






ORIGINAL RESEARCH

Preliminary study to determine an optimal mode for favorable residual hearing at low frequencies: Full electrical stimulation, electric acoustic stimulation, and electrical complement

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Abstract

Objective: In this prospective study, each subject experienced three modes electric acoustic stimulation (EAS), full electrical stimulation (FES), and electrical complement (EC), and the performance of each mode and subject preference were evaluated.

Methods: Eight ears (seven patients) with successfully preserved residual hearing after cochlear implantation (CI) were included. EAS, FES, and EC programs were set up on each patient's device, and each mode was used for at least 1 h per day for a month. The Speech Intelligibility test, the Speech, Spatial and Qualities of Hearing Scale, and the Hearing in Noise test (HINT) results in each stimulation mode.

Results: The mean monosyllabic word score (EAS: 90.3 ± 4.0 ; FES: 81.2 ± 16.1) and the mean sentence score (EAS: 98.3 ± 1.7 ; FES: 95.0 ± 3.0) were significantly higher in the EAS mode than in the FES mode. The mean bisyllabic word score (EAS: 95.6 ± 5.6 ; EC: 90.1 ± 5.6) was higher in the EAS mode than in the EC mode. In HINT, the signal-to-noise ratios under the noise front (EAS: 4.7 ± 2.5 ; FES: 7.9 ± 4.4) and noise composite conditions (EAS: 4.2 ± 2.7 ; FES: 6.6 ± 4.0) were significantly smaller in the EAS mode than in the FES mode. After trials of the three modes, five subjects preferred EAS, one preferred EC, and two preferred FES.

Conclusion: Among the three stimulation modes, EAS produced slightly better results, and subjects generally preferred EAS (five of seven patients, 71.4%). The use of hearing aids before CI was considered an important factor in mode preference. FES may be preferred when CI was performed at a young age and subjects had little experience with hearing aids. However, adults may prefer EC over EAS if there was little or no hearing-aid use before CI.

KEYWORDS

cochlear implantation, electric acoustic stimulation, sensorineural hearing loss

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1 | INTRODUCTION

Electroacoustic stimulation (EAS) has been commonly applied to patients with ski-slope type sensorineural hearing loss who underwent cochlear implantation (CI). EAS has advantage of the improvement of speech perception through acoustic amplification for residual hearing in the low frequencies. EAS has been proven to be beneficial in studies employing behavioral measures and is preferred by patients.¹⁻³ Although “soft-surgery technique” and steroid administration have been applied to preserve the residual hearing, but some degree of postoperative residual hearing loss was identified in the long-term follow-up studies.^{4,5}

Recently, patients with partial deafness, or normal low-frequency hearing with deafness at high frequencies have received CI.⁶ In these patients, the postoperative hearing status at low frequencies (125–500 Hz) is essential for decision making regarding auditory rehabilitation. At the time of CI consultation for the EAS candidates, the selective option of a stimulation mode according to the extent of postoperative residual hearing preservation is explained as follow:

Electrical complement (EC): Non-amplified low frequency hearing is complemented by electric stimulation with implant.

EAS: Low frequency hearing is amplified and combined with electric stimulation in the same ear.

Full electrical stimulation (FES): Electrical stimulation is covered to low frequency range.⁷

Because postoperative residual hearing varies, the selection of an optimal map for the EAS device should be individually tailored. In addition, various factors such as the cause of hearing loss, the state of language acquisition before the onset of the hearing loss, the duration of the hearing loss, the speed of the hearing loss, and the experience of using the hearing aid before surgery may be different for each individual. Therefore, these factors could also affect the selection of the stimulation mode after CI.

This study was designed to evaluate the optimal mode—EC, EAS, or FES—for patients with favorable postoperative residual hearing at low frequencies.

