European Archives of Oto-Rhino-Laryngology (2025) 282:3005–3017
https://doi.org/10.1007/s00405-024-09185-9

OTOLOGY

Exploring the relationship between electrophysiological measures of the electrically evoked auditory brainstem response and speech perception outcomes post-cochlear implantation

Zhongyan Chen[1] · Qingling Bi[1] · Yong Lv[1] · Yang Liu[1] · Yuanyuan Tian[1] · Jianfeng Liu[1] · Wenjing Yang[1] · Yukun Zhou[2] · Weiluo Huang[3] · Yuan Li[1]

Received: 26 September 2024 / Accepted: 19 December 2024 / Published online: 3 January 2025

Abstract

Objectives This study examined the relationships between electrophysiological measures of the electrically evoked auditory brainstem response (EABR) with speech perception measured in quiet after cochlear implantation (CI) to identify the ability of EABR to predict postoperative CI outcomes.

Methods Thirty-four patients with congenital prelingual hearing loss, implanted with the same manufacturer's CI, were recruited. In each participant, the EABR was evoked at apical, middle, and basal electrode locations. The following EABR measures were analyzed: wave III and V input/output (I/O) function, latency, threshold, threshold$_{0.5\ \mu V}$ and Gibson scoring. Patients' speech perception abilities were assessed using the Mandarin Speech Perception (MSP) materials presented in quiet. The Categories of Auditory Performance (CAP) and Speech Intelligibility Rating (SIR) were also used to assess CI outcomes. A regression model was developed to explore the relationship between EABR and each speech measure, to identify parameters with significant predictive ability.

Results A significantly shorter eV latency, lower eV threshold, lower eV threshold$_{0.5\ \mu V}$ and steeper I/O slopes for both eV and eIII were observed when these responses were evoked at the apical electrode, compared to the middle and basal positions. Implantation age was significantly negatively correlated with bisyllables recognition rate ($R^2 = 0.20$, $p = 0.0194$). The eIII slope at the apical site and the eV slope at the basal site demonstrated the highest R2 values in positive correlation with CAP, both with $R^2 = 0.09$. Among the EABR parameters, the regression models based on MSP bisyllables recognition rate, basal eV latency, eV thresholds and threshold$_{0.5\ \mu V}$ recorded at the apical and middle positions were statistically significant.

Conclusions Our study identified an apex-to-base gradient in EABR responsiveness following prolonged CI use. The threshold and I/O slopes of EABR appear to be informative predictors of speech perception performance in CI users, especially in the low-to-middle frequency range. However, further validation is needed.

Keywords EABR (electrically evoked auditory brainstem responses) · I/O slope (amplitude growth function) · Auditory performance · Speech perception · Threshold

Introduction

Cochlear implantation (CI) is a safe effective method of rehabilitating children with congenital severe-to-profound hearing loss. By stimulating the spiral ganglion neurons directly instead of the cochlear hair cells, CI enables age-appropriate speech perception and production in these children. Despite this overall success, outcomes with this sensory device are characterized by wide variability [1–3]. The speech recognition level often varies from 5 to 95% under different testing conditions. For example, Firszt et al. [4] observed perception scores ranging from 2 to 87% (average, 42%)

✉ Yuan Li
yuanli0702@263.net

1 Department of Otolaryngology, China-Japan Friendship Hospital, Beijing, China

2 Department of Otorhinolaryngology Head and Neck Surgery, Children's Hospital, Capital Institute of Pediatrics, Beijing, China

3 YouHear Academy, Guangzhou, China

for quietly spoken monosyllabic words. In another study, 14 ~ 20% of those with unilateral CI implants had abnormal speech and language skills [5]. In general, the variability can attribute to many factors, include but are not limited to, age at onset of the hearing loss, stimulation of the auditory pathway prior to implantation, age at implantation, cochlear implant experience and auditory training, residual hearing, etc. However, above factors can only explain approximately 10–40% of the variance in speech perception results among CI users [6]. Therefore, further studies to identify additional key factors accounting for the speech perception variability are urgently needed [7–9]. The variation in CI outcomes may at least partially be due to differences in the auditory nervous system from the original electrode–neural interface, and to differences in the brainstem and even central processing among individual implant users [10]. Hence, it is imperative to investigate the differences of the auditory conduction pathway post-CI using objective methods.

The electrically evoked auditory brainstem response (EABR) is a testing method similar to the acoustically ABR, but it uses an electrical stimulus delivered directly to the cochlea to assess auditory brainstem function [11]. The III and V waves are considered the most reliable and consistent components of the EABR. EABR parameters include the threshold, amplitude, and latency of eIII and eV; grading systems such as those of Gibson et al. [12] and Walton et al. (2010) are used to assess the configuration of EABR waveforms [13–16].

Compared to these single-value parameters, the amplitude-growth curve, also called the amplitude growth function (AGF) or input/output function (I/O slope), is thought to be more informative for assessing neural synchrony. In animals, the EABR I/O function was related to the number of surviving auditory nerve fibers [17]. Theoretically, post-implant performance might be related to the number or status of the surviving auditory nerve fibers. Accordingly, it is reasonable to infer that the threshold or slope of the EABR I/O function might predict post-CI performance. Unfortunately, to our knowledge, there is no clear relationship of the EABR latency, threshold, or I/O slope with post-CI speech perception ability. Some research found no correlation between the threshold or I/O function and speech recognition [18–21], while others found that the I/O slope of the EABR is correlated with the postoperative CAP [22–24]. The latency of EABR wave V and the III–V interval were also reported to be associated with speech recognition [25]. However, due to differences in the study populations (pre- or post-lingual deafness, children or adults) and EABR testing method (intra-operative EABR, post-EABR using different electrodes), this makes it challenging to compare research outcomes and draw consistent conclusions.

In this study, we examined the post-EABR in a prelingual deafness population who received same manufactured CI. This study had two primary objectives: to explore the characteristics of waves III and V evoked from the apical, middle, and basal cochlear electrodes; and to compare the commonly used EABR parameters (latency, and threshold) with I/O function to identify which electrophysiological parameters best predict CI outcomes. This study tested the hypothesis that EABR I/O function better predicts postoperative CI outcomes than latency and threshold.

Materials and methods

Subjects

Thirty-four patients with 35 ears, all diagnosed with severe-to-profound congenital, bilateral, prelingual sensorineural hearing loss without any history of neurological or psychological disorders, with same manufactured CI were collected. We chose cochlear implants from the same brand to reduce the confounding effects caused by differences in electrode placement and speech coding strategies on the analysis results. Their age at implantation and testing ranged from 1.2 to 16 (mean, 5.1 ± 4) years and 4.3 to 22.4 (mean, 11 ± 5.6) years, respectively. The duration of implantation ranged from 1 to 15 (average, 5.9 ± 2.9) years. Table 1 summarizes the subjects' demographic data, etiology of deafness, and hearing mode, which includes bilateral CI, bimodal solutions (CI + hearing aid) or unilateral CI use.

Of the patients, 15, 14, and 5 were implanted with the Nurotron CS-10A, CS-10A™, and CS-20A™, devices, respectively. These Nurotron CI systems share the same implantation depth (22 mm), number of channels (24 channels with no. 1 located at the cochlea apex), and electrode interval (0.85 mm). All procedures performed in this study involving human participants were in accordance with the ethical standards of institutional and national research committees. The protocols and experimental procedures in this study were reviewed and approved by the China–Japan Friendship Hospital Ethics Committee. Informed consent was obtained from the subjects or their legal guardians before participation.

