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Acceptance and Benefits of Electro-Acoustic Stimulation for Conventional-Length Electrode Arrays

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Keywords
Electro-acoustic stimulation · Cochlear implants · Conventional electrodes · Speech perception · Residual hearing

Abstract
Background: Prior studies have shown an advantage for electro-acoustic stimulation (EAS) in cochlear implant (CI) patients with residual hearing, but the degree of benefit can vary. The objective was to explore which factors relate to performance with and acceptance of EAS for CI users with conventional-length electrodes. ***Methods:*** A retrospective chart review was conducted for adults with an average threshold of 75 dB hearing loss or better across 250 and 500 Hz preoperatively (n = 83). All patients underwent cochlear implantation with a conventional-length electrode. Low-frequency audiometric thresholds were measured at initial activation as well as 3 and 12 months postoperatively to determine who met the criteria for EAS. Speech perception for CNC words and AzBio sentences in quiet and +10 dB SNR noise was evaluated 3 and 12 months after activation. ***Results:*** Speech perception in quiet and noise was similar regardless of whether or not the patient was eligible for EAS. Less than half of the patients who met the EAS criteria chose to use it, citing reasons such as physical discomfort or lack of perceived benefit. EAS users performed better on CNC words but not sentence recognition than EAS nonusers. ***Conclusions:*** EAS use is dependent on audiologic and nonaudiologic issues. Hearing preservation is possible with conventional electrodes, but hearing preservation alone does not guarantee superior speech perception.

Introduction

The success of cochlear implants (CIs) in restoring the ability to understand speech to those with severe to profound hearing loss (HL) has led to an expansion of the candidacy criteria to include patients with residual acoustic hearing [Holder et al., 2018]. Shortened electrode arrays and "soft" surgical techniques have been designed to restore high-frequency hearing with electric stimulation while preserving residual low-frequency acoustic hearing, allowing for combined electro-acoustic stimulation (EAS) [Incerti et al., 2013]. Recently, standard-length electrode arrays (i.e., either lateral wall or precurved/peri-

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modiolar electrode arrays designed to be inserted at least one full turn into the cochlea) have also been shown to preserve hearing in some cases [Adunka et al., 2013; Jurawitz et al., 2014; Hunter et al., 2016; Svrakic et al., 2016; Friedmann et al., 2019; Gomez Serrano et al., 2019].

The ability to preserve hearing has led to the use of EAS for patients with either short- or standard-length electrode arrays [Erixon et al., 2012; Adunka et al., 2013; Lenarz et al., 2013; Roland et al., 2018]. Many studies have shown a benefit for EAS users compared to either traditional CI users (i.e., those with no hearing preservation) or the same patient listening without acoustic amplification (i.e., electric only). These benefits include improved speech perception in quiet [Büchner et al., 2017], speech perception in noise [e.g., Turner et al., 2004], enhanced music appreciation [Gfeller et al., 2006; El Fata et al., 2009; Brockmeier et al., 2010], and improved sound quality [Kelsall et al., 2017].

Other studies have found little to no benefit for EAS. Fraysse et al. [2006] examined 9 Nucleus 24 users and found no difference between EAS and CI alone performance for sentences presented at +10 dB SNR. Gstoettner et al. [2009] found that 4 patients implanted with a FlexEAS array improved slightly in the EAS condition for sentences in +10 dB SNR noise, while 2 others saw a decrease in scores. Brockmeier et al. [2010] found that 13 EAS users were no better than traditional CI users at several music tasks, including chord discrimination, dissonance ratings, and instrument identification. Furthermore, EAS users performed the same whether or not the hearing aid component of the device was used, similar to the results of Dillon et al. [2015], who found no difference in speech perception in noise scores for 8 EAS users listening to a truncated frequency map with and without low-frequency acoustic amplification. More recently, Büchner et al. [2017] showed no difference in scores for sentences in +10 dB noise between 12 Flex20/24 EAS users and 25 Flex28 CI-only users. Battmer et al. [2019] also failed to find a significant speech perception improvement for 9 Advanced Bionics users (primarily HiFocus MidScala) when comparing EAS to CI-only listening in the same patients. Compared to the demonstrated benefits of EAS for short-electrode arrays, the benefits of EAS for music and speech in noise appear to be minimal for a variety of standard-length electrode arrays.