2 | MATERIALS AND METHODS

Our study was reviewed and approved by the Institutional Review Board of Ajou University Hospital (approval no. AJIRBMD-SUR-19-341). All personal information was kept confidential as required. Informed consent was obtained from all subjects. Eight ears of seven patients who underwent CI at the Ajou University Hospital Hearing Center between 2010 and 2017 were included. Inclusion criteria were as follows: use of a speech processor in either EAS or EC mode and better than partial hearing preservation according to the hearing preservation classification system (percent of residual hearing preserved >25% calculated in accordance with the protocol and equation proposed by the HEARING group).⁸ The mean age at CI was 30.7 ± 19.5 years (range: 5–57 years), and the mean duration of hearing-aid use was 2.9 ± 3.3 years (range: 0–8 years). The mean preoperative

pure tone average (PTA) (averaged over 0.5, 1, 2, and 4 kHz) of the ears that underwent CI was 92.0 ± 11.8 dB HL (decibels of hearing loss) and that of the contralateral ears was 87.3 ± 12.7 dB HL. Three ears received cochlear devices (Cochlear Ltd.), and five ears received MED-EL devices. The speech processor models were Hybrid ($n = 3$), Duet ($n = 4$), and Sonnet EAS ($n = 1$). The mean duration of device experience was 4.1 ± 1.9 years (range: 2.2–7 years). Original stimulation mode was EAS mode in seven of eight ears and EC mode in one ear. Demographic data are summarized in Table 1.

Three stimulation modes (EAS, FES, and EC) were set on each patient's speech processor. Fitting and mapping of the EAS mode were performed according to the guidelines provided by the two companies. The crossover point was the frequency at which an unaided threshold was maintained (≥65 dB HL for the MED-EL device and ≥70 dB HL for the Cochlear device). For the cochlear device, lower boundary frequencies predefined by the manufacturer were applied (313 Hz for two ears, 563 Hz for one ear). EC mode was set to the same setting as the electrical mapping of the EAS mode with the acoustic amplification setting turned off. For EC, all patients were remapped to the full frequency range. The electrodes inserted in the cochlea were activated. Each mode was used for at least 1 h/day for 1 month.

Speech intelligibility was assessed using open-set monosyllabic word, bisyllabic word, and sentence recognition test scores. The hearing level was measured preoperatively and postoperatively. The means of the thresholds at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz were used to calculate the PTA. Hearing in Noise tests (HINTs) were performed using a HINT Pro 7.2 audiometric system (Bio-Logic System) with Korean HINT sentences.

Subjective benefits according to the stimulation mode were assessed using the “other qualities of hearing” section of the Speech, Spatial and Qualities of Hearing Scale (SSQ) for parents of children with impaired hearing.⁹ In addition, sound quality and clarity were evaluated using a Visual Analogue Scale (VAS). Among the three modes, the most preferred mode for each questionnaire item was given the highest score, and scores were given differentially to the other two modes sequentially. For sound quality and clarity, the highest score was given to the most satisfactory mode among the three modes, and the scores were subtracted in order for the remaining two modes.

The Wilcoxon signed-rank test was used to identify differences among modes for each subject. The Kruskal-Wallis test was also used to identify differences among the stimulation modes. All statistical analyses were performed using IBM SPSS Statistics for Windows (version 23.0; IBM Corp.). In all analyses, $p < 0.05$ was taken to indicate statistical significance.

3 | RESULTS

Demographic data are summarized in Table 1. Three ears (Ears 1–3) exhibited prelingual deafness and were associated with more than 5 years of device experience. Three ears (Ears 4–6) were not

