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Development of a Novel Hearing-aid for the Profoundly Deaf using Bone-conducted Ultrasonic Perception: Evaluation of Transposed Modulation

Seiji Nakagawa, Chika Fujiyuki, Yuko Okubo, Takuya Hotehama and Takayuki Kagomiya

Abstract— **Bone-conducted ultrasound (BCU) is perceived even by the profoundly sensorineural deaf. A novel hearing aid using the perception of amplitude-modulated BCU (BCU hearing aid: BCUHA) has been developed. However, there is room for improvement particularly in terms of articulation and sound quality. BCU speech is accompanied by a strong high-pitched tone and contain some distortion. In this study, transposed modulation, that can be expected to reduce the high-pitched tone was newly employed as a modulation method in the BCUHA, and its resulting articulation, intelligibility and sound quality were evaluated. The results showed that transposed modulation showed nearly equal articulation and intelligibility scores to and better sound quality than the existing method, DSB-TC modulation. These results provide useful information for further development of the BCUHA.**

I. Introduction

Several studies have reported that high-frequency sound up to at least 100,000 Hz can be heard via bone conduction [1-3]. This “audible” ultrasound through bone conduction is referred to as bone-conducted ultrasound (BCU). Moreover, BCU hearing in humans has been found under various auditory pathological conditions, including sensorineural hearing loss and middle-ear disorders [3]. In particular, BCU is even perceived by profoundly deaf subjects, who cannot obtain sufficient audition even with the use of a conventional hearing aid.

The mechanisms of BCU perception remain unclear; however, our previous electrophysiological measurements in humans have reported that BCU evokes the same auditory pathway as audible-frequency sounds through the cochlear nerve, and there is no special organ for BCU perception [4 ,5]. Also, several characteristics of BCU perception suggest unique perception mechanisms in the inner ear, the inadequate vibration of the basilar membrane and small contribution of the outer hair cells to BCU perception [6], although the cochlea contributes substantially to BCU perception [4, 5]. Meanwhile, some reports suggest the possibility of transforming BCU into low-frequency audible sound [7]. However, this hypothesis cannot explain the brain activities of the profoundly deaf subjects [8-11]. Furthermore, no audible-frequency components were observed in physio-acoustical measurements during BCU presentation [12, 13].

In 1991, Lenhardt et al. reported that BCU amplitude-modulated by speech sounds was intelligible to some extent and suggested the possibility of developing novel hearing aids based on BCU perception [14]. We supported the arguments of Lenhardt et al. objectively with magneto- encephalographic findings [8, 9] and have developed a new hearing aid for the profoundly deaf—the BCU hearing aid (BCUHA, Fig. 1) [15]. In the BCUHA, ultrasonic sinusoids with a frequency of about 30 kHz are amplitude- modulated by speech and presented to the mastoid by a vibrator. Generally, two sounds are perceived by the BCUHA: one is a high-pitched tone due to the ultrasonic carrier, with a pitch corresponding to a 8–16 kHz AC sinusoid [2, 10, 16] and the other is the envelope of the modulated signal [17, 18]. As a method of amplitude modulation (AM), double-sideband with transmitted carrier (DSB-TC) modulation was used.

The BCUHA is the first device to be developed that enables the profoundly deaf to sense sufficient audition without surgery, and it is far easier to attach than a cochlear implant. In hearing tests on profoundly deaf subjects using this prototype, more than 40% of profoundly deaf subjects were able to perceive some sounds and 17% were able to recognize words [15]. The results already obtained have demonstrated the potential of the BCUHA; however, further developments are needed to use the device in practice. In particular, there is room for improvement in terms of articulation and sound quality. The high-pitched tone due to the ultrasonic carrier is appears to be a key factor in the degradation of the articulation and sound quality. It is thought that the high-pitched tone increases the discomfort of the speech and decreased articulation [18]. Applications of new AM methods are thought to be effective for reducing the high-pitched tone. In this study, transposed modulation [19], that can be expected to reduce the high-pitched tone due to the ultrasonic carrier with maintaining the pitch due to the envelope, was newly employed in the BCUHA and its resulting intelligibilities and sound qualities were evaluated. Further, mono-syllable

Figure 1. Prototype of BCUHA(AIST-BCUHA-005).

