better understand the mechanism of ultrasonic hearing and for further development of BCUHA, it is necessary to approach the subject from various aspects to clarify the mechanism; to clarify the propagation characteristics of ultrasonic vibration in the head is one of them. However, critical difficulties exist in observing phenomena taking place inside of human heads. In previous studies, numerical simulations were conducted to visualize the propagation of BCU stimuli within the human head [15,16], and measurements of frequency responses for BCU stimuli were also conducted to assess linearity and nonlinearity in propagation [17,18].

Propagation velocity is one of the most important physico-acoustic parameters for characterizing wave propagation of BCU in the head. By using the pattern of acoustic interference of bilaterally presented BCU stimuli, which was extracted from the distribution of acceleration responses induced as a function of frequency and inter-lateral phase difference, we estimated the propagation velocity of BCU in a living human head as approximately 300 m/s [19]. Although the obtained BCU velocities were similar to BC velocities in the sonic range that were obtained using a psychoacoustic method [20,21], there were considerable differences between estimated BCU velocities and that for biotic materials measured *in vitro*; the speed of sound through dry bone is ~2000–3000 m/s and through brain matter is ~1000–1400 m/s [22].

The large differences between propagation velocities *in vivo* [19-21] and those of biotic materials measured *in vitro* [22] might be due to the fact that the estimated propagation velocities in [19-21] were computed based on the phase velocity, which is not reflected by the delay of the first arrival pathway but that of the dominant pathway. Furthermore, it also might due to the fact that the velocities in [19-21] were calculated with assuming the straight-line pathway though the human head is heterogeneous transmission medium. To investigate the cause of the large differences, it is necessary to estimate the BCU propagation sequence *in vivo*. In the current study, to estimate propagation pathways and modes of BCU, we measured the transient responses of acceleration for ultrasonic pulses in the frequency range of 30 ± 2 kHz in a living human head.

II. Measurements of Transient Acceleration Response for Ultrasonic Pulse

Measurements of a transient acceleration response for an ultrasonic pulse were performed on the head of one listener in an anechoic room at the AIST Kansai Centre. The subject was 38 years old. The experimental set-up of the measurement is shown in Fig. 1. Piezoelectric ceramic vibrators (MA40E7S, Murata Manufacturing Co., Ltd.) were placed over the left and right mastoid processes of the temporal bone and the center of the forehead using over-the-head steel bands (similar to hair bands). The force of the coupling device at the 15 cm opening, which is the approximate average head width of Japanese adults, was set at 5 N. The ultrasonic pulse as excitation signals were 10-wave sinusoids with frequencies from 28–32 kHz in 100-Hz steps.

The excitation signals were synthesized digitally by a PC at a sampling frequency of 800 kHz, generated through a

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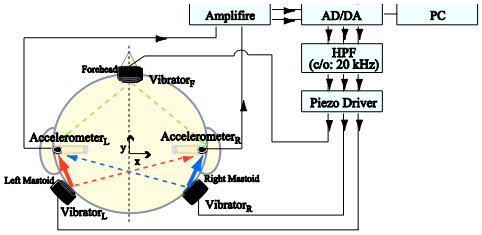

Figure 1. Experimental set-up for the measurement of the propagation characteristics of BCU in a human head.

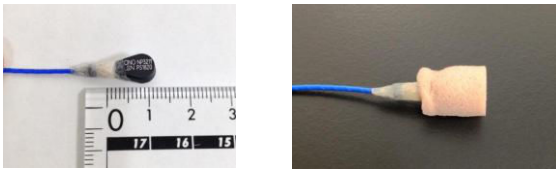

Figure 2. Accelerometer (left) and one wrapped in a sponge tube (right).

16-bit D/A converter (PXI-6120, National Instruments), and filtered by a low-cut filter (3625, NF Corporation) with a 20-kHz cut-off frequency. The voltages applied to the left, right and center vibrators were equal (8.5 Vrms).

