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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

重度難聴者のための骨導超音波補聴器の開発：明瞭度および異聴解析による変調方式評価

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1. Introduction

Bone-conducted ultrasound (BCU) can be experienced as sound even by the severely hearing-impaired. We have developed a novel hearing aid using BCU perception (BCU hearing aid: BCUHA) for the profoundly hearing-impaired.[1)] Results of evaluation tests suggested its practicability[1)], however, there is room for improvement in terms of articulation.

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 air-conducted (AC) sinusoid, and the other is the envelope of the modulated signal.[2)] As a method of amplitude modulation (AM), double-sideband with transmitted carrier (DSB-TC) modulation has been used.[1-3)] However, by the DSB-TC, the high-pitched tone due to the ultrasonic carrier is strongly perceived especially when the modulation depth is low.

In previous studies, we proposed a new AM method, transposed modulation (TM), to reduce the high-pitched tone.[4)] Since the peak of power at the carrier frequency is suppressed by the TM, 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. The evaluation tests showed that the TM has some advantages in terms of the sound quality over the other AM methods.[4, 5)] On the other hand, it is thought that the TM speech essentially contains some distortion because of its rectification process. Such distortion seems to produce some deterioration in articulation, however, no significant differences were observed in word intelligibility scores between the TM and the DSB-TC.

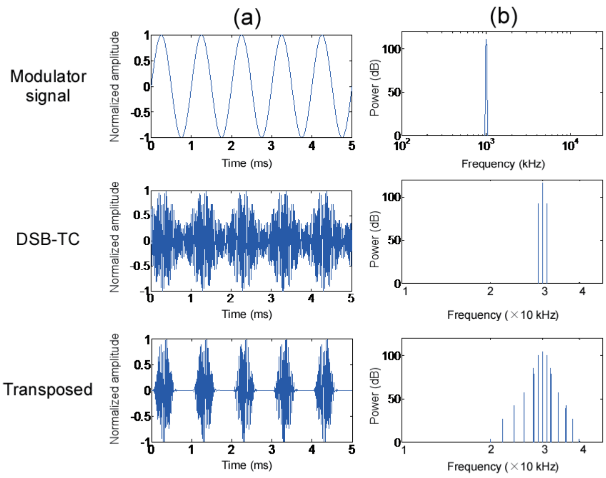

Fig. 1. Examples of waveforms obtained by two types of amplitude modulation: (a) modulated waveforms, (b) power spectra. The modulator is a 1000-Hz sinusoid and the carrier is a 30-kHz sinusoid. A low-pass filter at 8 kHz is applied to the TM. The modulation depth is set at 0.5 in the DSB-TC.

In this study, to observe distortion of speech associated with the TM precisely, mono-syllable articulation tests were conducted for DSB-TC and the TM and their confusion matrices were compared.

2. Methods

2.1 Two types of amplitude modulation

Tested two AM methods are expressed as follows, where *A*, *s(t)*, *fc(t)*, and m represent a

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constant, the modulator signal (speech), a carrier signal, and the modulation depth, respectively. Examples of waveforms and spectra obtained by these AM methods are shown in **Fig. 1**.

I) DSB-TC $f(t) = A(1 + m \times s(t)) \times fc(t)$ (1)

In this method, the envelope of the modulated signal corresponds to the modulator. On the other hand, it is accompanied by a strong high-pitched tone, especially when the modulation depth is low.

II) TM $f(t) = A(m \times s_{tp}(t)) \times fc(t)$ (2)

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 1, 4 or 8 kHz.

2.2 Mono-syllable articulation tests

11 normal-hearing Japanese subjects (22–40 years, mean 28.1 ± 6.4) participated. 100 Japanese mono-syllable recorded with a female voice were taken from a commercially available database (NTT-AT FW03) were presented by the both AM methods. In the DSB-TC stimuli, speech sounds were low-pass filtered at 1, 4, or 8 kHz. The intensities of both BCU speech were set at the most clearly perceived level for each subject. Confusion matrices were obtained using the results of the tests.

3. Results

The scores of the articulation of DSB-TC and transposed modulation were 43.5% and 35.2%, respectively. The TM tended to show lower articulation, however, no significant difference was observed.

Fig. 2 shows the respective confusion matrices for the DSB-TC and the TM, in each cutoff-frequency. Some differences were observed among them; two-way ANOVA showed that the number perceived as /j/ was significantly larger for the TM than for DSB-TC when voiced consonants were presented ($p<0.05$). Additionally, the number perceived as vowels was significantly larger for the TM than for the DSB-TC when consonants were presented ($p<0.05$).

4. Discussion

Some differences observed in confusion matrices of mono-syllables perception indicated that the TM speech contains more distortions than the DSB-TC speech. Considering the previous reports that the TM was better than the DSB-TC in terms of sound quality, it is suggested that appropriate selection of amplitude-modulation types according to scenes. The results provide useful information for further development of the BCUHA.

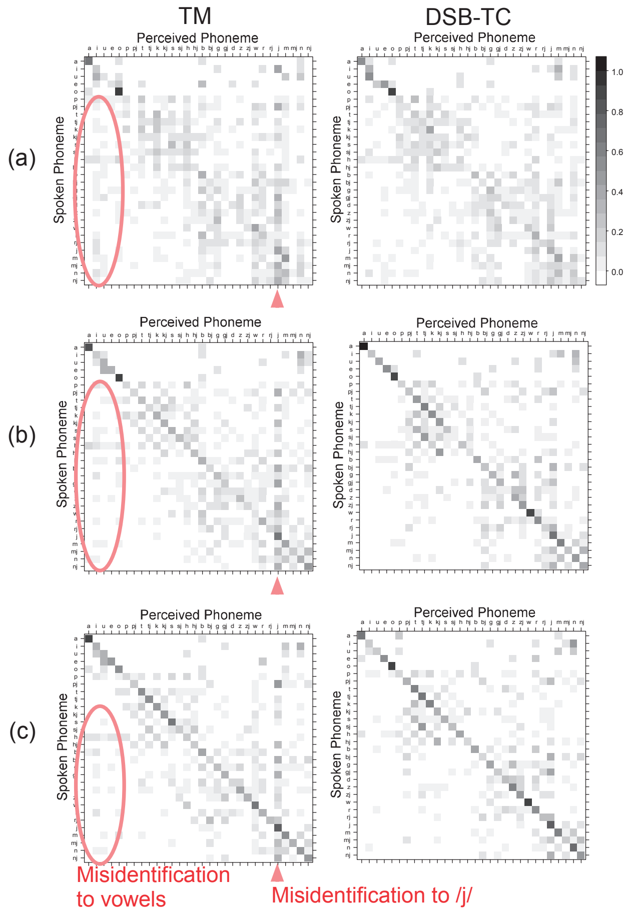

Fig. 2. Confusion matrices for two types of amplitude modulation at the cutoff frequencies of 1 , 4, and 8 kHz (a, b, and c, respectively). The phonemes were classified into four groups: (1) vowels, (2) unvoiced consonants, (3) voiced plosive and fricative consonants, and (4) other voiced consonants. Blocks with larger grey values indicate higher appearance frequencies for those pairs.

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