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S. Nakagawa is with the National Institute of Advanced Industrial Science and Technology (AIST), Ikeda, Osaka 563-8577, Japan (phone: +81-72-751-8785; fax: +81-72-751-9517; e-mail: s-nakagawa@aist.go.jp).

C. Fujiyuki, Y. Okubo, T. Hotehama and T. Kagomiya are also with AIST (e-mail: {c-fujiyuki, y-okubo, t-hotehama, t-kagomiya}@aist.go.jp).

articulation test was conducted to investigate perception characteristics in more detail.

II. Methods

Word intelligibility and subjective impression of the BCU and AC sounds were examined. In addition to DSB-TC and transposed modulations, double-sideband with suppressed carrier (DSB-SC) was used as amplitude modulation. Necessary information regarding the experiment was given to the subjects, and informed consent was obtained prior to the experiment. The experiment was approved by the Institutional Review Board on Ergonomic Research of AIST.

A. Methods of amplitude modulation

The three AM methods are expressed in terms of A, $s(t)$, $f_c(t)$, and m, which represent a constant, the modulator signal (speech sound), a carrier signal, and the modulation depth, respectively. Examples of waveforms and spectra obtained by these AM methods are shown in Fig. 2.

I) Double-sideband with Transmitted Carrier (DSB-TC)

$$f(t) = A(1 + m \times s(t)) \times f_c(t) \qquad (1)$$

In the DSB-TC modulation, the envelope of the modulated signal corresponds to the modulator, i.e., speech sounds. On the other hand, since the DSB-TC modulation has a substantial peak of power at the carrier frequency in the frequency domain, it is accompanied by a strong high-pitched tone, especially when the modulation depth is low.

II)Double-sideband with Suppressed Carrier (DSB-SC)

$$f(t) = A(m \times s(t)) \times f_c(t) \qquad (2)$$

In the DSB-SC modulation, the peak of power at the carrier frequency is suppressed. Therefore, it is thought that this method has the advantages of not only power saving, but also the reduction of the high-pitched tone. However, the envelope of the modulated signal does not correspond to the modulator signal. The pitch accompanied by the envelope is almost twice as high as that of the modulator signal [19] and is thought to contain some distortion.

III) Transposed Modulation

$$f(t) = A(m \times s_{tp}(t)) \times f_c(t) \qquad (3)$$

Here $s_{tp}(t)$ represents a half-wave-rectified and low-pass-filtered modulator signal. In this study, the modulator signal was low-pass filtered at 8 kHz, to avoid impairing the speech information. In this method, since the peak of power at the carrier frequency is suppressed, it is anticipated that the high-pitched tone due to the carrier is reduced. Furthermore, the intervals between peaks of the envelope of the modulated signal are the same as the intervals between the peaks of the modulator signal, thus; the pitch due to the envelope is expected to be similar to that of the modulator signal. On the other hand, it is thought that transposed BCU speech essentially contains some distortion because of the rectification process.

