Ultrasonic hearing by bone-conduction and its applications

Seiji Nakagawa¹,²,³,*

¹Center for Frontier Medical Engineering, Chiba University, 1–33 Yayoi-cho, Inage-ku, Chiba, 263–8522 Japan
²Graduate School of Engineering, Chiba University, 1–33 Yayoi-cho, Inage-ku, Chiba, 263–8522 Japan
³Med-Tech Link Center, Chiba University Hospital, 1–8–1 Inohana, Chuo-ku, Chiba, 260–8677 Japan

Abstract: Although the mechanisms involved remain unclear, several studies have reported that bone-conducted ultrasounds (BCUs) can be perceived even by those with profound sensorineural hearing impaired, who typically hardly sense sounds even with conventional hearing aids. We have identified both the psychological characteristics and the neurophysiological mechanisms underlying the perception of BCUs using psychophysical, electrophysiological, vibration measurements and computer simulations, and applied to a novel hearing aid for the profoundly hearing impaired. Also, mechanisms of perception and propagation of the BCU presented to distant parts of the body (neck, trunk, upper limb) were investigated.

Keywords: Bone-conduction, Ultrasound, Hearing aid, Distant presentation

PACS number: 43.66.Ts [doi:10.1250/ast.41.851]

1. INTRODUCTION

The sound that we usually perceive initially enters in the form of air particles vibration, and thus it is called as air conduction. On the other hand, the sound transmitted through our body structure such as the skin, muscle, and bone structures are called as bone-conduction. For the perception mechanisms of ordinary bone-conduction hearing, three general pathways have been proposed [1]: (1) the inertial route, which is based on relative motion between the middle ear ossicles and the temporal bone; (2) the compressional route, which results from the compression and expansion of the cochlear shell by an applied vibratory force; and (3) the osseotympanic route, which involves sound radiated into the outer ear canal (Fig. 1). Since some sound components bypass the outer and middle ears, the bone-conduction has been used as hearing aids for the conductive hearing impaired. Additionally, the bone-conduction is recently applied to head phones and smartphones for the normal hearing people, by utilizing its advantages that the outer ear canals are not plugged and can easily be perceived under noisy conditions.

However, the mechanism of the bone-conduction perception is more complex than that of air-conduction, and the perception characteristics varied depending on sound frequency and the vibrator placement.

Several studies have reported that high-frequency sounds above 20 kHz can be clearly perceived via bone-conduction [2,3]. This “audible” ultrasound through bone-conduction is referred to as bone-conducted ultrasound (BCU). BCU is perceived even under various auditory pathological conditions such as sensorineural hearing loss and middle ear impairment [4]. In 1991, Lenhardt et al. reported that BCUs modulated by speech sounds were somewhat intelligible even in the profoundly sensorineural hearing impaired [5], which suggested that it might be possible to develop a novel hearing aid based on BCU perception. We objectively proved the BCU hearing in the profoundly hearing impaired by using magnetoencephalography (MEG) [6], and have investigated the characteristics and mechanisms of BCU perception using psychophysical, electrophysiological, vibration measurements and computer simulations, and applied to a novel hearing aid for the profoundly hearing impaired. In this paper, we provide an outline of our studies on BCU perception and its applications.

2. PERCEPTION CHARACTERISTICS OF BONE-CONDUCTED ULTRASOUND

An overview of the perception characteristics of BCU is provided in this section.
2.1 Perceptible Region and Frequency

BCUs are perceived well if the vibrator is presented onto the mastoid or the sternocleidomastoid muscle [7]. Tones ranging up to at least 120,000 Hz can be perceived through bone-conduction [8].

2.2 Pitch of Sinusoidal BCUs

The subjective pitch of sinusoidal BCUs does not depend on the frequency but remains constant around the pitch induced by air-conducted pure tones at 10,000–14,000 Hz. Sinusoidal BCUs are perceived as monotonic sounds [3,9–11].

2.3 Pitch of Amplitude-modulated BCUs

In the BCU hearing-aid, ultrasounds were amplitude modulated by speech sounds. Amplitude-modulated BCUs have two pitches: one induced by the BCU carrier and the other induced by signal demodulation [12–14].

2.4 Loudness Characteristics

Threshold of bone-conducted sounds raises with increase of frequency above around 13 kHz [15] (Fig. 2). The dynamic range for BCUs (20 kHz–50 kHz) is extremely narrow (approximately 18 dB), whereas the dynamic range for air-conducted sound (1,000 Hz) exceeds 80 dB [16,17].