While these studies generally had small numbers of subjects (with the exception of Büchner et al. [2017]), they highlight the variability in outcomes for EAS when patients are implanted with standard-length electrode arrays (for further literature review, see Talbot and Hartley [2008]). Some of this variability may be explained by examining studies where all patients were given the choice to use EAS clinically and some chose not to, despite being eligible audiometrically. Incerti et al. [2013] summarized these reasons for not choosing EAS into three categories: too little hearing, too much hearing, or physical/non-threshold-based. There is good evidence that postoperative thresholds in the severe-to-profound range (typically ≥80 dB HL) or normal-hearing range (≤30 dB HL) often result in patients rejecting EAS [Gantz et al., 2009; Lenarz et al., 2009; Helbig and Baumann, 2010; Skarzynski et al., 2010; Helbig et al., 2011], though Santa Maria et al. [2013] found that the degree of residual hearing preservation did not predict EAS usage. Other studies have reported non-use due to lack of perceived benefit, physical discomfort of the device in the ear canal, or tinnitus [Gstoettner et al., 2008; Helbig et al., 2011; Plant and Babic, 2016; Büchner et al., 2017]. Besides having small sample sizes, prior literature on this topic does not directly compare outcomes for patients with similar levels of preoperative hearing based on whether or not they chose to use EAS.

Thus, the goal of the present study was to examine two issues related to EAS fitting: benefit for speech perception and acceptance. That is, compared to electric-only stimulation, is EAS beneficial and/or preferred for patients with residual hearing and standard-length electrode arrays? Fitting EAS is both time-consuming and potentially costly to the patient and clinic. Therefore, it is important to understand the benefits and acceptance of EAS in order to make surgical and programming decisions that maximize speech outcomes and patient satisfaction. Furthermore, acceptance of EAS may be indicative of the patient's subjective impression of the usefulness of their residual hearing. Using a group of patients with similar levels of preoperative residual hearing, we first compared speech perception outcomes based on whether or not that hearing was preserved after CI surgery. Then, for the group with hearing preservation, speech perception outcomes were compared based on whether or not the patient used EAS.

Materials and Methods

A retrospective chart review was conducted of adult patients who underwent CI surgery at our institution between 2013 and 2018 (n = 1,133). Inclusion criteria were age ≥18 years at the time of surgery, complete insertion of a standard-length electrode array (Table 1), and a low-frequency pure-tone average (LFPTA) at 250 and 500 Hz of 75 dB HL or better preoperatively. The average of the thresholds at 250 and 500 Hz was chosen as the criterion based

Table 1. Patient demographics

Age at implantation, years	65 (24–87)
Age at onset of HL, years	40 (0–72)
Duration of deafness, years	24 (1–62)
Sex	
Female	56.8%
Male	43.2%
Manufacturer	
Advanced Bionics	11
HiRes90K Advantage/HiFocus MidScala	6
HiRes Ultra/HiFocus MidScala	3
HiRes Ultra 3D/HiFocus MidScala	2
MED-EL	5
Synchrony/Flex28	4
Concerto/Flex24	1
Cochlear	67
CI532	58
CI512	3
CI522	2
CI422	4
Side	
Left	51.2%
Right	48.8%
Etiology	
Unknown	51.8%
Positive family history/genetic	19.3%
Infection	6.0%
Noise exposure	6.0%
Other	16.9%
Sudden versus progressive	
Sudden	8.4%
Progressive	91.6%
Other ear preoperatively	
Hearing aid	69.8%
Cochlear implant	15.7%
Unaided	14.5%
LFPTA preoperatively, dB HL	52.5 (10–72.5)

Values are presented as *n*, %, or median (range). HL, hearing loss; LFPTA, low-frequency pure-tone average.

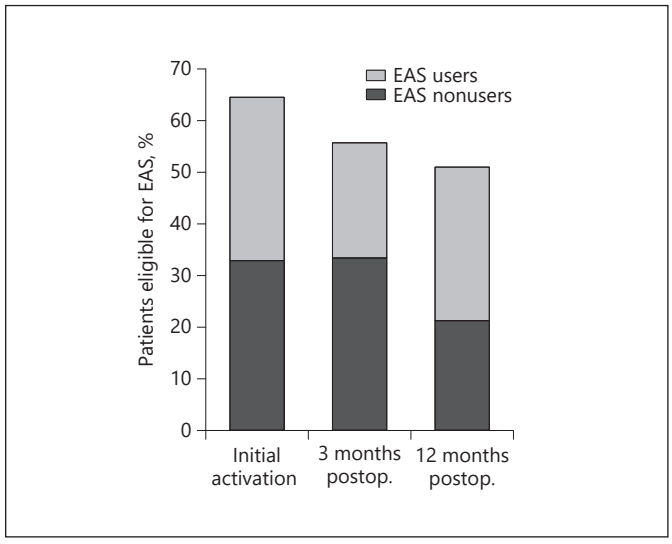

Fig. 1. Stacked bar chart showing the proportion of EAS users (grey) and EAS nonusers (black) among patients eligible for EAS at each time point. EAS, electro-acoustic stimulation.

on an approximate average of current CI manufacturer recommendations for EAS use as well as current practice in our center. Cochlear Americas recommends thresholds of 80 dB HL or better 500 Hz and below for EAS usage (N7 Hybrid fitting guide); Advanced Bionics recommends thresholds of 90 dB HL or better (Naida Q90 fitting guide); MED-EL recommends thresholds of 65 dB HL or better (Sonnet EAS fitting guide). Exclusion criteria were inconsistent use or nonuse of the implant and lack of follow-up (i.e., the patient did not return for regular evaluations and/or mapping appointments). Patients with single-sided deafness were also excluded. Eighty-one patients (83 ears) met these criteria and were included in the study. Further demographic data can be found in Table 1.