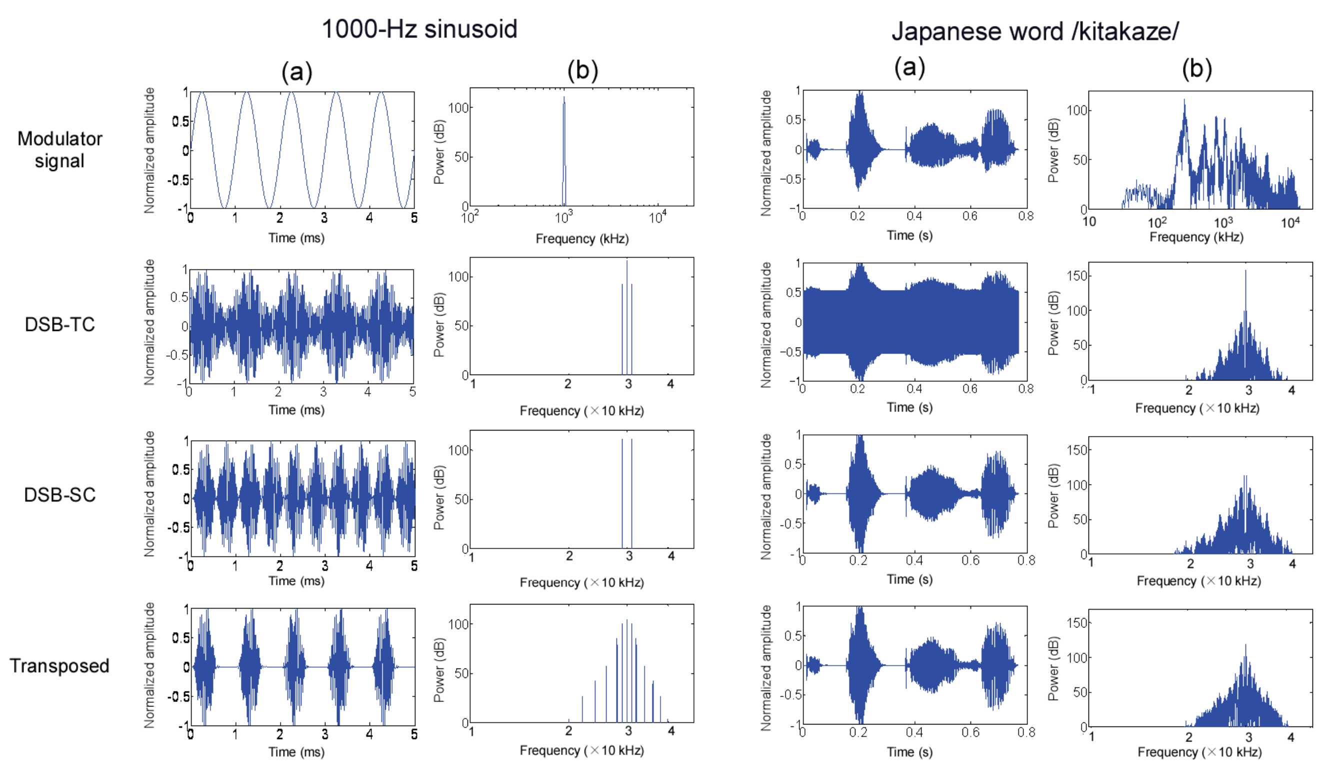

Figure 2. Examples of waveforms obtained by three types of amplitude modulation: (a) modulated waveforms, (b) power spectra. The carrier signal is a 30-kHz sinusoid. A low-pass filter at 8 kHz is applied to the transposed modulation. Left: The modulator signal is a 1000-Hz sinusoid. The modulation depth is set at 0.5 in the DSB-TC. Right: The modulator signal is the Japanese word /kitakaze/ (north wind) uttered by a female speaker. The modulation depth is 1.0 at the maximum of the modulator signal in the DSB-TC modulation.

B. *Apparatus*

All types of BCU speech were presented to one of the two mastoid portions of the subject's temporal bone by a piezoelectric ceramic vibrator. The vibrator was fixed by a headset with a clamping pressure of approximately 5 N (see Fig. 1). Before the session, each subject was requested to confirm that no AC sounds were sensed via the vibrator. Additionally, AC speech, i.e., the modulator signal itself, was presented to the same side as the BCU stimuli by headphones. All experiments were carried out in a soundproof room.