2.5 Discrimination of Laterality of Bilateral Amplitude-modulated BCUs

Although the discrimination threshold of BCUs is much larger than that observed for air-conducted sound, the polarities of the time differences in the amplitude envelopes (envelope-ITDs) of bilaterally presented amplitude-modulated BCUs (AM-BCUs) were discriminated. In addition, the interaural intensity differences (IIDs) of bilateral AM-BCUs were discriminated with smaller thresholds for BCUs than for air-conducted sounds [18]. Further, the discrimination thresholds of the polarities of IIDs were compensated by envelope-ITDs, i.e., time-intensity trading was observed during amplitude-modulated BCU perception [19,20]. These results indicate that envelope-ITDs and IIDs can be used as cues for the lateralization of bilaterally presented AM-BCUs and suggest that bilateral AM-BCUs are processed in the normal auditory pathway associated with lateralization in a similar manner as amplitude-modulated sounds.

3 VERIFICATION OF TRANSFORMATION INTO LOW-FREQUENCY AUDIBLE SOUNDS

Some reports suggest the possibility of transforming BCUs into low-frequency audible sounds [21,22]. However, this hypothesis cannot explain the brain activities of profoundly hearing impaired participants, who have little sensitivity to audible sound below 20 kHz [5,6,13]. Furthermore, evidence for the generation of audible-frequency components has not been obtained from acoustical measurements on/around the living human head. For example, no audible-frequency signals corresponding to the subjective pitch of a BCU tone have been found in the acoustic fields for the auditory meatus and vibrations of the tympanic membrane [23,24]. Additionally, no nonlinear behavior in the transmission in the human head has been observed [25,26].

4 NEUROPHYSIOLOGICAL MECHANISMS UNDERLYING BCU PERCEPTION

Although the neurophysiological mechanisms underlying BCU perception have not been clarified, our recent studies have shown some important results. Our findings suggest that BCUs are received in the cochlea through a mechanism that is distinct from that employed for the perception of audible-frequency sounds. This mechanism
involves an inadequate vibration of the basilar membrane and minimal contribution from the outer hair cells to BCU perception [27]. An overview is provided in this section.

4.1. Inner Ear Mechanisms

In electrocochleogram (EcochG) measurements, compound action potentials of the auditory nerve were clearly observed [28]. In addition, psychoacoustic evidence that BCUs mask air-conducted audible sounds indicates that the cochlea makes a substantial contribution to the perception of BCUs [16,17]. However, several characteristics observed in BCU perception, such as a broad masking pattern [17], a pitch that is independent of frequency [3,9–11] and cortical activity that does not follow tonotopic organization, suggest that some of the differences between the perception mechanisms of audible sounds and BCUs occur in the inner ear [27]. The extremely narrow dynamic range of loudness in the perception of BCUs [16,17] suggests that outer hair cells (OHCs) play only a minimal role in BCU perception.

4.2. Brainstem Pathway

Auditory brainstem responses (ABRs) and middle latency responses (MLRs) are elicited by BCUs [27] (Fig. 3). These results indicate that BCUs evoke similar auditory pathways as air-conducted audible sounds after the cochlear nerve.

4.3. Cortical Activity

The auditory cortices, such as Heschl’s gyrus and the planum temporale, are activated by both BCUs and air-conducted audible sounds (Fig. 4). However, the cortical activity induced in response to BCUs is characterized by a larger latency and smaller magnitude than the activity induced by audible sounds. Moreover, the magnitude of responses evoked by BCUs and those evoked by audible sounds are significantly larger for contralateral than for ipsilateral stimuli [27]. This result indicates that the two BCU channels presented to the left and right mastoid were localized separately. In other words, the signal from each BCU entered the ipsilateral auditory pathway before the superior olivary nucleus. The precise locations of cortical activity evoked by BCUs did not follow the tonotopic organization at the cortical level. Indeed, BCU-induced activity occurs more posterior and lateral than the activity induced by audible sounds, and it is obviously different from 10-odd-kHz air-conducted sounds with the similar pitch and loudness [27].

5. COMPUTER STIMULATIONS OF SOUND FIELDS IN THE HEAD

In bone-conducted audible sounds, the direction of the sound image is generally ipsilateral to the source of stimulation, and it shifts negligibly with slight changes in the location of the oscillator. In contrast, the direction of BCU sound images is not always ipsilateral; sometimes, it is contralateral to the source of simulation. In addition, the direction of BCU sound images typically shifts with slight

---

Fig. 3 Auditory brainstem responses evoked by 30-kHz bone-conducted tone pip.