TABLE 1 Demographic data

Ear	Sex	Side	Onset	Age at CI (year)	Duration of HA (years)	Device experience (years)	Brand	Electrode	HP	LFPTA (dB HL)		Original mode
										Pre-CI	Post-CI	
1	Female	L	Pre	11.1	2	7	M	Flex24	P	47.5	73.3	EAS
2	Female	R	Pre	5.1	1.3	6.8	M	Medium	C	55	60	EAS
3	Female	R	Pre	13	4	5	M	Flex24	C	53.3	58.3	EAS
4	Female	R	Post	57.3	-	3.5	Co	CI422	P	33.3	78.3	EAS
5	Female	L	Post	44	-	3.2	M	Flex28	C	46.7	51.7	EAS
6	Female	L	Post	39.8	-	2.8	M	Flex28	C	28.3	45	EC
7	Male	R	Post	26.1	7.5	2.5	Co	CI422	C	16.7	30	EAS
8	Female	L	Post	50.3	8	2.2	Co	CI422	P	48.3	56.7	EAS

Abbreviations: C, complete; CI, cochlear implantation; Co, cochlear; EAS, electroacoustic stimulation; EC, electrical complement; HA, hearing aid; HP, hearing preservation; L, left; LFPTA, low frequencies pure tone average (average threshold of 125, 250, 500 Hz); M, MED-EL; R, right; P, partial; pre, prelingual; post, postlingual.