C. *Word intelligibility test*

31 normal-hearing Japanese subjects (21–41 years old, mean 24.2 ± 4.9 years old) participated. Four-mora Japanese words recorded with a female voice and a male voice were taken from a commercially available database (NTT-AT FW03) in which Japanese words are classified into four levels of 'familiarity' to control the degree of word difficulty. In this study, words were selected from mid-range familiarity groups to avoid ceiling and floor effects. Three types of BCU stimuli were produced using the DSB-TC, the DSB-SC, and the transposed modulation. AC stimulus was also used. The test was carried out in four sessions with different stimulus types. In each session, 50 words were selected for both female and male speakers; thus, 100 words were used in a session.

D. *Sound quality test*

After each session of the word intelligibility test, the subjective impression of the sound was recorded in a questionnaire. Appropriate questions were selected from *A questionnaire for listening by hearing aids* [20], which is designed to assess the subjective impression of listening with hearing aids. Subjects were asked to rate the following on three-point scales.

1）Loudness: loud − not loud
2）Distortion: distorted − not distorted
3）Indistinctness: indistinct − not indistinct
4）Shrillness: shrill − not shrill
5）Unpleasantness: unpleasant − pleasant
6）Clarity: not clear − clear

E. *Monosyllable articulation test*

Mono-syllable articulation for DSB-TC and transposed modulations were measured and confusion matrices were obtained. 11 normal-hearing Japanese subjects (22–40 years old, mean 28.1 ± 6.4 years old) participated. 100 Japanese monosyllable recorded with a female voice were taken from a commercially available database (NTT-AT FW03).

III. Results

A. *Word intelligibility test*

Figure 3 shows the results of the word intelligibility test. Two-way analysis of variance (ANOVA) showed the effects of the stimulus type ($p < 0.001$) and speaker's gender ($p < 0.001$). A post-hoc test (Tukey's HSD) revealed that all types of BCU speech have lower intelligibility than AC speech ($p < 0.001$), and DSB-TC speech and transposed speech have higher intelligibility than DSB-SC speech ($p < 0.001$). For each type of BCU speech, the intelligibility for the female voice is higher than that for the male voice (DSB-TC, transposed: $p < 0.001$; DSB-SC: $p < 0.05$).

B. *Sound quality test*

Figure 4 shows the result of the questionnaire on listening by the hearing aid. One-way ANOVA showed the effect of the stimulus type on the answers to all questions ($p < 0.001$). A post-hoc test (Tukey's HSD) revealed that the DSB-SC stimulus was less clear than the other BCU stimuli and more distorted than the DSB-TC stimulus ($p < 0.001$). The transposed stimulus was more pleasant than the other BCU stimuli ($p < 0.005$) and less shrill than the DSB-TC stimulus ($p < 0.05$). In terms of the differences between BCU and AC speech, all BCU stimuli were louder, more distorted, shriller, less pleasant, and less clear than the AC stimulus ($p < 0.001$).

C. *Monosyllable articulation test*

The scores of the articulation of DSB-TC and transposed modulation were 43.5% and 35.2%, respectively. The transposed modulation tended to show lower articulation, however, significant difference was observed between the both scores. In confusion matrices, some differences between DSB-TC and transposed modulations were found; two-way ANOVA regarding the number of misidentified phonemes with spoken phonemes and sound types showed that the number perceived as /j/ was significantly larger for the transposed modulation than for DSB-TC modulation when voiced consonants were presented ($p<0.05$). Additionally, the number perceived as vowels was significantly larger for the

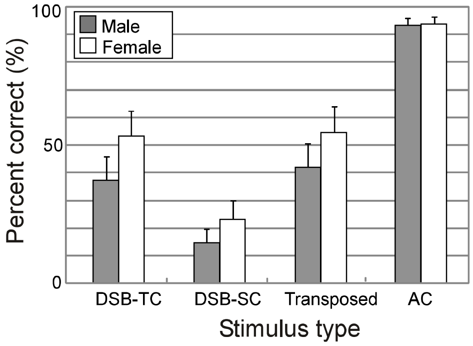

Figure 3. Scores of intelligibility for each stimulus type (mean + S.D.).