Assessment of speech and listening ability

The Mandarin Speech Perception (MSP) materials present in quiet were utilized to evaluate speech perception performance. Stimuli were presented in the sound field at 65 dBA via a single loudspeaker; subjects were seated directly facing the loudspeaker at a 1 m distance. The MSP system encompassed open-set tests for monosyllable (MONO) and disyllable (DSP) recognition, with the DSP list containing 35 items and the MONO list containing 50 items, each test resulting in a percentage score for speech recognition [26,

Table 1 Demographic information of subjects who participated in this study (n = 34)

Patient No	Gender M/F	Implanted Ear	Mode	Etiology	Type of CI	Type of Sound processor	Testing Age/Y	Implantation Age/Y	CAP	SIR	MONO	DSP	A-G	M-G	B-G
1	M	R	B		CS-10A	NSP-60B	4.8	2.2	4	2	0.4400	0.5000	3	3	2
2	F	R	B		CS-10A	Voyager	5.7	3	6	3	0.6200	0.8860	3	3	2
3	M	L	M	GJB2	CS-10A	Voyager	6.5	1.2	6	4	0.8200	0.8570	3	3	3
4	M	R	M	GJB2c.235del(p.Leu79Cysfs*3) and c.299_300del (p.His100Argfs*13)	CS-10A	Enduro	12.5	5.1	4	2	0.1200	0.1710	3	3	3
5	M	R	M		CS-10A	Enduro	16	5.1	6	4	0.7200	0.7710	3	3	2
6	F	R	M		CS-10A	Enduro	11	5.4	NA	NA	NA	NA	3	3	3
7	M	R	M		CS-10A	Enduro	21	10	5	4	0.6600	0.7430	3	3	2
8	F	R	M		CS-10A	Enduro	7	1.6	7	4	NA	NA	3	3	3
9	M	R	M		CS-10A	Enduro	22	7	5	3	0.7400	0.6290	3	3	2
10	F	R	M	LVAS, SLC26A4 chr:107330593;c.1174A > Ta	CS-10A	Enduro	15	8.3	5	2	0.3800	0.4570	3	3	3
11	M	R	B	EYA1 chr8:72127661; CNC narrowingb	CS-10A	Enduro	9.3	1.3	3	2	NA	NA	0	2	0
12	F	L	M		CS-10A	NSP-60B	16.2	13.1	7	4	0.8200	0.7710	3	3	3
13	F	R	M		CS-10A	Enduro	8	4.2	NA	NA	NA	NA	0	0	0
14	M	L	B	LVAS, SLC26A4 NM_00041:c[919-2A > G];[(2168A > G)]	CS-10A	Voyager	15	6	7	4	0.4600	0.5400	3	3	3
15	M	R	M	LVAS	CS-10A	NSP-60B	6.3	2	9	5	1.0000	1.0000	3	3	2
16	M	R	B	GJB2c.176_191del/c.9G > A	CS-10A(TM)	Voyager	8.8	2.9	6	5	0.8000	0.8290	3	3	3
17	M	R	M	GJB2	CS-10A(TM)	Voyager	4.5	1.4	6	4	0.7200	0.8000	3	3	3
18	M	L	B		CS-10A(TM)	Voyager	9.4	2.1	6	4	0.8600	0.8000	3	3	3
19	M	R	M	GJB2(235delC)	CS-10A(TM)	Voyager	13.7	5.4	6	4	0.8800	0.8860	3	3	3
20	F	L	B		CS-10A(TM)	NSP-60C	7.6	3.7	6	4	0.9400	0.9430	3	3	2
21	M	R	B		CS-10A(TM)	Voyager	13.8	6.6	5	2	0.6200	0.6000	3	3	2
22	F	R	M		CS-20A(TM)	Voyager	10.5	2.5	6	4	0.8800	0.8860	3	3	3
23	M	R	B		CS-10A(TM)	NSP-60C	22.4	14.8	5	3	0.6400	0.6290	3	3	3
24	F	R	BCI	GJB2	CS-10A(TM)	Voyager	4.7	1.8	9	5	1.0000	1.0000	3	3	3
25	F	R	M		CS-10A(TM)	Enduro	10.3	5.8	4	2	0.5400	0.5140	3	3	3
26	M	R	M		CS-20A(TM)	Voyager	7.3	2.4	5	3	0.6400	0.6570	3	3	3
27	M	L	M		CS-10A(TM)	Voyager	4.3	2.1	6	4	0.8600	0.9430	3	3	3
28	M	R	B		CS-20A(TM)	NSP-60C	6.3	2	9	5	0.9700	1.0000	3	3	3
29	F	L	M		CS-10A(TM)	Enduro	17	10	6	4	0.7400	0.8290	3	3	3
30	F	L	B	PTPN11 chr12:112926258; c.1391G > C	CS-20A(TM)	Voyager	6.7	1.5	7	4	0.8400	0.8570	3	3	3

Table 1 (continued)

Patient No	Gender M/F	Implanted Ear	Mode	Etiology	Type of CI	Type of Sound processor	Testing Age/Y	Implantation Age/Y	CAP	SIR	MONO	DSP	A-G	M-G	B-G
31	M	R	B		CS-10A(TM)	NSP-60B	16	10	NA	NA	NA	NA	3	3	3
32	M	R	B		CS-10A(TM)	NSP-60B	22	16	4	2	0.3800	0.3140	3	3	3
33	F	L	M		CS-10A(TM)	Enduro	6.5	1.5	6	3	0.6000	0.7140	NA	NA	NA
34	F	L	B		CS-20A(TM)	Enduro	6.3	5.3	7	5	0.9800	1.0000	3	3	2
24-L	F	L	BCI		CS-10A(TM)	Voyager	4.7	3.7	9	5	0.9200	1.0000	3	3	3

LVAS Enlarged Vestibular Aqueduct Syndrome, *CNC* cochlear nerve canal, *A* apical, *M* middle, *B* basal, *G* Gibson scoring, *NA* non available

27]. The Categories of Auditory Performance (CAP) and Speech Intelligibility Rating (SIR) scores were also used to evaluate auditory perception and speech production [28, 29]. The MSP, CAP and SIR assessments were conducted on the same day as the post-EABR recording.

EABR procedures

Post-EABR Recording: The EABR was recorded using Neuro-Audio NET 1.0.103.3 (Neurosoft, Ivanovo, Russia). The positive, negative, and ground electrodes were body surface button electrodes (impedances below 1 KΩ) placed at the forehead (at the hairline), contralateral shoulder, and mid-point between the eyebrows, respectively [22, 30]. The recording parameters were set to a bandwidth between 100 Hz and 3 kHz, averaged from 500 sweeps at each stimulus level with a time window of 15 ms and a rejection level of ± 10 μV. Testing began after patients fell asleep; if this was not possible, they were given chloral hydrate (30–80 mg/kg) to acquire stable and clear EABR waveforms.

Stimulus: Alternating biphasic pulses (Monopolar mode (MP1 + 2)) with a pulse width of 50 μs and an interphase gap of 5 μs were used as stimuli. These stimuli, presented at a stimulation rate of 30 Hz, were seamlessly delivered through an interface device for the Nurotron Processor Interface, and controlled by NuroSound 1.1.0 software. The stimulus intensity was decreased gradually for 10 cochlear loudness (CL) steps until EABR wave disappeared. This process was repeated twice for each stimulus intensity. Following this process, the stimuli were then increased for 20 CL steps. The EABR responses were recorded from the threshold level to the maximum comfortable level.

Testing electrodes: To explore the EABR characteristics from high- to low-frequency stimulation sites, EABR was obtained by applying electric stimulation at one apical, one middle, and one basal electrode (i.e., electrodes 1, 11, and 22) representing low, middle, and high frequencies, respectively.