Charts were reviewed for etiology of HL, age at onset of HL, and duration of deafness. The LFPTA was collected at four different time points: (1) preoperatively, (2) at initial activation, (3) 3 months postoperatively, and (4) 12 months postoperatively. Speech perception was measured at time points 3 and 4 only. Scores were obtained using recorded materials presented in the sound field at 60 dBA for CNC words, AzBio sentences in quiet, and AzBio sentences in 10-talker babble at +10 dB SNR (babble presented at 50 dBA from the same speaker as the target talker). Patients were tested in their everyday listening condition, thus scores reported here are electric and acoustic for EAS users and electric only for EAS nonusers. If the contralateral ear had measurable thresholds, it was plugged and muffled during testing to isolate the implanted ear. Charts were also reviewed for information about usage of EAS. In cases who met audiometric criteria but in whom EAS was not used, an explanation was sought in the audiology notes. If not explicitly mentioned in the chart, the patient's clinician was queried and provided a rationale for use or nonuse.

Results

EAS Use

In order to be eligible for EAS at our center, postoperative thresholds must be ≤75 dB HL for both 125 and 250 Hz. These criteria were chosen as a realistic level for patients implanted with conventional electrode arrays and to reflect current practice at our center. Two patients had postoperative low-frequency thresholds in the normal hearing range. These patients did not use acoustic amplification, but instead were fit with maps with higher cutoff frequencies. Therefore, they were included as EAS users. Figure 1 shows the relative proportions of patients

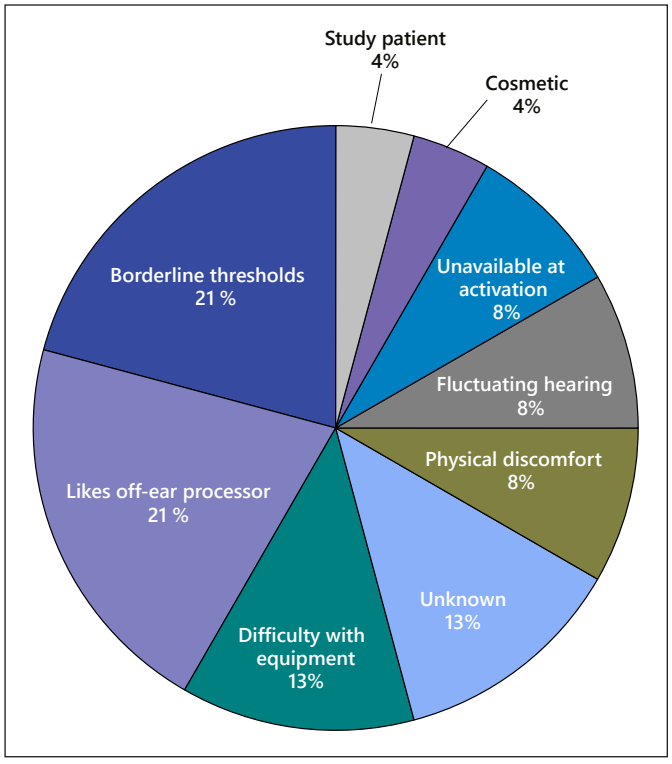

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Fig. 2. Pie chart showing reasons for EAS rejection among patients who were eligible at initial activation ($n = 25$). "Unavailable at activation" means that EAS technology was not available for that manufacturer at the time of device fitting. "Study patient" means that the patient was enrolled in a different research study that precluded the use of EAS. EAS, electro-acoustic stimulation.

who chose to use or not use EAS out of the total percentage of patients who were eligible at each time point. Approximately half of the eligible patients chose to use EAS at each time point. There is 1 patient included as an EAS user who chose to wear EAS despite not being eligible audiometrically. There are also 6 patients who continue to use EAS beyond the 12-month follow-up, including 1 patient implanted 6 years earlier with a CI422. Not all patients had audiometric thresholds measured at each appointment. For those who did, the percentage of patients who were eligible to use EAS decreased over time, from 64.5% (49/76) at initial activation to 55.7% (44/79) 3 months postoperatively and 51% (24/47) 12 months postoperatively. The reasons for nonuse of EAS are shown in Figure 2.