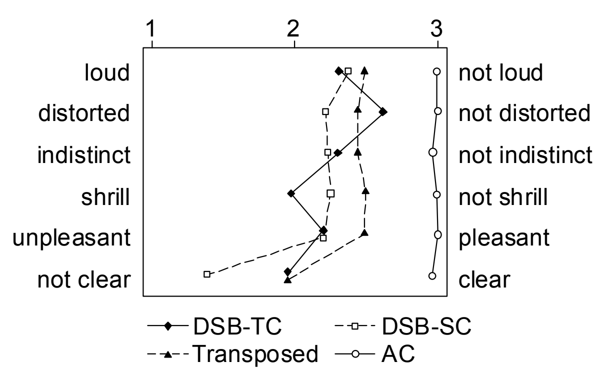

Figure 4. Results of the questionnaire on listening with hearing aids.

transposed modulation than for DSB-TC modulation when consonants were presented ($p<0.05$).

IV. Discussion

A. Word intelligibility and monosyllable articulation

DSB-SC speech was less intelligible than other BCU speech. In the DSB-SC speech, the high-pitched tone due to the carrier was reduced, however, the pitch of the sound due to the envelope was twice as high as that of the modulator signal [17]. Additionally, the sound due to the envelope contained some distortion. These changes in the shape of the envelope can be considered as the causes of the lower intelligibility of the DSB-SC speech.

On the other hand, no significant difference was observed between intelligibility and articulation of DSB-TC and transposed speech, whereas the transposed modulation tended to show lower articulation. In the DSB-TC and the transposed speech, the pitch of the sound due to the envelope is almost identical of that of the modulator signal [18], whereas the DSB-TC speech is accompanied by a relatively strong high-pitched tone due to the carrier. Nishimura et al. reported that BCU masked 10–14 kHz AC sounds significantly but did not mask AC sound below 8 kHz [6]. Therefore, it is reasonable to consider that the high-pitched tone due to the carrier did not disturb the perception of speech, which consists of only lower-frequency components below 8 kHz in the DSB-TC speech. It is also indicated that BCU speech is intelligible to some extent if the pitch of the sound due to the envelope is maintained.

Some significant differences were observed in confusion matrices for DSB-TC and transposed modulations. Generally, the results indicated that transposed sound contains more distortions than DSB-TC sound. It is considered that such distortions result from the rectification process.

B. Sound quality test

Differences among the AM methods for BCU speech were observed. Generally, the sound quality of the transposed speech is closer than that of other AM methods to the sound quality of AC speech. In particular, the transposed speech was not only less shrill but also more pleasant than DSB-TC speech. The smaller high-pitched tone due to the carrier can be considered as the causes of the lower shrillness. Besides, since the score for pleasantness involves an integrated evaluation of speech perception [20], these results suggested a comprehensive advantage of the transposed modulation.

On the other hand, the DSB-TC speech has a significantly higher score for shrillness than the other stimulus types, indicating the effects of the strong high-pitched tone accompanying the DSB-TC speech. Furthermore, it is thought that the higher score for distortion of the DSB-SC speech and the transposed speech reflect distortions in the shape of the envelope resulting from these AM methods.

V. Conclusion

Transposed modulation, that can be expected to reduce the high-pitched tone was newly employed in the BCUHA, and its resulting intelligibility, sound quality, and articulation were evaluated. The results showed that transposed modulation has nearly equal intelligibility and articulation scores to and better sound quality than the exiting method, DSB-TC modulation. These results provide useful information for further development of the BCUHA.

References

[1] V. Gavreau, "Audubillite de sons de frequence elevee," Compt. Rendu. vol. 226, pp. 2053-2054, 1948 (In French).