EABR data processing and analysis

All EABR analyses were conducted by two professionals: an ear, nose, throat (ENT) specialist and a skilled audiologist. Their expertise and collaboration ensured accurate marking and evaluation of the eIII and eV.

Routine parameters: The degree of differentiation of EABR waveforms was quantified according to the Gibson scoring system, where a maximum score of three indicates the presence of distinct II, III, and IV–V waves, along with a V-wave amplitude exceeding 0.5 μV [12]. The latencies of eIII and eV at 20 CL above the threshold were recorded. Two kinds of threshold were adopted: threshold was achieved by identifying the precise intensity just before the amplitude dropped below 0.1 μV or when repeated, stable, and high-quality wave V responses could no longer be discerned; threshold$_{0.5\ \mu V}$ was defined as the intensity just before the amplitude fell below 0.5 μV. The response rate was determined by dividing the number of patients with a positive EABR response by the total number of subjects participating in the study.

AGF function (Fig. 2): To visualize the relationship between the stimulation level and the amplitudes of eIII and eV, I/O functions were constructed. A new slope fitting method proposed by Skidmore et al. [31] was adopted. Step 1: Plot the eIII and eV amplitudes against the stimulus current, measured in nanocoulombs (nC). Note that the Nurotron software uses CL as the unit for stimulus level, necessitating conversion to microamperes that are then multiplied by the pulse width. Step 2: Sliding window linear regression was performed. Briefly, a window consisting of four data points slid from the first of the four points (i.e. window 1) to the last of the four points. The maximum slope was selected from among all subsets of data points (i.e., windows). The maximum slope is the most reliable slope for comparison across various patient populations [31].

Statistical analysis

Statistical analyses were performed using R version 4.2.2 ggplot2 version 3.5.0. The I/O slopes of EABR waves III and V were calculated using the above sliding window method.

Figure 1 gives an example of the EABR obtained from apical, middle, and basal electrodes in two subjects (no. 11 and 14), and Fig. 2 shows how linear slopes were calculated.

The results are expressed as the mean ± standard deviation for parameters such as threshold, latency, and slopes. To compare the wave III and V threshold, latency and I/O slope among the apical, middle, and basal locations, paired *t*-tests were conducted. To analyze the correlation between speech assessment results and EABR data, the data was first processed to remove observations with missing values. A univariate regression analysis was then conducted on this data, examining the age at implantation, age at testing, the difference between these ages (Agediff), and each EABR data point. Subsequently, implantation age, testing age, and their difference were included as covariates in the regression model to analyze each EABR data point. We set statistical significance at $p < 0.05$.

Results

Among the 34 patients, 32 underwent cochlear reimplantation (RCI) surgery, all performed at our center by the same CI surgeon. One No.24 patient underwent a contralateral CI at the time of RCI. Follow-up was conducted 1–2 years after the RCI surgery to minimize the impact of the RCI surgery. EABR were acquired in 33 patients (34 ears), excluding patient No. 33 who did not undergo EABR. Two patients with partial or unsuccessful RCI were excluded from subsequent correlation analyses. Ultimately, complete electrophysiological data and auditory speech assessment results for CAP and SIR were collected from 28 individuals, with 27 also undergoing MSP evaluation. The etiology was confirmed in 12 subjects. Of the subjects, 19 opted to wear only a cochlear implant, while 14 preferred bimodal solutions (CI + hearing aid).

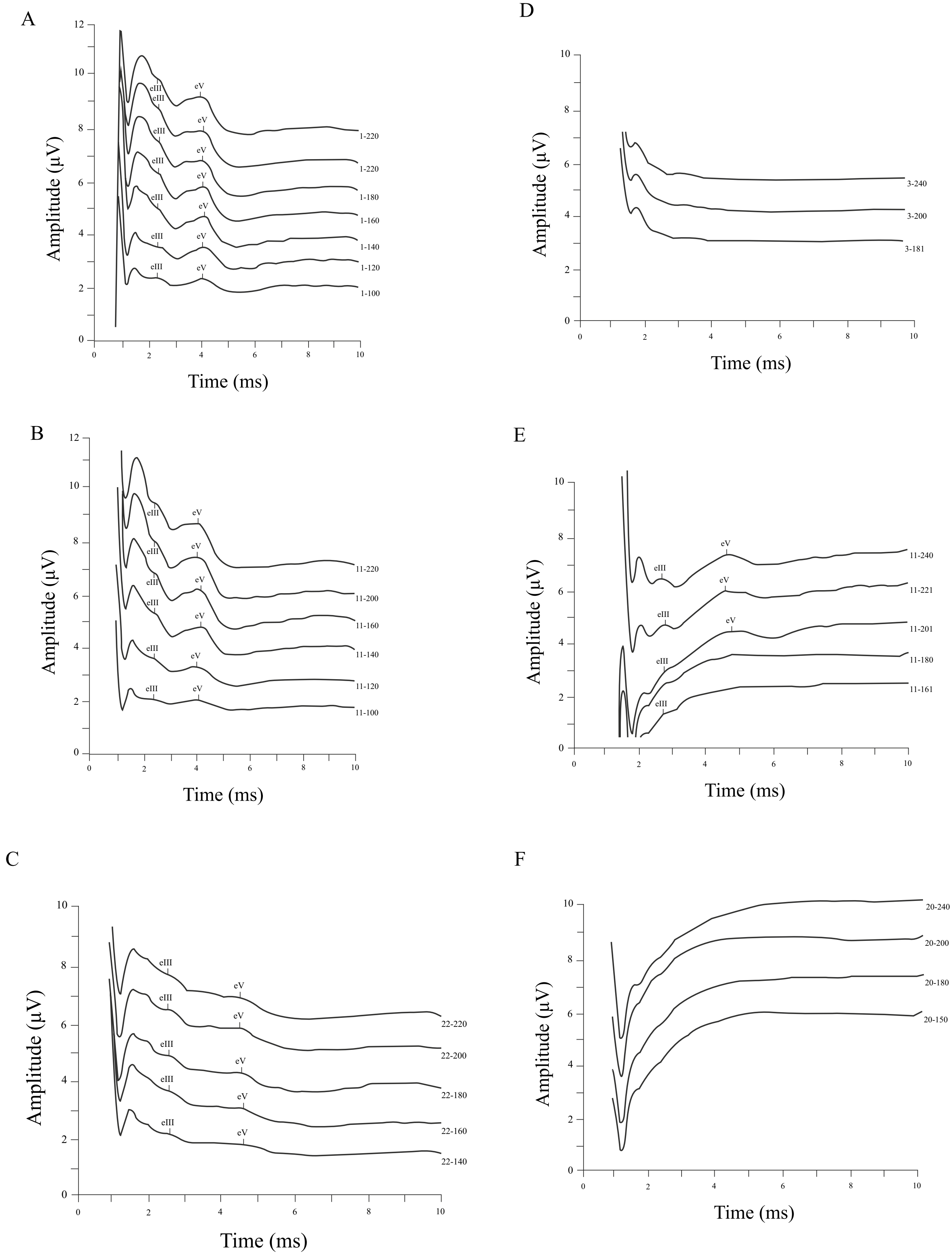
The overall EABR elicitation rate and waveforms

33 patients with 34 ears, except for subjects no. 13 (who had partial implantation during RCI with minimal rehabilitation training and no evoked EABR Gibson 0/0/0) and no. 11 (who showed cochlea new bone formation during RCI, cochlear nerve canal narrowing and large vestibular aqueduct syndrome with the EABR recorded only from the middle electrode, Gibson 0/2/0), had high-quality EABR waveforms recorded in all three locations, for an elicitation rate of 94.1% (32/34). The EABR of 24 ears was rated with a Gibson score of 3/3/3, whereas the remaining 8 ears were scored at 3/3/2. Figure 1 shows a representative good EABR waveforms recorded at electrodes 1, 11, and 22 in subjects No. 14 (CAP/SIR 7/4) and a poor waveform of No. 11, who had poorer speech perception and production (CAP/SIR 3/2).