Speech Perception

Figure 3a shows the scores for all participants based on whether or not they were eligible to use EAS at the 3-month time point. Speech perception scores were compared between the group eligible to use EAS 3 months after activation and the remaining patients (including 4 patients who did not have audiometric thresholds measured at 3 months but had LFPTAs worse than 90 dB HL at initial activation). Using independent *t* tests, no differences were detected between the two groups for any of the speech tests.

Figure 3b compares the scores for EAS users and EAS nonusers at the 3-month time point. Speech perception scores were also compared within the eligible group between the EAS users and the EAS nonusers 3 months after activation. CNC scores were better for the EAS users ($t_{(43)} = 2.41$, $p = 0.02$), but no difference was detected between the groups for AzBio scores in quiet or in noise. After type I error correction using Rom's method [Rom, 1990], the difference for CNC scores was no longer significant.

Figure 4a shows scores for on each speech test based on whether or not the patient was eligible to use EAS. Similar comparisons were made at 12 months between the group eligible for EAS use and the remaining patients who were not eligible for EAS use (including 3 patients who did not have audiometric thresholds measured at 12 months but had LFPTAs poorer than 90 dB HL at initial activation), as at the 3-month time point no differences in speech perception scores on any of the 3 speech perception tests were detected.

Within the group eligible to use EAS at 12 months, speech scores were compared between EAS users and nonusers (Fig. 4b). CNC scores were again significantly better for EAS users ($t_{(22)} = 4.40$, $p = 0.0002$), though no group differences were detected for performance on AzBio sentences in quiet ($t_{(15)} = 2.49$, $p = 0.025$) or noise ($t_{(12)} = 1.42$, $p = 0.181$) after type I error correction. All comparisons are detailed in online supplementary Appendix 1 (see www.karger.com/doi/10.1159/000507975).

Audiometric Thresholds

Table 2 shows a summary of audiometric results, including mean thresholds at each time point. Pearson correlations failed to detect a relationship between LFPTA and age at surgery ($r = 0.12$, $n = 83$, $p = 0.29$), age at onset of HL ($r = 0.04$, $n = 79$, $p = 0.76$), or duration of deafness ($r = 0.04$, $n = 79$, $p = 0.70$). Figure 5a shows preoperative low-frequency thresholds for the 83 ears included in the study. Figure 5b–d shows low-frequency thresholds at initial activation as well as 3 and 12 months postoperatively based on whether or not the patient was eligible to use EAS. As expected, preoperative thresholds were