Fig. 4 Auditory evoked cortical responses evoked by bone-conducted bursts with various frequencies, presented to the left mastoid. In all stimuli, equivalent current sources were estimated in the Heschl’s Gyrus. Lpsi: Ipsilateral. Cont: Contralateral.
changes in the location of the oscillator [7]. Our computer-
simulation study provided a partial explanation for this
phenomenon; several peaks in the spatial distribution of the
maximal sound pressure can be observed both ipsilaterally
and contralaterally when a BCU is presented, an effect that
is due to the relationship between the size of the head and
the wavelength of the sound wave (Fig. 5) [29].

6. DEVELOPMENT AND EVALUATION OF
A BONE-CONDUCTED ULTRASONIC
HEARING AID

Worldwide, there are several million profoundly hear-
ing impaired people who cannot obtain sufficient hearing
even with the use of conventional hearing aids. Although
cochlear implants, which are implanted into the temporal
cranial bone and electrically stimulate the cochlear nerve,
can restore hearing ability, the results obtained with this
procedure are not always satisfactory. Presently, there are
no hearing aids that sufficiently restore the sense of hearing
in the profoundly hearing-impaired. On the basement of
previous studies, we have been developing a novel hearing
aid for the profoundly hearing impairments.

Figure 6 shows a prototype of a BCU hearing aid. Basic parameters of the BCU hearing aid were determined
using the results of previous studies of the psychoacoustic
and physical characteristics of BCU perception. The
prototype is pocked-sized and can perform general digital
signal processing. Two types of amplitude-modulation
method, double-sideband transmitted-carrier (DSB-TC)
method, and the transposed method [30,31] can be
selected.

In an assessment test in the mid-range and profoundly
hearing impaired subjects, 100% of the midrange hearing
impaired and 42% of the profoundly hearing impaired
were able to obtain a sound sensation. Also, 73% of the
midrange hearing impaired and 17% of the profoundly
hearing impaired subjects were able to recognize words.
Additionally, some of the profoundly hearing impaired can
have simple conversation with the BCU hearing aid.

7. DISTANT PRESENTATION OF BONE-
CONDUCTED ULTRASOUND

One of the largest disadvantages of bone-conduction
devices is the discomfort in wearing the vibrator. The
vibrator is usually pressed against a part of the cranial
bone behind the ear (mastoid process of the temporal bone,
see Fig. 6) by a head band with a clamping pressure of
approximate 5 N. It is difficult to hold the vibrator steadily
on a rounded surface of the mastoid process, and it is
sometimes accompanied by pain and esthetic problems.

On the other hand, BCU can be heard not only via the
mastoid process but also via wider areas of the body, for
example, the forehead, the muscle of the neck, the clavicle,
and the upper limbs [7]. If it is possible to present bone-
conducted sound to distant locations, i.e., not to the head,
and obtain significant hearing, the above problems can be
solved. Furthermore, BCU hearing via distant parts of the
body can be applied to the development of a new type of
audio interface; the user can obtain sound information by
using the device attached to a certain part of the body.

We have investigated basic perception and propagation
characteristics of the distantly-presented bone-conducted
ultrasound.

7.1. Perception Characteristics

The hearing threshold, temporal resolution [32], fre-
quency resolution [33] were measured when 30-kHz tone
bursts were presented to the neck, trunk, and the upper
and lower arms in normal-hearing participants (Fig. 7). The
results showed that BCU presented to parts of the body
distant from the head, including the lower arm, can be
perceived at least by normal-hearing persons, whereas the
threshold increased depending on the distance from the
head. Both the temporal- and frequency-resolutions of
distantly-presented BCU were comparable to that presented
to the mastoid process.
7.2. Propagation Characteristics

Vibration at the external auditory meatus were measured when 30-kHz tone was presented distal parts of the body like the neck, shoulder, upper limb, the breastbone and the back bone [34]. The results showed that a prominent peak of the spectrum corresponding to the stimulation frequency (30 kHz) and sufficiently smaller subharmonic components were observed at all presented parts of the body. Although the vibration tended to decrease depending on the distance between the external auditory meatus and the stimulation part, other anatomical conditions, efficiency of the pathway and/or coupling between the vibrator and skin, also seem to affect the results. Also, significant demodulated-components, generated by the nonlinearity existing in the human body parts, were observed when amplitude-modulated BCUs were presented to the distant locations [33,35].