The characteristics of latency, threshold and I/O slope of eIII and eV recorded from the apical, middle, and basal electrodes (Table 2)

The eIII and eV peak latencies, as evoked from the apex to middle and basal electrode positions, were 2.5 ± 0.4, 2.5 ± 0.3, and 2.5 ± 0.3 ms and 4.4 ± 0.4, 4.3 ± 0.4, and 4.5 ± 0.5 ms, respectively. The EABR eV threshold and threshold$_{0.5\ \mu V}$ were 15.8 ± 17.5, 16.1 ± 13.5, and 22.1 ± 20.4 nC and 20 ± 17, 24.1 ± 17.7, and 43.6 ± 26.6 nC, respectively, from apical to basal. The I/O slope calculated at eIII and eV was 0.06 ± 0.04, 0.04 ± 0.03, and 0.01 ± 0.01 and 0.1 ± 0.07, 0.07 ± 0.07, and 0.04 ± 0.03 from apical to basal, respectively.

No significant differences were found between electrode locations for eIII latency. However, the EABR latency evoked by the basal electrode was significantly longer than those evoked by the apical and middle sites. Based on the difference test results for the threshold, threshold$_{0.5\ \mu V}$, and AGF from three electrode sites presented in Table 2, statistically significant differences were observed between each pair of sites for the I/O slopes of eIII, eV, and eV threshold$_{0.5\ \mu V}$. The thresholds at the apical and middle sites are significantly


A
B
C
D
E
F
Amplitude (μV)
Time (ms)
eIII
eV
1-220
1-220
1-180
1-160
1-140
1-120
1-100
11-220
11-200
11-160
11-140
11-120
11-100
22-220
22-200
22-180
22-160
22-140
3-240
3-200
3-181
11-240
11-221
11-201
11-180
11-161
20-240
20-200
20-180
20-150

◂**Fig. 1** Sample EABR waveforms evoked from the apical (electrode 1, **A**), middle (electrode 11, **B**), and basal electrodes (electrode 22, **C**) from subject no. 14 (**A**–**C**) with CAP/SIR 6/4 and subject no. 11 (**D**–**F**), who had poorer speech perception and production (CAP/SIR: 3/2). *eIII* wave III, *eV* wave V

lower than at the basal site, while no significant difference is found between the apical and middle sites. Figure 3 illustrates that the median values for threshold and threshold$_{0.5\ \mu V}$ increase, while the I/O slopes decreases progressively from the apical to middle to basal sites. This statistically significant trend indicates a gradual change from the cochlea apex to the base.

Correlations of EABR variables with auditory and speech performance from apical to basal

Univariate regression analysis showed that age at implantation, Agediff (difference between testing age and implantation age), and various EABR parameters did not exhibit a significant correlation with CAP and SIR (shown in Supplement Table 1). The eIII slope at the apical site and the eV slope at the basal site demonstrated the highest R^2 values in positive correlation with CAP, both with $R^2 = 0.09$ (Fig. 4a–c). Subsequently, these variables were included as covariates in the regression model to analyze the relationship between each electrophysiological data point and the CAP and SIR. The results, summarized in Table 3, show that none of the EABR parameters, including the threshold and threshold$_{0.5\ \mu V}$ for eV, as well as the I/O slope for eIII and eV, demonstrated a meaningful correlation with CAP or SIR.

As for MONO and DSP, univariate regression analysis showed that implantation age negatively correlates with bisyllables recognition rates ($R^2 = 0.20$, $p = 0.0194$) (Fig. 4d). Agediff and other EABR parameters did not display a statistically significant correlation with either monosyllabic or bisyllabic word recognition rates (shown in Supplement Table 2).

In the regression model using implantation age and Agediff as covariates, among the EABR parameters, the regression models based on MSP bisyllables recognition rate, basal eV latency, eV thresholds, and threshold$_{0.5\ \mu V}$ evoked by the apical and middle electrodes were statistically significant (Table 4).

Discussion

Research on CI outcomes prediction has consistently been a central focus in the field. Current studies revolve around predicting outcomes through genetic analysis and the identification of pathogenic sites [32], while also analyzing various demographic, hearing loss, and surgery-related clinical factors to develop big data models using machine learning [33]. From an electrophysiological perspective, this study explored EABR parameters that strongly correlate with CI outcomes by examining the relationship between various electrophysiological parameters and postoperative speech recognition.

We found that the EABR I/O slope exhibited the strongest correlation with speech perception (CAP) compared to other parameters, consistent with the findings reported by Wang et al. [22]. The regression model based on the threshold$_{0.5\ \mu V,}$ overall threshold, and implantation age may have predictive value for bisyllabic word recognition. Although these results indicate the potential predictive capabilities of the EABR threshold and I/O slopes for CI outcomes, they lack statistical significance. The slope and threshold of the EABR reflect the number and activity of neurons in the auditory brainstem pathway [17]. Kubo et al. suggest that EABR parameters primarily influence hearing development during the initial period for CI recipients. In contrast, long-term speech perception outcomes depend more on the plasticity of the central auditory hierarchy than on the peripheral system [24]. This indicates that higher cortical electrophysiological data, such as MMN and the N1-P2 components of ERP, hold greater predictive value [24, 34]. Therefore, EABR measures are particularly useful for predicting outcomes in CI patients with cochlear nerve deficiency [35] or inner ear malformation [36], who exhibit a deficiency in the primary stage of auditory conduction process. In the patients analyzed for correlation in this study, both the apical and middle Gibson scores were three, indicating well-differentiated EABR waveforms and similar levels of auditory brainstem responsiveness. Moreover, these 28 patients exhibited no cochlear or internal auditory canal anomalies. Therefore, EABR did not demonstrate strong predictive capabilities for speech perception of this group patients. In fact, the reported associations between EABR parameters and speech recognition vary across studies. While some propose a link between EABR waveform scores and speech recognition, others failed to identify such correlations [19, 37]. Upon examining the reasons underlying these inconsistencies, it becomes apparent that the studies involve diverse populations, encompassing individuals with pre- and post-lingual deafness [19], and use disparate speech testing methods and materials, resulting in significant variation.