The acceleration responses were measured using accelerometers (NP3211, Ono Sokki), which were wrapped in a sponge tube (Fig. 2) and placed inside the left and right ear canals. The acceleration responses at the left and right ears were obtained simultaneously for each excitation. The accelerometers had a resonant frequency of 92.6 kHz and an almost flat frequency response in the frequency range used in this study. Acceleration responses with 1500 μs pulse lengths were recorded 100 times for each stimulus, averaged to increase the signal to noise ratio, and stored digitally at a sampling frequency of 800 kHz through a 16 bit A/D converter (PXI-6120, National Instruments) to a PC. Obtained signals were filtered with zero-phase digital filtering using a 5th order band-pass Butterworth filter with a low frequency cut-off of 1000 Hz and a high-cut frequency of 120 kHz.

III. Results and Discussion

In Figs. 3–8, the upper panels show the time-frequency representation of the transient responses as a function of the excitation frequency, and the lower panels show the superposed transient responses across excitation frequencies. Figs. 3 and 4 are responses for left-side stimulation at the left and the right ears, respectively. Similarly, Figs. 5 and 6 are for right-side stimulation and Figs. 7 and 8 are for the forehead stimulation at the left and right ears, respectively.

For transient acceleration responses for ipsilateral transmission (in Figs. 3 and 6), the first wavefront arrived at ~15 μs from presentation almost simultaneously with no frequency dependence for both left- and right-side stimulations. The superposed waveform for ipsilateral transmission (in the lower panels of Figs. 3 and 6) shows that the amplitude of the peaks increased monotonically from the first peak up to the 12th peak. After the 12th peak, the peaks decrease monotonically up to the 20th peak for all frequencies of the excitation signals. In addition, time-frequency responses at the ipsilateral ear (in the upper panels of Figs. 3 and 6) show that the peaks and troughs were lined up regularly at intervals that correspond to the period of excitation signals at the first 15–20 waves. However, there were components containing phase discontinuity after the 20th wave (e.g., around 32 kHz at 730 μs in Fig. 3 and around 28.5 kHz at 780 μs in Fig. 6). The above results suggest that the dominant component of ipsilateral transmission was the component of the first arrival at 15 μs.

On the other hand, as for contralateral transmission (in Figs. 4 and 5), the first wavefront arrived at ~90 μs with no frequency dependence of the excitation signal for both right- and left-side stimulations. The time-frequency responses of acceleration at the contralateral ear (in the upper panels of Figs. 4 and 5) do not show "simple" stripe patterns as shown in the ipsilateral responses (as in the upper panels of Figs. 3 and 6), and the patterns of the stripes seem to be different between right and left side stimulations. Observing the initial portion following the first wave arrival showed that the phases of transient responses shifted regularly, which corresponds to the period of excitation signals at the first few waves, and then aligned up across all frequencies of excitation signals at 160 and 270 μs for left- and right-side excitations, respectively. These results suggest that there are overlapping multiple wave components with frequency dependence whose transmission pathways or transmission mode are different; the second component was reached at ~160 and 270 μs for left- and right-side stimulations, respectively. After arrival of the second component, there were many components of phase discontinuity (which were marked on the upper panels of Figs. 4 and 5) and these discontinuities appear to have frequency dependence. In addition, because the envelopes of the superposed waveforms of contralateral transmission had several dominant peaks for the left-side excitation and one dominant peak for the right-side excitation after the second arrivals, there appears to be several other dominant transmission components outside the second arrival for left-side excitation. The third arrival can be estimated to be at ~300 μs and the fourth at 500–600 μs with no other dominant component for right-side excitation than the second component. The above results suggest that there were at least four different transmission paths or modes for left-side stimulation and two for the right.