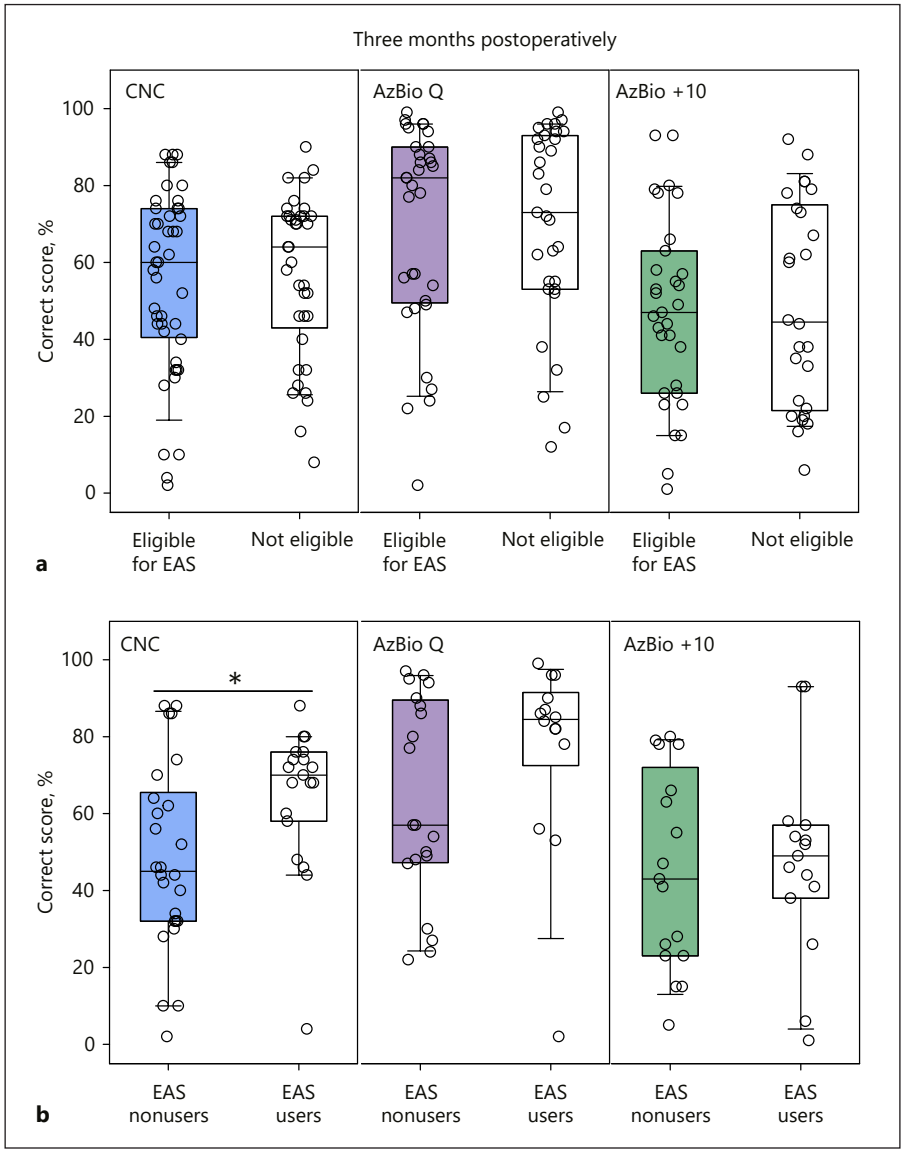

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Fig. 3. Box plots showing speech perception scores at the 3-month time point. **a** Comparison of patients who were eligible for EAS (left shaded boxes, $n = 44$) or not eligible for EAS (right open boxes, $n = 37$) on scores for CNC words (left plot), AzBio sentences in quiet (middle plot), and noise (right plot). **b** Comparison of patients who were eligible for EAS on CNC words (left plot), AzBio sentences in quiet (middle plot), and noise (right plot) based on whether they were EAS nonusers (left shaded boxes, $n = 26$) or EAS users (right open boxes, $n = 19$). Not all participants were tested on sentence materials. * $p < 0.05$. EAS, electro-acoustic stimulation.

Table 2. Audiometric thresholds

Time point	Audiometric data	125-Hz threshold	250-Hz threshold	500-Hz threshold	No measurable hearing
Preoperatively	83	38.5 (15.1%)	42.6 (17.3%)	55.4 (18.9%)	0
Initial activation	76	59.2 (16.1%)	67.5 (19.0%)	82.2 (20.3%)	5 (6.6%)
3 months	79	61.4 (17.8%)	69.6 (21.2%)	83.0 (20.2%)	9 (11.3%)
12 months	47	59.6 (17.4%)	68.5 (18.1%)	84.2 (18.3%)	7 (14.9%)

Values are presented as n or n (%). Mean thresholds (±1 standard deviation) are shown for patients with measurable hearing.