The only statistically significant finding was the negative correlation between age at implantation and bisyllabic word recognition, indicating that older age at implantation is associated with lower MSP speech recognition rates. This is consistent with the literature, which reports that age at the time of CI influences speech perception in children, with younger children showing more rapid improvement than older children [38]. However, a retrospective study by Kang et al. [39] found that the main factors affecting CI outcomes

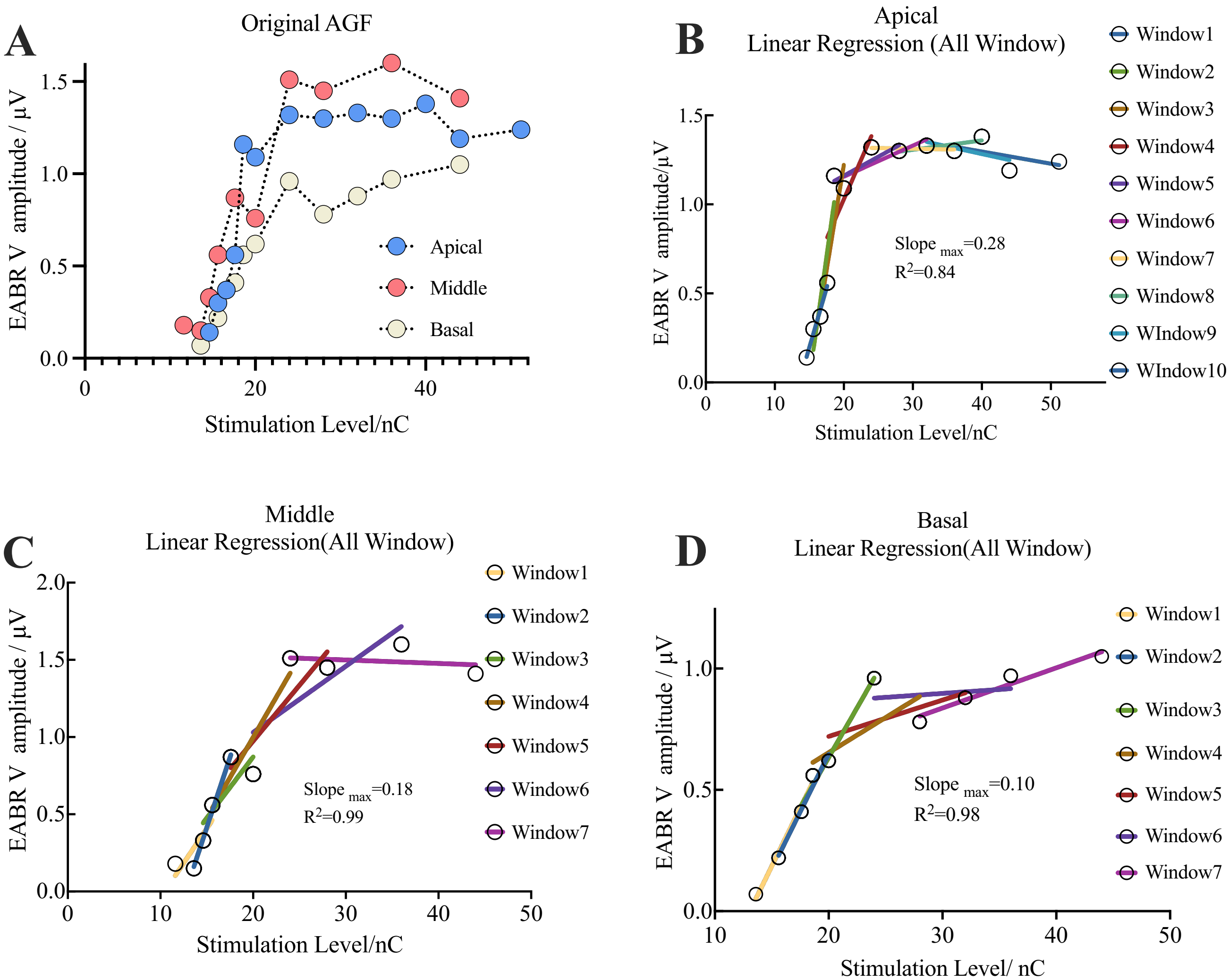


Fig. 2 A visual representation of the sliding window method for calculating the maximum slope of the EABR amplitude growth function. **A** All data points evoked by the apical, middle, and basal electrodes were plotted in a single figure, and a gradual change of I/O slope is apparent. **B**–**D** For each electrode, the maximum slope among all windows is selected

Table 2 Paired t-test results comparing latency, threshold, and I/O slope across three electrode sites

		Latency	AGF	Threshold	Threshold (0.5)
eIII	Apical VS Middle	P = 0.1038	P = 0.0020		
		t = 1.68	t = 3.37		
	Middle VS Basal	P = 0.2081	P = 0.0004		
		t = − 1.29	t = 3.97		
	Apical VS Basal	P = 0.8740	P < 0.0001		
		t = 0.16	t = 6.88		
eV	Apical VS Middle	P = 0.6995	P < 0.0001	P = 0.8448	P = 0.0004
		t = 0.39	t = 4.70	t = − 0.20	t = − 3.98
	Middle VS Basal	P = 0.0001	P = 0.0002	P = 0.0099	P < 0.0001
		t = − 4.40	t = 4.20	t = − 2.74	t = − 5.48
	Apical VS Basal	P = 0.0013	P < 0.0001	P = 0.0062	P < 0.0001
		t = − 3.55	t = 8.05	t = − 2.92	t = − 5.86

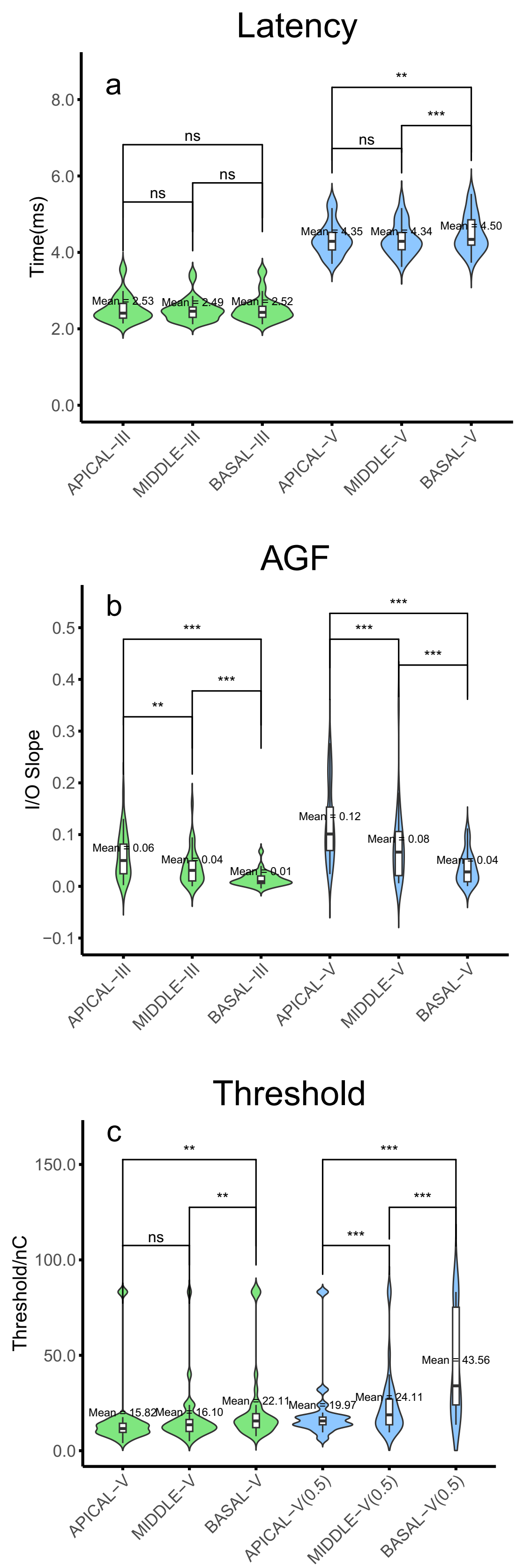


Fig. 3 This figure illustrates a gradual increase in eV latency of the ▸ EABR, recorded from the apical to basal electrodes of the CI (**a**). The lower two graphs display the threshold and I/O slope values of the EABR across various electrode locations, with both threshold and AGF slope showing a gradient from the apex to the base (**b**, **c**). $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$, $^{****}p<0.0001$

in prelingually deaf patients were perinatal problems, inner ear anomalies, narrow bony cochlear nerve canal, and intra-operative issues, rather than age at implantation. It is worth noting that this study used the CAP as a method for assessing speech recognition ability, which is relatively coarse.