For forehead excitation (in Figs. 7 and 8), the first wave front arrived in both left and right ears simultaneously at about 95 μs with no frequency dependence of the excitation signal. The superposed waveforms for forehead excitation (in the lower panels of Figs. 7 and 8) suggest that the first arrival component was the dominant pathway or mode in both the left- and right-ear pathways, though there were noticeable subsequent components for the right-ear pathway. In the time-frequency responses, there were several components of phase discontinuity (which were also marked on the upper panels of Figs. 7 and 8; these discontinuity parts appear to have a frequency dependence and different temporal structures between left- and right-ear pathways.

Roughly measured straight-line distances using a caliper between the transducers and accelerometers were about 3, 13.5 and 13 cm for the ipsilateral, contralateral and forehead-ear pathways, respectively. While referencing these straight-line distances, the first arrival time for the ipsilateral (15 μs), contralateral (90 μs) and forehead-ear pathways (95 μs) correspond to transmission velocities of ~2000, 1500

and 1421 m/s, respectively. The estimated transmission velocities of the first wave for the contralateral and forehead-ear pathways were apparently slower than that for the ipsilateral pathway; this suggests that the actual transmission pathways were along the skull base or the calvaria instead of the straight-line pathway. For example, the length of the forehead-ear pathway along the calvaria was about 18 cm and the estimated velocity of the first wave along this pathway was 1894 m/s, which was similar to the estimated velocity of the ipsilateral straight-line pathway.

The arrival time of the second, third and fourth components of the contralateral transmission for left-side excitation (160, 300 and 550 μs, respectively) correspond to transmission velocities of 844, 450 and 246 m/s, respectively. The arrival time of the second and third components of the contralateral transmission for right-side excitation (270 μs) correspond to transmission velocities of 500 m/s. Considering the correspondence between the obtained phase velocities of BCU [19] and the velocity of the third and second components, shown in in Figs. 4 and 5, respectively, the BCU velocities in [19] seem to be reflected in the dominant transmission modes or pathways that have the largest amplitude among multiple transmission components.

IV. Conclusion

In the present study, to estimate the propagation sequence of bone-conducted ultrasound in the head *in vivo*, we measured transient acceleration responses for ultrasonic pulse waves inside the left and right ear canals for left, right and forehead excitations. The results can be summarized as follows:

(a) For ipsilateral transmission, the first arrival component was dominant, and there were little differences between left- and right-side excitation conditions.

(b) On the other hand, for contralateral transmission, the first arrival component was not dominant; after a first weak component the subsequent large amplitude component(s) were reached. The number of subsequent components after the second wave was different between left- and right-side excitation, and it also appears to depend on frequency.

(c) Differences of estimated transmission velocities of the first component between the ipsilateral, contralateral and forehead-ear transmissions assuming straight-line pathways suggest that actual transmission pathways were along the skull base or the calvaria instead of the straight-line pathway.

(d) The BCU velocities in [19] appear to be reflected in the dominant transmission modes or pathways that have the largest amplitude among multiple transmission components.

In our future work, we plan to compare the results of different subjects with different head sizes and shapes, and also we plan to analyze the frequency dispersion of the components after the second arrival for the contralateral transmission.

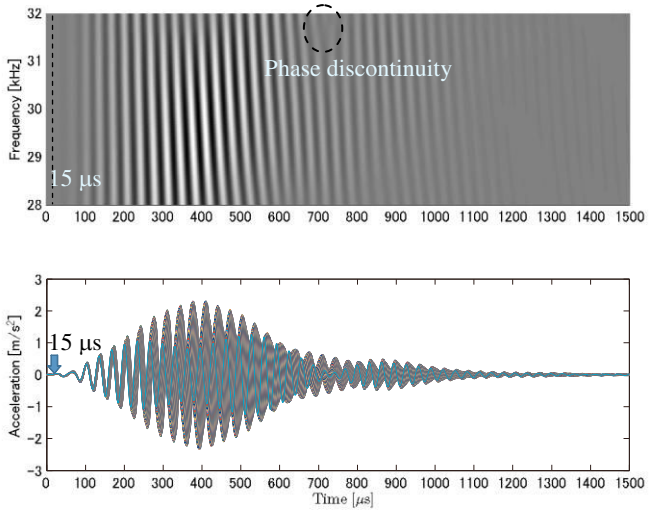

Figure 3. Transient acceleration responses for left-side excitation recorded at the left ear (ipsilateral side)