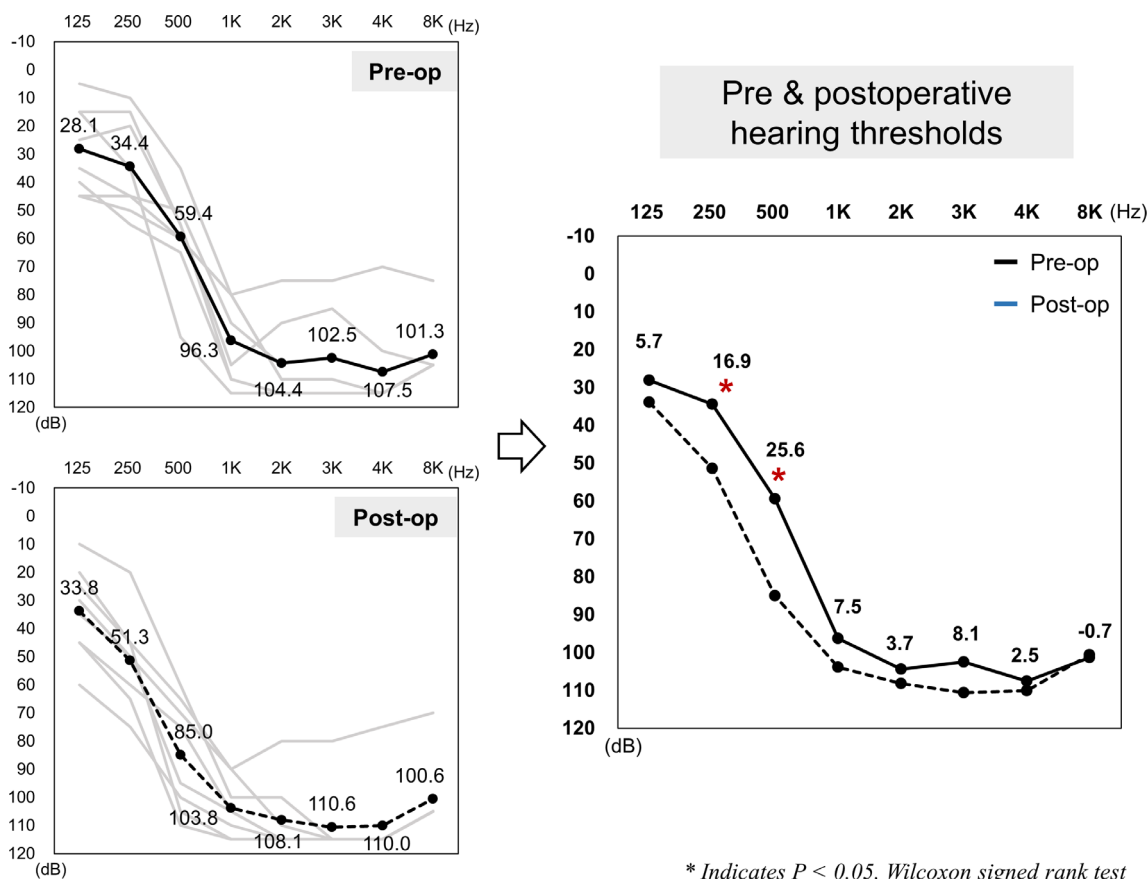


FIGURE 1 Pre- and postoperative pure tone thresholds in all subjects

associated with hearing-aid use (Table 1). Figure 1 shows the preoperative PTA at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz in the implanted and contralateral sides. Mean thresholds <250 Hz were below serviceable hearing (40 dB HL). Postoperative (right before 1-month trial) PTAs at each frequency were compared, and the mean thresholds at 250 and 500 Hz significantly increased after CI

(Figure 1). The mean pure tone thresholds with an implant ranged from 30 to 40 dB HL at each frequency in the three stimulation modes. Speech intelligibility was compared among the three modes, and the mean performance score in the EAS mode was higher than those in the other two modes. In particular, the mean monosyllabic word score and mean sentence score were significantly higher in the

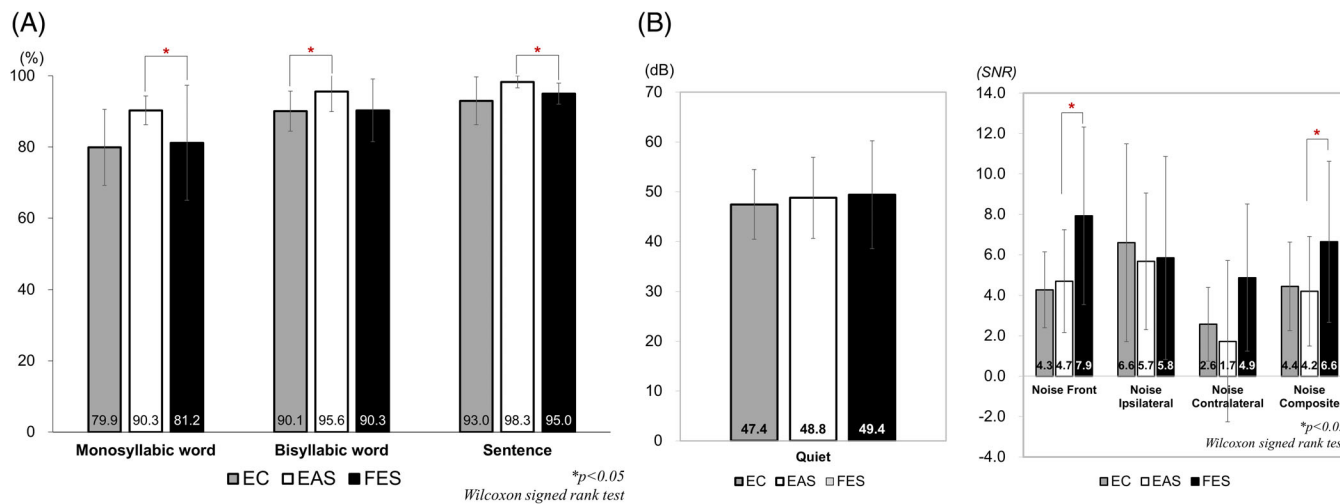


FIGURE 2 Results of Speech Intelligibility tests (monosyllabic word, bisyllabic word, and sentence tests) (A) and the Hearing in Noise test (HINT) (B) in each mode. The Wilcoxon signed-rank test was used to compare test results among the three modes. EAS, electric acoustic stimulation; EC, electrical complement; FES, full electrical stimulation

EAS mode than in the FES mode, and the mean bisyllabic word score was higher in the EAS mode than in the EC mode (Figure 2A). In terms of HINT results, although the mean signal-to-noise ratios under fossur conditions (noise front, noise ipsilateral, noise contralateral, and noise composite) were similar between the EC and EAS modes, those under the noise front and noise composite conditions were significantly smaller in the EAS mode than in the FES mode (Figure 2B).