We performed correlation analyses between the EABR responses in distinct frequency regions of the cochlea, ranging from the apex to the base, and overall speech recognition in recipients of cochlear implants. This revealed varying predictive effects of EABR due to electrodes being in different frequency bands.

This study analyzed two different thresholds: threshold was defined as the intensity just before the amplitude fell below 0.1 μV or when repeated, stable, and high-quality wave V responses disappeared, and threshold$_{0.5\ \mu V}$ was defined as the intensity just before the amplitude fell below 0.5 μV. Interestingly, the threshold$_{0.5\ \mu V}$ appears to have better correlations with MONO compared to the threshold. This may be because, in the early stages of low stimulation, although it is possible to elicit waveforms, the stimulus intensity is insufficient to generate an adequate level of neural excitation to produce practical effects. This is also consistent with the changes in slope. With the sliding window method, the maximum slope often occurs in the second or third window (in Fig. 2, the intensity–amplitude plot had a sigmoid shape). Therefore, when the threshold is set to 0.5, the III/V waves at this point are more mature/stable, theoretically leading to better correlations with auditory and speech performance.

Our study also investigated the trend in EABR parameters from apex to base. A significantly shorter latency, lower threshold, and steeper slope were observed in both eV and eIII evoked at the apical electrode compared with the middle and basal electrodes. This is the first report of this gradient in threshold and I/O slope. This is important for understanding how the implanted electrode array interacts with auditory function. These findings concur with previous reports [37, 40–42]. Animal experiments have demonstrated that, in the healthy cochlea following CI surgery, the organ of Corti and spiral ganglion in the apical region survive, while neurodegeneration occurs in the cochlea near the basal electrodes [43]. Therefore, this phenomenon may be due to a lower density of spiral ganglion cells in the basal (high-frequency) region of the cochlea compared to the apical (low-frequency) region, resulting in different neural responses between the apical

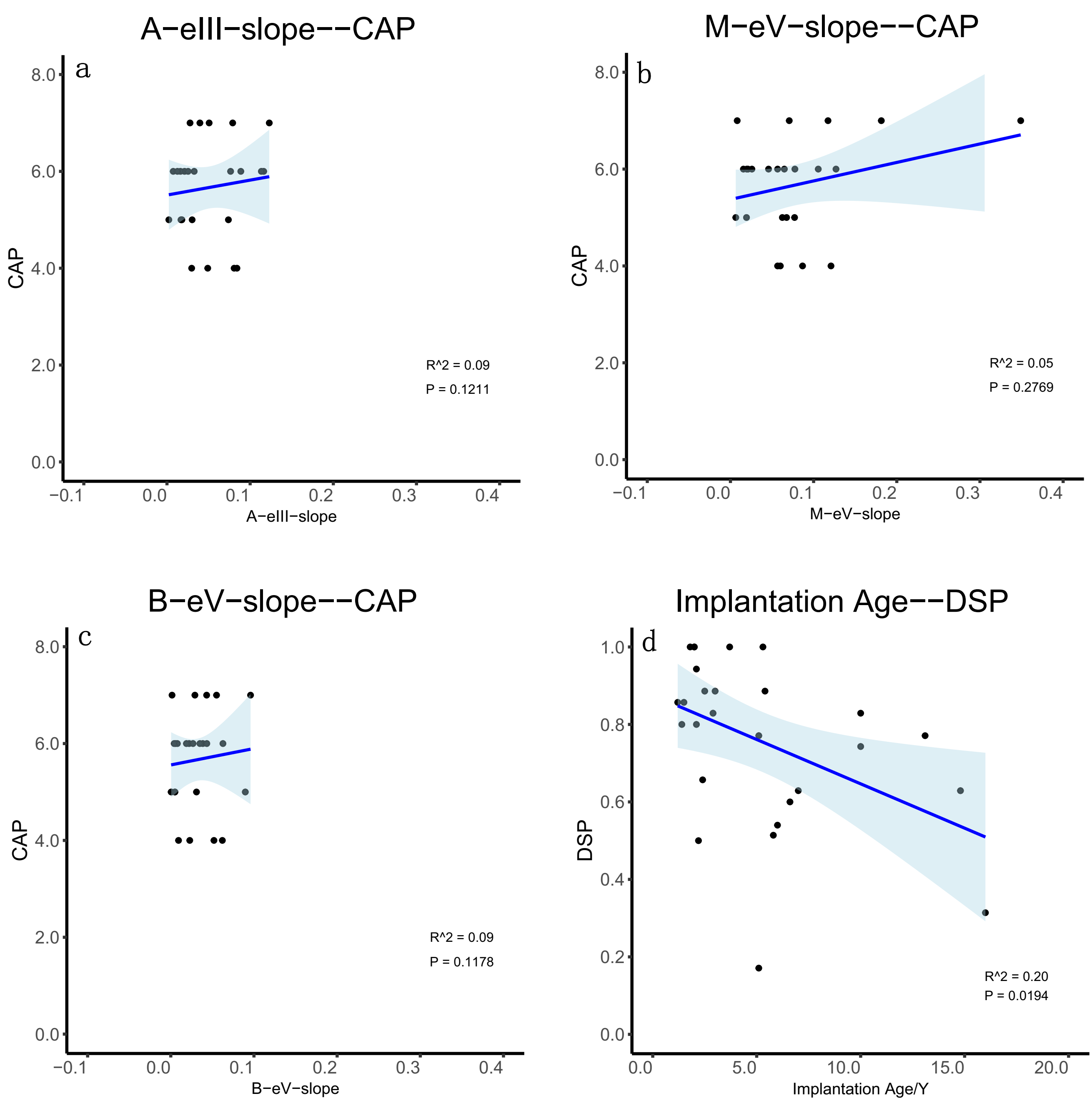


Fig. 4 Scatterplots showing the relationships between (**a**–**c**) CAP and EABR I/O slope, and **d** bisyllabic recognition rates and implantation age

and basal electrodes [40]. Children with prelingual deafness often retain residual hearing at low and intermediate frequencies, leading to improved performance in EABR recordings obtained from apical and middle electrodes. Current research indicates that the variation observed in auditory nerve responses along the apical–basal axis is associated with the underlying cause of prelingual hearing loss [44]. These findings provide valuable insights into the complex neural mechanisms underlying CI, which can inform the optimization of implant programming and ultimately improve auditory outcomes for individuals with prelingual deafness.