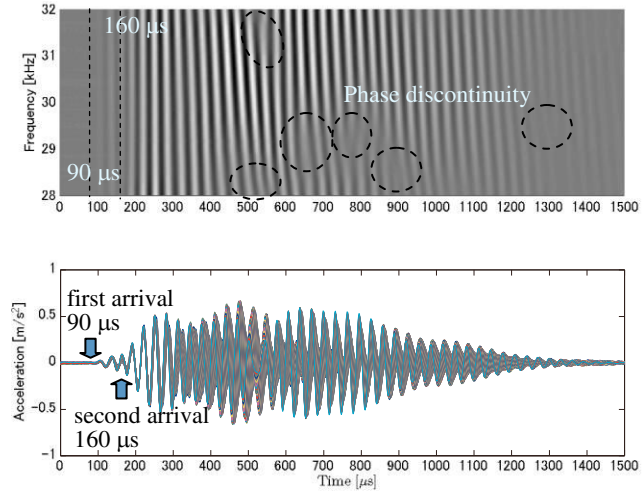

Figure 4. Transient acceleration responses for left-side excitation recorded at the right ear (contralateral side)

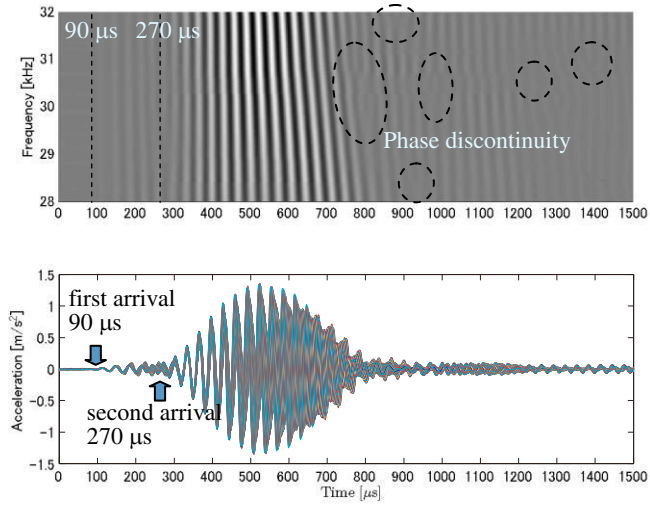

Figure 5. Transient acceleration responses for right-side excitation recorded at the left ear (contralateral side)

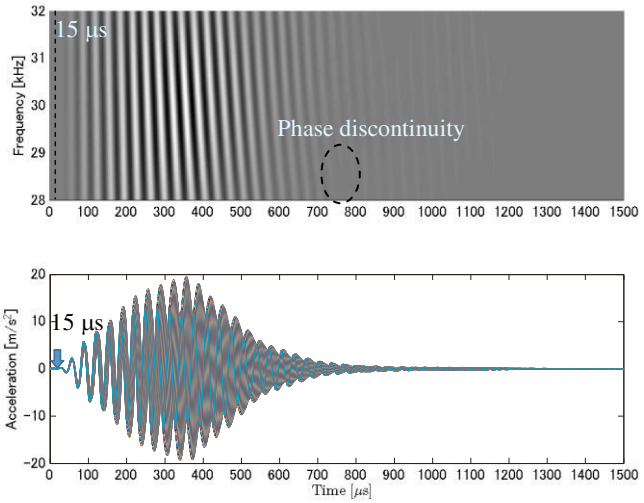

Figure 6. Transient acceleration responses for right-side excitation recorded at the right ear (ipsilateral side)