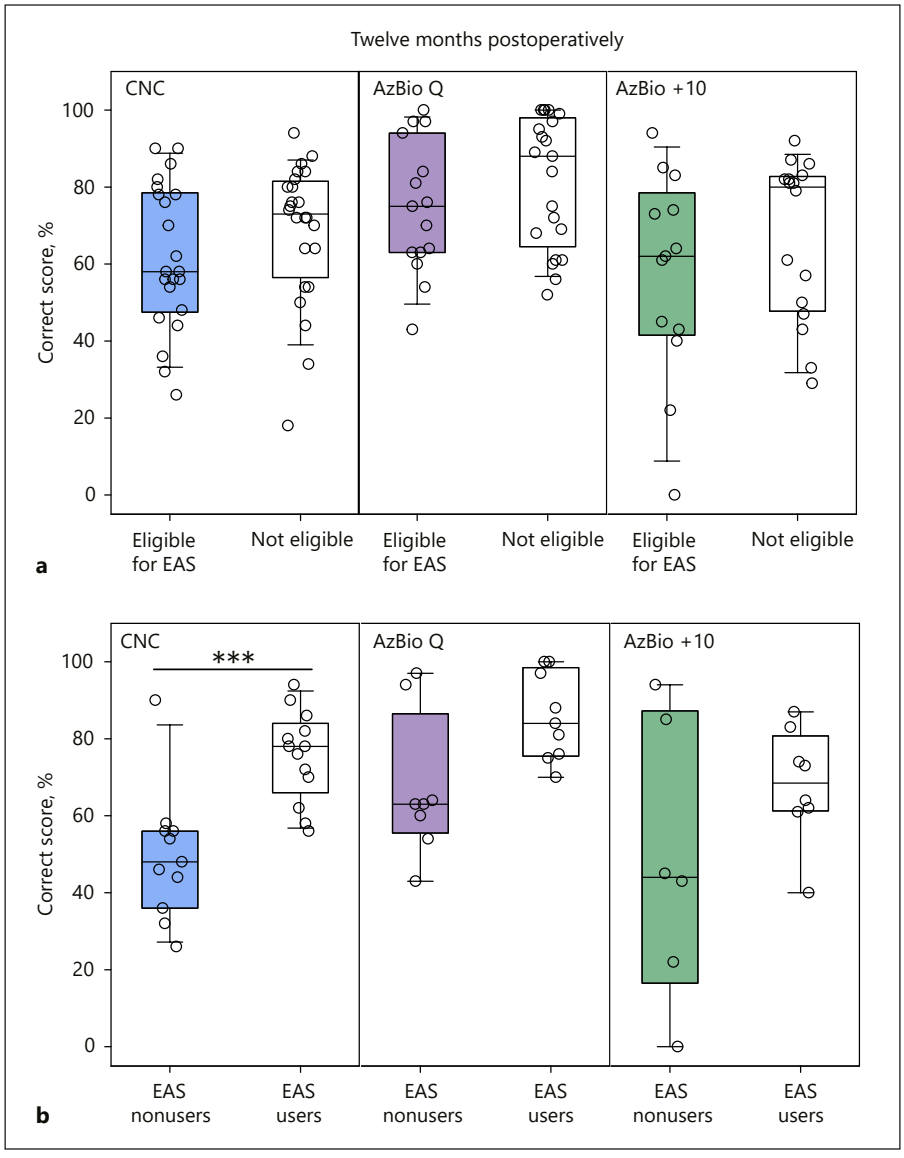

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Fig. 4. Box plots showing speech perception scores at the 12-month time point. **a** Comparison of patients who were eligible for EAS (left shaded boxes, $n = 22$) or not eligible for EAS (right open boxes, $n = 22$) on scores for CNC words (left plot), AzBio sentences in quiet (middle plot), and noise (right plot). **b** Comparison of patients who were eligible for EAS on CNC words (left plot), AzBio sentences in quiet (middle plot), and noise (right plot) based on whether they were EAS nonusers (left shaded boxes, $n = 11$) or EAS users (right open boxes, $n = 13$). Not all participants were tested on sentence materials. *** $p < 0.001$. EAS, electro-acoustic stimulation.

highly predictive of postoperative thresholds at 12 months, as shown by a Wilcoxon signed rank test due to nonnormal distribution of the data ($W = 1{,}272$, $n = 49$, $p < 0.0001$).

Discussion

When considering who would be eligible for EAS use at our center, relatively restrictive criteria were used. Using this definition, our EAS eligibility rates were 55.7% at 3 months and 51% at 1 year, similar to those in other studies using similar criteria [James et al., 2005; Friedmann et al., 2015; Moran et al., 2017]. We were unable to detect a difference in postoperative speech perception performance between the group which had enough preserved hearing to be eligible for EAS and the group that did not. These results suggest that eligibility for EAS on the basis of audiometric thresholds, at least the cutoffs chosen in the present study, may be insufficient to predict enhanced speech perception compared to traditional CI users in this sample of patients, even when tested in noise. Future studies are needed to determine whether different cutoffs or a measure other than the audiogram may be more predictive of outcomes.