7.3. Comparison with Low-frequency Bone-conducted Sounds

The hearing threshold and the vibration at the ear canal were compared between 30-kHz BCU and low-frequency bone-conducted sounds [36]. The results showed that, both in the BCU and the low-frequency bone-conducted sound, the hearing threshold increased, and the vibration at the ear canal attenuated as the vibrator placement moved away from the head. However, in the BCU hearing, the increase in the hearing threshold and the attenuation of the vibration were much smaller than the low-frequency bone-conducted sounds. BCU doesn’t generate tactile sensation and audible sound leakage, therefore, it is suggested that the BCU has advantages over low-frequency bone-conducted in application to distant-presentation bone-conducting devices.

7.4. Applications

The results obtained are useful not only for elucidation of the propagation mechanism of distantly presented BCUs, but also for the improvements of the BCU hearing aid; suggesting that the sternocleidomastoid muscle and the sternal extremity of clavicle, that show relatively small decrease of vibration, can be used as new presentation parts. Moreover, it is also suggested the possibility of development of novel devices, that can provide sound information selectively to the specific persons who touch the device by the arms.

8. CONCLUSION

BCU perception and its applications were briefly outlined. Although details of the neurophysiological mechanisms remain unclear, BCU perception has been applied to communication devices by utilizing its unique characteristics. Further development is anticipated based on elucidation of the perception mechanisms.

REFERENCES

[1] S. Stenfelt, N. Hato and R. Goode, “Factors contributing to bone conduction: The middle ear,” J. Acoust. Soc. Am., 111, 947–959 (2002).
[2] V. Gavreau, “Audibillite de sons de frequence elevee,” Compt. Rendu. Acad. Sci., 226, 2053–2054 (1948) (in French).
[3] R. J. Pumphrey, “Upper limit of frequency for human hearing,” Nature, 166, 571 (1950).
[4] R. J. Bellucci and D. E. Schneider, “Some observations on ultrasonic perception in man,” Ann. Otol. Rhinol. Laryngol., 71, 719–726 (1962).
[5] M. L. Lenhardt, R. Skellett, P. Wang and A. M. Clarke, “Human ultrasonic speech perception,” Science, 253, 82–85 (1991).
[6] H. Hosoi, S. Imairumi, T. Sakaguchi, M. Tonoike and K. Murata, “Activation of the auditory cortex by ultrasound,” Lancet, 351, 496–497 (1998).
[7] S. Nakagawa, “Bone-conducted ultrasonic perception: An elucidation of perception mechanisms and the development of a novel hearing aid for the profoundly deaf,” in Technological Advancements in Biomedicine for Healthcare Applications (IGI Global, Hershey, 2012), pp. 148–159.
[8] J. F. Corso, “Bone-conduction thresholds for sonic and ultrasonic frequencies,” J. Acoust. Soc. Am., 35, 1738–1743 (1963).
[9] H. G. Dieroff and H. Ertel, “Some thoughts on the perception of ultrasonics by man,” Arch. Oto-Rhino-Laryngol., 209, 277–290 (1975).
[10] S. Kono, Y. Suzuki and T. Sone, “Some consideration on the auditory perception of ultrasound and its effects on hearing,” J. Acoust. Soc. Jpn. (E), 6, 3–8 (1985).

[11] S. Nakagawa and M. Tonoike, “Measurement of brain magnetic fields evoked by bone-conducted ultrasound: Effect of frequencies,” in Unveiling the Mystery of the Brain, ICS1278 (Elsevier, Amsterdam, 2005), pp. 333–336.

[12] K. Fujimoto and S. Nakagawa, “Non-linear explanation for bone-conducted ultrasonic hearing,” Hear. Res., 204, 210–215 (2005).

[13] S. Nakagawa, Y. Okamoto and Y. Fujisaka, “Development of bone-conducted ultrasonic hearing aid for the profoundly deaf,” Trans. Ipn. Soc. Med. Biol. Eng., 44, 184–189 (2006).

[14] Y. Okamoto, S. Nakagawa, K. Fujimoto and M. Tonoike, “Word intelligibility of bone-conducted ultrasound,” Hear. Res., 208, 107–113 (2005).

[15] K. Ito and S. Nakagawa, “Perception of bone-conducted ultrasonic hearing assessed by its loudness characteristics,” Proc. 94th Int. Congr. Acoust., 1-PPA-09-13, pp. 1–6 (2007).

[16] S. Nakagawa, M. Yamaguchi, M. Tonoike, H. Hosoi, S. Imaizumi and Y. Watanabe, “Effects of tone frequency on perception of bone-conducted sounds,” Proc. Biol. Phys. Symp., 17, 169–172 (2002) (in Japanese).