[2] R. J. Pumphrey, "Upper limit of frequency for human hearing," Nature, 166, 571, 1950.

[3] R. J. Bellucci, and D. E. Schneider, "Some observations on ultrasonic perception in man," Ann. Otol. Rhinol. Laryngol., vol. 71, pp. 19–726, 1962.

[4] S. Nakagawa, and A. Nakagawa, "Mechanisms of bone-conducted ultrasonic perception assessed by electrophysiological measurements in human", J. Acoust. Soc. Am., vol. 120, pp. 3123-3124, 2006.

[5] S. Nakagawa, "Mechanisms of bone-conducted ultrasonic (BCU) perception assessed by EEG and MEG measurements. Brain topography and multimodal imaging, pp. 95-98, 2009.

[6] T. Nishimura, S. Nakagawa, T. Sakaguchi and H. Hosoi, "Ultrasonic masker clarifies ultrasonic perception in man," Hear. Res., vol. 175, pp. 171–177, 2003.

[7] R. A. Dobie and M.L. Wiederhold, "Ultrasonic hearing," Science vol. 255, pp. 1584–1585, 1992.

[8] H. Hosoi, S. Imaizumi, T. Sakaguchi, M. Tonoike and K. Murata, "Activation of the auditory cortex by ultrasound," The Lancet, vol. 351, pp. 496–497, 1998.

[9] S. Nakagawa, T. Sakaguchi, M. Yamaguchi, M. Tonoike, S. Imaizumi, H. Hosoi, and Y. Watanabe, "Characteristics of auditory perception of bone-conducted ultrasound in humans revealed by magnetoencephalography," NeuroImage, vol. 11, p. s746, 2000.

[10] S. Nakagawa, and M. Tonoike, "Measurement of brain magnetic fields evoked by bone-conducted ultrasounds: Effect of frequencies," Unveiling the Mystery of the Brain, ICS, vol. 1278, pp. 333-336, 2005.

[11] S. Nakagawa, "Objective assessment of bone-conducted ultrasonic perception using magnetoencephalography," Trans. Jpn. Soc. Med. Biol. Eng., vol. 45, pp. 129–133, 2007.

[12] K. Ito, and S. Nakagawa, "Perception Mechanisms of bone-conducted ultrasound assessed by acoustic characteristics in the external auditory meatus," Jpn. J. Appli. Phys., vol. 49, 07HF31, 2010.

[13] K. Ito, and S. Nakagawa, "Assessment of linearity of bone-conducted ultrasound transmission in the human head," Jpn. J. Appli. Phys., vol. 50, 07HF04, 2011.

[14] M. L. Lenhardt, R. Skellett, P. Wang and A. M. Clarke, "Human ultrasonic speech perception," Science, vol. 253, pp.82-85, 1991

[15] 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, pp. 184–189, 2006.

[16] H.G. Dieroff and H. Ertel, "Some thoughts on the perception of ultrasound," Arch.Otorhinolaryng., vol. 209, pp. 277–290, 1975.

[17] K. Fujimoto, and S. Nakagawa, "Non-linear ultrasonic perception," Hear. Res., vol. 204, pp. 210–215, 2005.

[18] Y. Okamoto, S. Nakagawa, K. Fujimoto and M. Tonoike, "Intelligibility of bone-conducted ultrasonic speech," Hear. Res., vol. 208, pp. 107–113, 2005.

[19] L. R. Bernstein and C. Trahiotis, "Enhancing sensitivity to interaural delays at high frequencies by using "transposed stimuli"," J. Acoust. Soc. Am., 112, 1026-, 1975.

[20] M. Okamoto, K. Suzuki, Y. Kimura, T. Matsudaira, H. Sano, Y. Ono and A. Okamoto, "The research report of 2001 health labor sciences research grant," H11-sensory organ-004, 2002 (in Japanese).