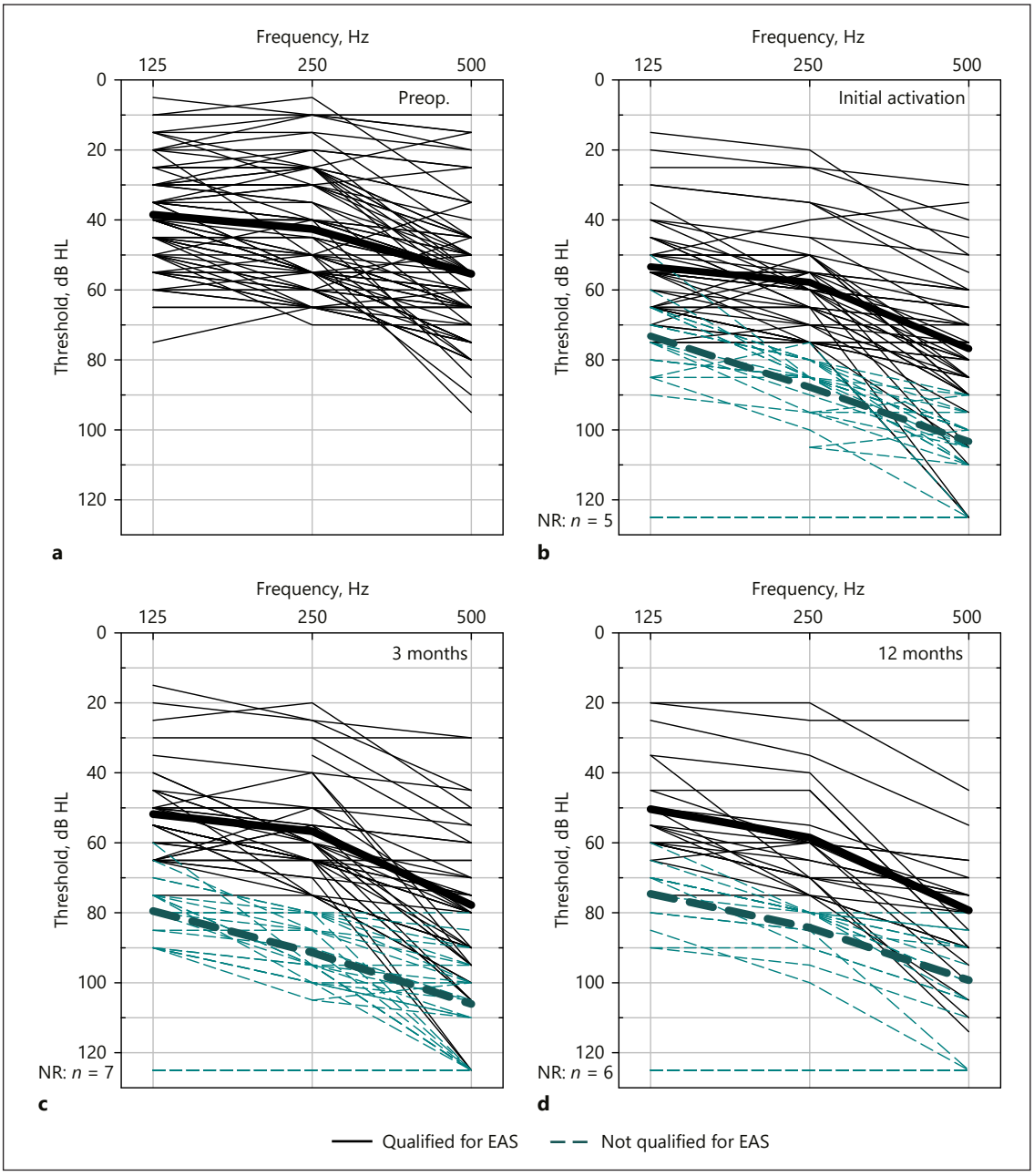

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Fig. 5. Low-frequency audiograms at four time points: preoperatively (**a**), at initial activation (**b**), 3 months postoperatively (**c**), and 12 months postoperatively (**d**). Individual audiograms of EAS-eligible patients are shown in grey (mean audiogram: black); audiograms for patients who were not eligible for EAS are shown in green (mean audiogram: dark green). EAS, electro-acoustic stimulation; HL, hearing loss; NR, no response at any frequency.

While some studies have found an advantage for speech perception with residual hearing [Carlson et al., 2011; Helbig et al., 2011, 2015; Büchner et al., 2017], others have not [Cosetti et al., 2013; Helbig et al., 2016; Hunter et al., 2016; O'Connell et al., 2017]. These conflicting findings might be due to the differences in the definition of EAS eligibility across studies or the presentation of test material from a single loudspeaker, which does not allow patients to take advantage of localization cues to separate speech from background noise [Gifford et al., 2013, 2014].

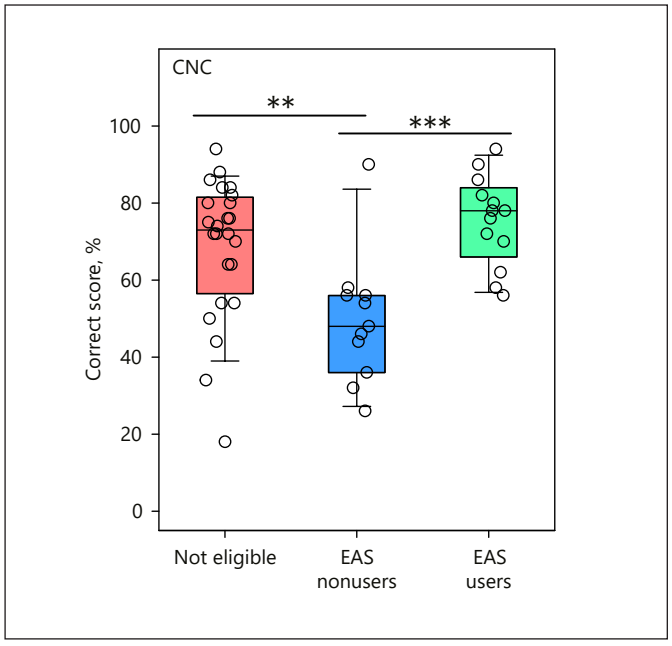

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Fig. 6. Box plots comparing CNC word scores 12 months postoperatively for patients who were not eligible for EAS (left box, n = 24), eligible for EAS but not using it (middle box, n = 11), and eligible for EAS and using it (right box, n = 13). ** $p < 0.01$, *** $p < 0.001$. EAS, electro-acoustic stimulation.