The mean scores in the other qualities of hearing sections of the SSSQ were 105.2 ± 44.3 , 106.2 ± 50.8 , and 107.2 ± 54.5 in the EAS, FES, and EC modes, respectively, and did not differ among the three modes (all, $p > 0.05$). The VAS scores for sound quality and clarity were compared, and those assessed in the EAS mode (quality: 8.4 ± 1.8 ; clarity: 8.3 ± 1.7) were higher than those in the EC (quality: 6.8 ± 2.7 ; clarity: 6.5 ± 2.4) and FES modes (quality: 7.1 ± 2.5 ; clarity: 6.8 ± 1.9). However, these differences were not significant. After completing trials using the three modes, five subjects preferred EAS (Ears 2, 4, 5, 7, and 8), one subject preferred EC (Ear 6), and two subjects preferred FES (Ears 1 and 3). The overlap ranges of EAS, individual speech intelligibility scores, and subject preferences are summarized in Table 2.

4 | DISCUSSION

Many studies have reported on the effects of EAS as an effective hearing rehabilitation option for patients with residual hearing after CI.^{10,11} Because most studies have reported comparisons between subjects who underwent unilateral CI and EAS, other influences could not be excluded. To elucidate the effects from stimulation mode alone, this study attempted to analyze intraindividual differences among EAS, EC, and FES. Few studies have used this kind of clinical design.

Several outcomes can be derived from this study. First, there was greater speech perception in quiet and noisy conditions during EAS compared to FES, which is consistent with other clinical trials.^{12,13} This could be explained by the acoustic amplification of the remaining low-frequency hearing. As shown in Table 1, all patients had well-preserved low-frequency PTA (LFPTA) up to 500 Hz ($30\text{--}78.3$ dB HL). This low-frequency hearing conveys useful information on prosodic features, fundamental frequency, and the first formant frequencies of speech sounds.¹¹ Additional acoustic amplification with a hearing aid uses low-frequency hearing to a greater extent.

Second, the LFPTA and preoperative hearing-aid use determined which type of electrical stimulation was optimal. Ears 6 and 7 had LFPTAs of 45 and 30 dB HL, respectively, and their respective preferred modes were the EC and EAS modes. Interestingly, a hearing aid had not been used in Ear 6, but one had been used in Ear 7 for 7.5 years preoperatively. Even though speech intelligibility was better in the EAS mode than in the EC mode, the subject with Ear 6 preferred the EC mode.

Third, subject preferences did not always coincide with outcomes of objective evaluation such as speech intelligibility and HINT results (i.e., for Ears 1, 3, 4, and 6). In particular, Ears 1 and 3 were both ears of one patient with prelingual deafness who chose the FES mode despite the speech intelligibility score being poorer in the FES mode than in other modes. This patient had used bilateral hearing aids for more than 2 years preoperatively and bilateral devices in the EAS mode for more than 5 years. However, Preoperative LFPTA in this patient was similar in both ears (right 53.3 dB HL, left 47.5 dB HL) but left LFPTA was relatively increased postoperatively (right 58.3 dB HL, left 73.3 dB HL). Due to this asymmetric postoperative residual hearing, the sound heard in both ears in EAS mode may have become less balanced and more uncomfortable than before surgery (Figure 3). In the interview after test, she said that it was good because there was no noise under the EAS condition, but the sound was resonant and

TABLE 2 Overlap ranges, speech intelligibility scores, and subjective preferences