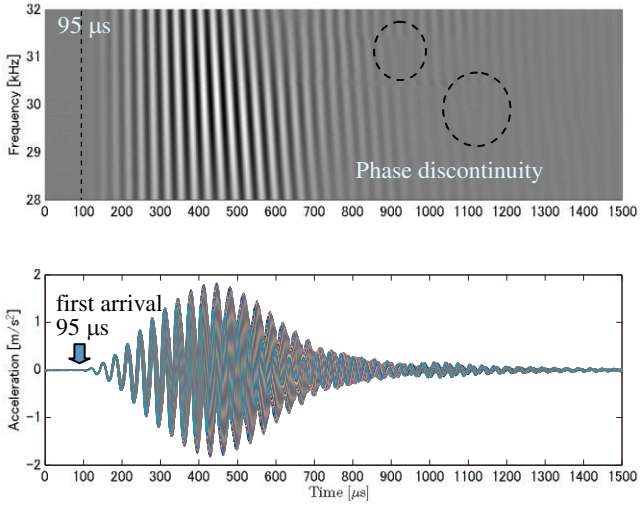

Figure 7. Transient acceleration responses for forehead excitation recorded at the left ear

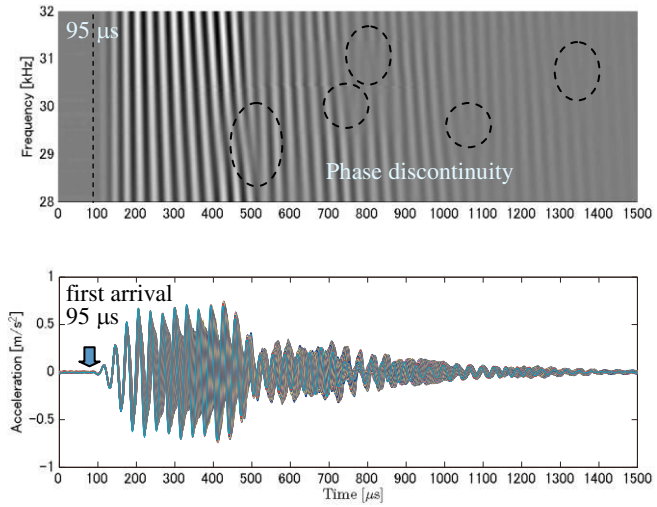

Figure 8. Transient acceleration responses for forehead excitation recorded at the right ear

REFERENCES

[1] V. Gavreau, "Audibilité de sons de fréquence élevée," *C. R. Acad. Sci.* vol. 226, pp. 2053–2054, Jun. 1948.

[2] R. J. Pumphrey, "Upper limit of frequency for human hearing," *Nature*, vol. 166, no. 4222, p. 571, Sep. 1950.

[3] A. V. Haeff and C. Knox, "Perception of ultrasound," *Science*, vol. 139, pp. 590–592, Feb. 1963.

[4] J. F. Corso, "Bone-Conduction Thresholds for Sonic and Ultrasonic Frequencies," *J. Acoust. Soc. Am.*, vol. 35, no. 11, pp. 1738–1743, Nov. 1963.

[5] B. H. Deatherage, L. A. Jeffress, and H. C. Blodgett, "A note on the audibility of intense ultrasonic sound," *J. Acoust. Soc. Am.*, vol. 26, p. 582, Jul. 1954.

[6] R. J. Bellucci and D. E. Schneider, "Some observations on ultrasonic perception in man," *Ann. Otol. Rhinol. Laryngol.*, vol. 71, pp. 719–726, Sep. 1962.

[7] H. G. Dieroff and H. Ertel, "Some thoughts on the perception of ultrasonics by man.," *Arch. Otorhinolaryngol.*, vol. 209, no. 4, pp. 277–90, Aug. 1975.

[8] J. F. Corso and M. Levine, "Sonic and ultrasonic equal-loudness contours.," *J. Exp. Psychol.*, vol. 70, no. 4, pp. 412–416, Oct. 1965.