For the present study, EAS was accepted and worn in the everyday listening condition for approximately 50% of the patients who met these criteria. Lack of perceived benefit or fluctuating low-frequency hearing was the primary reason for lack of use. In practice, the benefits of aiding minimal residual hearing must be weighed against potential costs to the patient of earmolds, time, and frustration with a suboptimal fitting. In some chart notes, patients who had thresholds near the manufacturer-recommended cutoff for EAS noted no difference between an EAS and a fully electric map when trialing EAS in the center. Therefore, a fully electric map was used. Other patient preferences, such as cosmetics, off-ear processor use, and difficulty managing equipment also played a role in the lack of EAS use among patients who were eligible audiometrically. Incerti et al. [2013] notes three categories of patients who decline to use EAS: those who have enough residual hearing to not need it, those who have very little residual hearing and do not notice a benefit, and those who cite nonaudiologic reasons. In the present study, the first category of patients are included as using EAS because they used maps with cutoff frequencies higher than fully electric maps. The remainder of patients comprised the other two categories, with most having very little residual hearing.

Among patients who met the eligibility criteria for EAS use, the group who selected to use it (EAS users) performed significantly better on CNC word repetition at 1 year after activation than the group who selected not to use it (EAS nonusers). This result was not explained by any difference between the groups in LFPTA at 1 year, any demographic measure (sex, age at implantation, duration of deafness, age at test), or any preoperative measure (LFPTA, CNC scores). Since patients were allowed to select whether or not to use EAS, it remains unknown whether the group that chose not to use EAS would perform similarly to the EAS users if tested with EAS. Our laboratory is currently investigating this question. The EAS nonusers performed significantly worse on CNC words than the group without residual acoustic hearing, despite having better LFPTA and no other observed demographic differences (Fig. 6). That is, even when receiving equivalent treatment (fully electric stimulation), the group with better audiometric thresholds performed worse than the group with little to no measurable hearing. To our knowledge, there is a lack of literature surrounding the differences between patients who self-select to use or not use EAS. It may be that EAS nonusers self-select as such because their residual hearing is of poorer quality than that of EAS users. This may be representative of a neural substrate that is more degraded than that of the average CI user. Therefore, an audiogram may not be the best predictor of the underlying quality of residual hearing. Future research is needed to determine whether other measures of auditory function, such as spectral or temporal resolution, localization ability, or musical appreciation, better explain the decision to not use EAS. Objective measures such as fMRI, cortical auditory evoked potentials, and functional near-infrared spectroscopy may also provide valuable insights into patient preferences.

In this study, 51% of patients were eligible to use EAS 12 months postoperatively, demonstrating that preservation of low-frequency residual hearing is possible for some patients. However, outcomes were variable and a wide range of postoperative LFPTAs were seen, from near-total preservation to complete loss. These findings are consistent with those of others who have examined hearing preservation for standard-length electrode arrays [Gstoettner et al., 2006; Erixon et al., 2012; Campbell et al., 2016; Helbig et al., 2016; Hunter et al., 2016]. As in other studies, preoperative thresholds were highly predictive of postoperative thresholds [Carlson et al., 2011; Dalbert et al., 2016; Moran et al., 2017].

The current study is limited by the retrospective nature of the data. In order to understand more clearly who will benefit from and accept EAS, prospective studies are needed. If a difference in the quality of residual hearing is explanative of EAS benefit/acceptance, it would be important to devise a way to test hearing quality preoperatively. Given that fitting EAS is time-consuming and potentially costly for the patient if earmolds are needed, the ability to predict who will benefit from EAS would help audiologists to counsel patients most effectively and encourage use among those who are most likely to benefit. As cochlear implantation candidacy expands to include children with residual hearing, it will be important to determine whether EAS benefit and acceptance for this population are similar to or different from those in adults.

Conclusions

In this retrospective review of patients with residual hearing implanted with standard-length electrode arrays, we found the following: (1) One year postoperatively, 51% of patients were eligible to use EAS. However, no significant differences were detected between the group that preserved hearing (regardless of EAS usage) and the group that did not preserve hearing for postoperative speech perception, age, sex, or duration of HL. (2) One year postoperatively, approximately 50% of the patients eligible for EAS chose to use EAS. The primary reasons for not using EAS were poor audiometric thresholds noted by the audiologist or nonauditory reasons. Patients who chose to use EAS had significantly better word scores than those who did not, despite similar levels of hearing preservation. There were no significant differences in speech perception for sentences, either in quiet or noise.

Acknowledgement

We would like to thank the clinical audiology team at our center for help with data collection.

Statement of Ethics

Approval of this study and exemption from the consent process was obtained from our center's institutional review board (s19-01188).

Conflict of Interest Statement

D.R. Friedmann has previously served as a consultant for Cochlear Americas. The other authors have no conflicts of interest to declare.

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Author Contributions

E.R. Spitzer contributed to data collection, data analyses, and manuscript preparation. S.B. Waltzman, D.M. Landsberger, and D.R. Friedmann contributed to study design, data analyses, and manuscript preparation.

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