Nonetheless, it is important to acknowledge some limitations of our study. Firstly, the sample size was limited, preventing analysis of additional factors such as cognition, etiology of hearing loss, and duration of deafness, all of which have been shown to correlate with speech perception outcomes in CI patients. Secondly, only 34 prelingually deafened participants were included in the study. Although the correlation analysis included 28 participants, minimizing

Table 3 The regression model results for 28 cases of CAP and SIR, using implantation age and Agediff as covariates

	Location	CAP				SIR			
		R^2	P	β	P	R^2	P	β	P
eIII-slope	Apical	0.25	0.0697	7.14	0.2819	0.15	0.2648	2.56	0.5862
	Middle	0.26	0.0586	10.43	0.2162	0.15	0.2764	2.66	0.6579
	Basal	0.21	0.1176	3.09	0.9095	0.15	0.2532	12.04	0.5270
eV-slope	Apical	0.24	0.0820	3.32	0.3698	0.14	0.2999	0.17	0.9470
	Middle	0.26	0.0652	4.49	0.2544	0.14	0.2898	0.82	0.7705
	Basal	0.25	0.0758	8.91	0.3236	0.14	0.2889	1.95	0.7611
eV-threshold	Apical	0.22	0.1027	0.04	0.5775	0.14	0.2843	0.02	0.7182
	Middle	0.24	0.0787	0.05	0.3443	0.15	0.2555	0.02	0.5379
	Basal	0.22	0.1152	− 0.01	0.8076	0.14	0.2936	0.00	0.8148
eV-threshold(0.5)	Apical	0.24	0.0851	0.04	0.3954	0.14	0.2899	0.01	0.7708
	Middle	0.24	0.0794	0.03	0.3498	0.16	0.2233	0.02	0.4062
	Basal	0.22	0.1082	0.00	0.6566	0.15	0.2606	0.00	0.5638
eIII-latency	Apical	0.21	0.1158	0.22	0.8279	0.14	0.2807	0.29	0.6893
	Middle	0.21	0.1168	− 0.19	0.8656	0.14	0.2985	− 0.10	0.8999
	Basal	0.26	0.0599	1.24	0.2230	0.17	0.2129	0.64	0.3712
eV-latency	Apical	0.21	0.1154	− 0.15	0.8166	0.14	0.2993	− 0.05	0.9228
	Middle	0.21	0.1173	− 0.09	0.8902	0.14	0.2924	0.12	0.7991
	Basal	0.22	0.1025	0.35	0.5744	0.18	0.1794	0.48	0.2757

Table 4 The regression model results for 27 cases of DSP and MONO, using implantation age and Agediff as covariates

	Location	MONO				DSP			
		R^2	P	β	P	R^2	P	β	P
eIII-slope	Apical	0.15	0.2786	0.23	0.8147	0.25	0.0782	− 0.06	0.9505
	Middle	0.17	0.2321	− 0.86	0.4894	0.27	0.0569	− 0.98	0.4056
	Basal	0.16	0.2564	1.97	0.6185	0.26	0.0693	1.95	0.6059
eV-slope	Apical	0.15	0.2683	− 0.21	0.7055	0.26	0.0662	− 0.31	0.5461
	Middle	0.18	0.1955	− 0.54	0.3512	0.27	0.0597	− 0.42	0.4428
	Basal	0.15	0.2848	0.08	0.9539	0.25	0.0762	− 0.31	0.8081
eV-threshold	Apical	0.16	0.2604	0.01	0.6449	0.29	0.0441	0.01	0.2660
	Middle	0.17	0.2342	0.01	0.4992	0.30	0.0418	0.01	0.2450
	Basal	0.15	0.2834	0.00	0.9028	0.26	0.0658	0.00	0.5385
eV-threshold(0.5)	Apical	0.18	0.2012	0.01	0.3697	0.29	0.0476	0.01	0.3001
	Middle	0.19	0.1840	0.00	0.3158	0.31	0.0342	0.01	0.1822
	Basal	0.15	0.2848	0.00	0.9507	0.25	0.0780	0.00	0.9226
eIII-latency	Apical	0.15	0.2785	0.04	0.8132	0.26	0.0731	0.06	0.6983
	Middle	0.15	0.2852	0.00	0.9956	0.25	0.0781	0.01	0.9403
	Basal	0.18	0.2038	0.13	0.3788	0.27	0.0566	0.12	0.4017
eV-latency	Apical	0.15	0.2761	− 0.03	0.7831	0.25	0.0783	0.00	0.9668
	Middle	0.15	0.2841	0.01	0.9220	0.26	0.0742	0.03	0.7327
	Basal	0.17	0.2113	0.08	0.4052	0.30	0.0387	0.11	0.2188

the impact of RCI, we must still consider the relatively wide age range of the study population. Variations in patients' cognitive functions and comprehension abilities can introduce certain biases in the assessment of MSP. Further studies are needed to validate the reliability of models based on clinical data, the I/O slope, and the $\text{threshold}_{0.5\,\mu V}$ to predict post-CI outcomes.

In conclusion, our study identified an apex-to-base gradient in EABR responsiveness following prolonged CI use. The threshold and I/O slopes of EABR appear to be informative predictors of speech perception performance in CI users, especially in the low-to-middle frequency range. This work provides some clues for the future development of an electrophysiological model for predicting CI outcomes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00405-024-09185-9.

Acknowledgements We would like to express our appreciation to all the patients and their families who participated in this study. Their cooperation and unwavering support have been instrumental in the success of our research.

Author contributions Zhongyan Chen: conception or design of the study; data collection or acquisition. analysis or interpretation of data; drafting or critically revising the manuscript. Qingling Bi, Yong Lv: data collection or acquisition; analysis or interpretation of data. Yukun Zhou, Yang Liu, Yuanyuan Tian, Jianfeng Liu, Wenjing Yang Weiluo Huang: data collection or acquisition. Yuan Li: conception or design of the study. Final approval of the version to be published.

Funding National High Level Hospital Clinical Research Funding (No: 2024-NHLHCRF-PYII-03; 2023-NHLHCRF-PY-02).

Data availability The data is available via a publicly accessible repository at the following link: https://osf.io/typks/files/osfstorage/676fdf80a277b28d28af0e76.

Declarations

Conflict of interest The authors declare that they have no competing interests. The authors alone are responsible for the content and writing of this paper.

Ethics approval and consent to participate The study was supported by National High Level Hospital Clinical Research Funding (Grant No: 2024-NHLHCRF-PYII-03; 2023-NHLHCRF-PY-02). All procedures performed in studies involving human participants were in accordance with the ethical standards of the China-Japan Friendship Hospital Ethical Committee. Informed consent was obtained from all individual participants involved in the study.

Consent for publication Consents for publication were obtained from all participants.