Ear	EAS Overlap (Hz)	Speech intelligibility (%)												Subjective preference
		EAS				EC				FES				
		Monosyllabic word	Bisyllabic word	Sentence	monosyllabic word	Bisyllabic word	Sentence	Monosyllabic word	Bisyllabic word	Sentence	Monosyllabic word	Bisyllabic word	Sentence	
1	247-250	83.3	75	99	55.6	80	99	61.1	85	99	61.1	85	99	FES
2	187-188	77.8	95	97	72.2	80	90	77.8	80	90	77.8	80	94	EAS
3	310-366	83.3	95	100	61.1	90	98	27.8	55	95	27.8	55	95	FES
4	313-433	66.7	95	96	66.7	75	100	77.8	90	98	77.8	90	98	EAS
5	247-250	72.2	90	96	61.1	85	88	61.1	85	88	61.1	85	95	EAS
6	462-500	77.8	95	99	66.7	90	95	33.3	60	80	33.3	60	80	EC
7	563-685	77.8	90	100	50	80	94	55.6	65	89	55.6	65	89	EAS
8	313-433	88.9	95	99	83.3	95	95	88.9	85	95	88.9	85	95	EAS

Abbreviations: EAS, electroacoustic stimulation; EC, electrical complement; FES, full electrical stimulation.

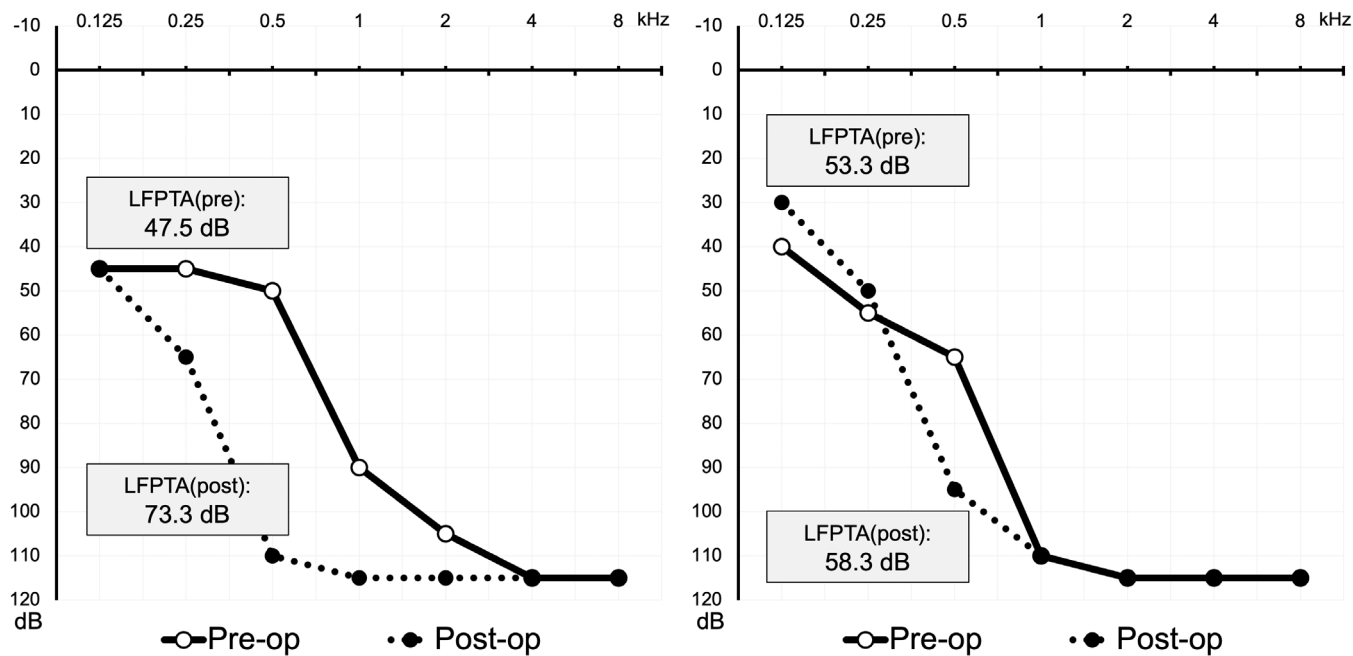


FIGURE 3 Pre- and postoperative residual hearing and LFPTA in Ears 1 (left) and 3 (right). LFPTA, average threshold of 125, 250, 500 Hz