[17] T. Nishimura, S. Nakagawa, T. Sakaguchi and H. Hosoi, “Ultrasonic masking clarifies ultrasonic perception in man,” Hear. Res., 175, 171–175 (2003).

[18] T. Hotehama and S. Nakagawa, “Modulation detection for amplitude-modulated bone-conducted sounds with sinusoidal carriers in the high- and ultrasonic-frequency range,” J. Acoust. Soc. Am., 128, 3011–3018 (2010).

[19] T. Hotehama and S. Nakagawa, “Time-intensity trading for amplitude-modulated bone-conducted ultrasound,” Proc. Spring Meet. Acoust. Soc. Jpn., pp. 431–432 (2007) (in Japanese).

[20] T. Hotehama and S. Nakagawa, “Lateralization of amplitude-modulated bone-conducted ultrasound: Location of sound image by interaural time difference of the envelopes,” Proc. Autumn Meet. Acoust. Soc. Jpn., pp. 449–450 (2008) (in Japanese).

[21] R. A. Dobie and M. L. Wiederhold, “Ultrasonic hearing,” Science, 255, 1584–1585 (1992).

[22] J. Tonndorf, “Bone conduction. Studies in experimental animals,” Acta Otolaryngol. Suppl., 213, 1–132 (1966).

[23] K. Ito and S. Nakagawa, “Perception of bone-conducted ultrasound assessed by optical measurements of tympanic membrane vibration,” Trans. Ipn. Soc. Med. Biol. Eng., 47, 588–594 (2009) (in Japanese).

[24] K. Ito and S. Nakagawa, “Perception mechanisms of bone-conducted ultrasound assessed by acoustic characteristics in the external auditory meatus,” Jpn. J. Appl. Phys., 49, 07HF31 (2010).

[25] K. Ito and S. Nakagawa, “Bone-conducted ultrasonic hearing assessed by tympanic membrane vibration in living human beings,” Acoust. Sci. & Tech., 34, 413–423 (2013).

[26] K. Ito and S. Nakagawa, “Assessment of linearity of bone-conducted ultrasound transmission in the human head,” Jpn. J. Appl. Phys., 50, 07HF04 (2011).

[27] S. Nakagawa, “Mechanisms of bone-conducted ultrasonic (BCU) perception assessed by electrophysiological measurements in man,” J. Acoust. Soc. Am., 120, 3123–3124 (2006).

[28] S. Nakagawa and D. Nakagawa, “Mechanisms of bone-conducted ultrasonic perception assessed by electrophysiological measurements in man,” J. Acoust. Soc. Am., 120, 3123–3124 (2006).

[29] T. Sakaguchi, T. Hirano, Y. Watanabe, T. Nishimuta, 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., 41, 3604–3608 (2002).

[30] 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., 51, 07GF22 (2012).

[31] S. Nakagawa, C. Fujiyuki and T. Kagomiya, “Development of a bone-conducted ultrasonic hearing aid for the profoundly deaf: Assessments of the modulation type with regard to monosyllable articulation and confusion analyses,” Jpn. J. Appl. Phys., 52, 07GF22 (2013).

[32] S. Nakagawa, R. Ogino and S. Otsuka, “Assessment of detection threshold and temporal resolution of distantly presented bone-conducted ultrasonic hearing,” Jpn. J. Appl. Phys., 57, 07LD22 (2018).

[33] K. Ito, “Self-demodulation characteristics of amplitude-modulated bone-conducted ultrasound in the living human body presented to the neck, trunk and arms,” Jpn. J. Appl. Phys., 59, SKKE26 (2020).

[34] R. Ogino, S. Otsuka and S. Nakagawa, “Measurements of vibration at the external auditory meatus and the upper limb in the living human body caused by distantly presented bone-conducted ultrasound,” Jpn. J. Appl. Phys., 58, SGGE12 (2019).

[35] S. Nakagawa, K. Doi, R. Ogino and S. Otsuka, “Propagation characteristics of amplitude-modulated bone-conducted ultrasound presented to the neck, trunk and arms,” Jpn. J. Appl. Phys., 58, SGGE18 (2019).

[36] R. Ogino, K. Doi, S. Otsuka and S. Nakagawa, “Propagation and perception characteristics of distantly-presented bone-conducted sounds: Comparison between ultrasonic and low-frequency ranges,” Proc. 40th Symp. Ultrasonic Electronics, 1P5-1 (2019).