References

1. Tyler RS, Kelsay DM, Teagle HF, Rubinstein JT, Gantz BJ, Christ AM (2000) 7-year speech perception results and the effects of age, residual hearing and preimplant speech perception in prelingually deaf children using the Nucleus and Clarion cochlear implants. Adv Otorhinolaryngol 57:305–310
2. Illg A, Haack M, Lesinski-Schiedat A, Buchner A, Lenarz T (2017) Long-term outcomes, education, and occupational level in cochlear implant recipients who were implanted in childhood. Ear Hear 38(5):577–587
3. Koch DB, Osberger MJ, Segel P, Kessler D (2004) HiResolution and conventional sound processing in the HiResolution bionic ear: using appropriate outcome measures to assess speech recognition ability. Audiol Neurootol 9(4):214–223
4. Firszt JB, Holden LK, Reeder RM, Waltzman SB, Arndt S (2012) Auditory abilities after cochlear implantation in adults with unilateral deafness: a pilot study. Otol Neurotol 33(8):1339–1346
5. Geers AE (2004) Speech, language, and reading skills after early cochlear implantation. Arch Otolaryngol 130(5):634–638
6. Skidmore J, Oleson JJ, Yuan Y, He S (2023) The relationship between cochlear implant speech perception outcomes and electrophysiological measures of the electrically evoked compound action potential. Ear Hear 44(6):1485–1497
7. Gantz BJ, Woodworth GG, Knutson JF, Abbas PJ, Tyler RS (1993) Multivariate predictors of audiological success with multichannel cochlear implants. Ann Otol Rhinol Laryngol 102(12):909–916
8. Gfeller K, Oleson J, Knutson JF, Breheny P, Driscoll V, Olszewski C (2008) Multivariate predictors of music perception and appraisal by adult cochlear implant users. J Am Acad Audiol 19(2):120–134
9. Guevara N, Hoen M, Truy E, Gallego S (2016) A cochlear implant performance prognostic test based on electrical field interactions evaluated by eABR (Electrical Auditory Brainstem Responses). PLoS One 11(5):e0155008
10. Abbas PJ, Brown CJ (2015) Assessment of responses to cochlear implant stimulation at different levels of the auditory pathway. Hear Res 322:67–76
11. Nada N, Kolkaila E, Schendzielorz P, El Mahallawi T (2022) Electrically evoked auditory brainstem response in cochlear implantation: what you need to know (short review). Egypt J Otolaryngol 38(67):1–8
12. Gibson WP, Sanli H, Psarros C (2009) The use of intra-operative electrical auditory brainstem responses to predict the speech perception outcome after cochlear implantation. Cochlear Implants Int 10(Suppl 1):53–57
13. Lammers MJ, van Eijl RH, van Zanten GA, Versnel H, Grolman W (2015) Delayed auditory brainstem responses in prelingually deaf and late-implanted cochlear implant users. J Assoc Res Otolaryngol 16(5):669–678
14. Sheffield SW, Haynes DS, Wanna GB, Labadie RF, Gifford RH (2015) Availability of binaural cues for pediatric bilateral cochlear implant recipients. J Am Acad Audiol 26(3):289–298
15. Kan A, Litovsky RY (2015) Binaural hearing with electrical stimulation. Hear Res 322:127–137
16. Gordon KA, Wong DD, Papsin BC (2013) Bilateral input protects the cortex from unilaterally-driven reorganization in children who are deaf. Brain 136(Pt 5):1609–1625
17. Miller CA, Abbas PJ, Brown CJ (1993) Electrically evoked auditory brainstem response to stimulation of different sites in the cochlea. Hear Res 66(2):130–142
18. Abbas PJ, Brown CJ (1991) Electrically evoked auditory brainstem response: growth of response with current level. Hear Res 51(1):123–137
19. Firszt JB, Chambers R, Kraus N (2002) Neurophysiology of cochlear implant users II: comparison among speech perception, dynamic range, and physiological measures. Ear Hear 23(6):516–531
20. Makhdoum MJ, Groenen PA, Snik AF, van den Broek P (1998) Intra- and interindividual correlations between auditory evoked

potentials and speech perception in cochlear implant users. Scand Audiol 27(1):13–20
21. Nikolopoulos TP, Mason SM, Gibbin KP, O'Donoghue GM (2000) The prognostic value of promontory electric auditory brain stem response in pediatric cochlear implantation. Ear Hear 21(3):236–241
22. Wang B, Guo X, Cao K, Wei C, Gao Z, Wang S (2023) Evaluation of auditory pathway by EABR before cochlear implantation and the postoperative effect analysis. Eur Arch Oto-rhino-laryngol 280(1):105–114
23. Wang Y, Pan T, Deshpande SB, Ma F (2015) The relationship between EABR and auditory performance and speech intelligibility outcomes in pediatric cochlear implant recipients. Am J Audiol 24(2):226–234
24. Kubo T, Yamamoto K, Iwaki T, Matsukawa M, Doi K, Tamura M (2001) Significance of auditory evoked responses (EABR and P300) in cochlear implant subjects. Acta Otolaryngol 121(2):257–261
25. Gallego S, Frachet B, Micheyl C, Truy E, Collet L (1998) Cochlear implant performance and electrically-evoked auditory brainstem response characteristics. Electroencephalogr Clin Neurophysiol 108(6):521–525
26. Fu QJ, Zhu M, Wang X (2011) Development and validation of the Mandarin speech perception test. J Acoust Soc Am 129(6):EL267–EL273
27. Zhu M, Wang X, Fu QJ (2012) Development and validation of the Mandarin disyllable recognition test. Acta Otolaryngol 132(8):855–861
28. Allen MC, Nikolopoulos TP, O'Donoghue GM (1998) Speech intelligibility in children after cochlear implantation. Am J Otol 19(6):742–746
29. Archbold S, Lutman ME, Marshall DH (1995) Categories of auditory performance. Ann Otol Rhinol Laryngol 166:312–314
30. Chen L, Zhang JG, Sun JW, Guo XT, Sun JQ (2021) Electrically evoked auditory brainstem responses to electrical stimulation at round window membrane in congenitally deaf children at different ages. Int J Pediatr Otorhinolaryngol 148:110821
31. Skidmore J, Ramekers D, Colesa DJ, Schvartz-Leyzac KC, Pfingst BE, He S (2022) A broadly applicable method for characterizing the slope of the electrically evoked compound action potential amplitude growth function. Ear Hear 43(1):150–164
32. Eppsteiner RW, Shearer AE, Hildebrand MS et al (2012) Prediction of cochlear implant performance by genetic mutation: the spiral ganglion hypothesis. Hear Res 292(1–2):51–58
33. Skidmore J, Xu L, Chao X et al (2021) Prediction of the functional status of the cochlear nerve in individual cochlear implant users using machine learning and electrophysiological measures. Ear Hear 42(1):180–192
34. Berger JI, Gander PE, Kim S et al (2023) Neural correlates of individual differences in speech-in-noise performance in a large cohort of cochlear implant users. Ear Hear 44(5):1107–1120
35. Yamazaki H, Leigh J, Briggs R, Naito Y (2015) Usefulness of MRI and EABR testing for predicting CI outcomes immediately after cochlear implantation in cases with cochlear nerve deficiency. Otol Neurotol 36(6):977–984
36. Zhu HY, Chen L, Hou XY et al (2022) Electrically evoked auditory brainstem responses in deaf patients with Mondini malformation during cochlear implantation. Eur Arch Oto-rhino-laryngol 279(10):4847–4852
37. Lundin K, Stillesjo F, Rask-Andersen H (2015) Prognostic value of electrically evoked auditory brainstem responses in cochlear implantation. Cochlear Implants Int 16(5):254–261
38. Zwolan TA, Ashbaugh CM, Alarfaj A et al (2004) Pediatric cochlear implant patient performance as a function of age at implantation. Otol Neurotol 25(2):112–120
39. Kang DH, Lee MJ, Lee KY, Lee SH, Jang JH (2016) Prediction of cochlear implant outcomes in patients with Prelingual deafness. Clin Exp Otorhinolaryngol 9(3):220–225
40. Gordon KA, Papsin BC, Harrison RV (2007) Auditory brainstem activity and development evoked by apical versus basal cochlear implant electrode stimulation in children. Clin Neurophysiol 118(8):1671–1684
41. Said Abdelsalam NM, Afifi PO (2015) Electric auditory brainstem response (E-ABR) in cochlear implant children: effect of age at implantation and duration of implant use. Egypt J Ear Nose Throat Allied Sci 16(2):145–150
42. Bayrak S, Mutlu B, Kirkim G, Serbetcioglu B (2019) Examination and comparison of electrically evoked compound action potentials and electrically evoked auditory brainstem response results of children with cochlear implantation without inner ear anomaly. Turkish Arch Otorhinolaryngol 57(2):81–85
43. Kang SY, Colesa DJ, Swiderski DL, Su GL, Raphael Y, Pfingst BE (2010) Effects of hearing preservation on psychophysical responses to cochlear implant stimulation. J Assoc Res Otolaryngol 11(2):245–265
44. Propst EJ, Papsin BC, Stockley TL, Harrison RV, Gordon KA (2006) Auditory responses in cochlear implant users with and without GJB2 deafness. Laryngoscope 116(2):317–327