[9] T. Nishimura, S. Nakagawa, T. Sakaguchi, and H. Hosoi, "Ultrasonic masker clarifies ultrasonic perception in man.," *Hear. Res.*, vol. 175, no. 1–2, pp. 171–177, Jan. 2003.

[10] J. H. Combridge and J. O. Ackroyd, "Upper limit of frequency for human hearing," *Nature*, vol. 167, pp. 438–439, Mar. 1951.

[11] M. L. Lenhardt, R. Skellett, P. Wang, and A. M. Clarke, "Human ultrasonic speech perception.," *Science*, vol. 253, no. 5015, pp. 82–85, Jul. 1991.

[12] H. Hosoi, S. Imaizumi, T. Sakaguchi, M. Tonoike, and K. Murata, "Activation of the auditory cortex by ultrasound.," *Lancet*, vol. 351, no. 9101, pp. 496–7, Feb. 1998.

[13] S. Nakagawa, Y. Okamoto, and Y. Fujisaka, "Development of a Bone-conducted Ultrasonic Hearing Aid for the Profoundly Sensorineural Deaf," *Trans. Jpn. Soc. Med. Biol. Eng.*, vol. 44, no. 1, pp. 184–186, 2006.

[14] S. Nakagawa, C. Fujiyuki, and T. Kagomiya, "Development of Bone-Conducted Ultrasonic Hearing Aid for the Profoundly Deaf: Assessments of the Modulation Type with Regard to Intelligibility and Sound Quality," *Jpn. J. Appl. Phys.*, vol. 51, p. 07GF22, Jul. 2012.

[15] T. Sakaguchi, T. Hirano, Y. Watanabe, T. Nishimura, H. Hosoi, S. Imaizumi, S. Nakagawa, and M. Tonoike, "Inner Head Acoustic Field for Bone-Conducted Sound Calculated by Finite-Difference Time-Domain Method," *Jpn. J. Appl. Phys.*, vol. 41, No. 5B, pp. 3604–3608, May 2002.

[16] Y. Fujisaka, S. Nakagawa, and M. Tonoike, "Relationship Between Detecting Pitch via Bone-conducted Ultrasound and Eigenfrequencies of Human Head," *J. Comput. Acoust.*, vol. 14, no. 03, pp. 369–378, Sep. 2006.

[17] K. Ito and S. Nakagawa, "Perception Mechanisms of Bone-Conducted Ultrasound Assessed by Acoustic Characteristics in the External Auditory Meatus," *Jpn. J. Appl. Phys.*, vol. 49, no. 7, p. 07HF31, Jul. 2010.

[18] K. Ito and S. Nakagawa, "Assessment of Linearity of Bone-Conducted Ultrasound Transmission in the Human Head," *Jpn. J. Appl. Phys.*, vol. 50, no. 7, p. 07HF04, Jul. 2011.

[19] T. Hotehama and S. Nakagawa, "Propagation Velocity of Bone-Conducted Ultrasound in the Human Head," *Jpn. J. Appl. Phys.*, vol. 51, p. 07GF21, Jul. 2012.

[20] J. Zwislocki, "Acoustic Attenuation between the Ears," *J. Acoust. Soc. Am.*, vol. 25, no. 4, pp. 752–759, Jul. 1953.

[21] J. Tonndorf and A. F. Jahn, "Velocity of propagation of bone-conducted sound in a human head," *J. Acoust. Soc. Am.*, vol. 70, no. 5, pp. 1294–1297, Nov. 1981.

[22] P. Henry and T. R. Letowski, *Bone Conduction: Anatomy, Physiology, and Communication*, Aberdeen, MD: Army Research Laboratory, 2007.

[23] A. V. Oppenheim and R. W. Schafer, *Discrete Time Signal Processing*, Prentice Hall, 1989. pp.284–285.