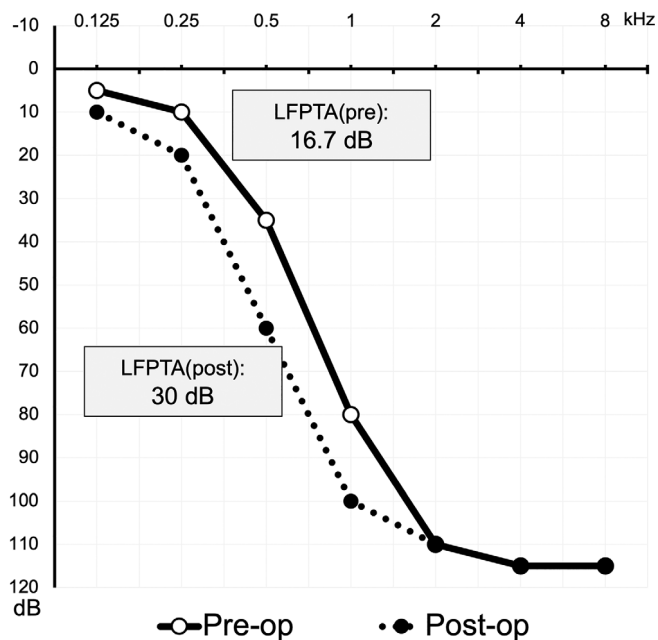


FIGURE 4 Pre- and postoperative residual hearing and LFPTA in Ear 7. LFPTA, average threshold of 125, 250, 500 Hz

she often got a headache. On the contrary, she explained that although noise was heard minimally under the FES condition, the sound was not accompanied by an echo, so it was comfortable to hear. Furthermore, our patients, except for the bearer of Ear 6, had to acclimatize to EAS after activation, and therefore an additional application of three stimulation modes during only 1 month may be insufficient for habituation.

EC mode was set to the same setting as the electrical mapping of the EAS mode with the acoustic amplification setting turned off. Therefore, the more low-frequency residual hearing remains, the better the auditory performance of EC mode. In that sense, most ears except Ear 7 in this study are not completely suitable as a candidate for EC mode. Ear 7 seems to be an ideal candidate for EC mode based on good residual hearing and has the highest overlap frequency (563–685 Hz) (Figure 4). In the private interview, however, he told that the sound quality of EC mode was the lowest, and speech discrimination was not good, so there were many cases of asking again. In the case of EAS mode, he described that the sound quality was exceptionally good, especially in a noisy place or in a car and the music and machinery sounds much more like the real sound, respectively. It is thought that the experience of wearing a hearing aid for 7.5 years with residual hearing that the effect of the hearing aid can be sufficient maximized the satisfaction of the EAS mode. Although the residual hearing loss after surgery was less than that of other ears, it is judged that the EC mode without acoustic amplification in the low-frequency region was insufficient to improve auditory performance.

It was reported that slim straight electrodes array (CI422) is beneficial for hearing preservation and audiologic performance.^{14,15} The effect of electrode array length was significant in terms hearing preservation and speech recognition at short-term follow-up (postoperative 12 months) but not at long-term follow-up (postoperative 24 months).^{16–18} In this study, electrode arrays with heterogeneous length were inserted in eight ears (two Flex24, two Flex28, one Medium, three CI422), respectively. All ears showed more than partial hearing preservation. This suggests that, besides the length of the electrode, there are several factors that affect the preservation of

residual hearing, such as steroid administration and soft-surgery technique.

Most patients with partial deafness may not satisfy the audiologic criteria for CI according to our National Health Insurance guidelines. Given that proper selection of a mode out of the three investigated here can be useful depending on residual hearing status, the expansion of candidacy for CI in both children and adults with residual low-frequency hearing and severe high-frequency hearing loss should be considered.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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