Audiology and
Neurotology

Research Article

Audiol Neurotol 2023;28:294–307
DOI: 10.1159/000529797

Received: October 17, 2022
Accepted: February 13, 2023
Published online: March 23, 2023

Direct Elicitation of Cortical Auditory Evoked Potentials by Electrical Stimulation and Their Use to Verify the Most Comfortable Level of Stimulation in Cochlear Implant Users

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Keywords

Cochlear implant programming · Event-related potentials · Cortical auditory evoked responses · Objective measures · Most comfortable level

Abstract

Introduction: This study was designed to investigate the use of electrically evoked cortical auditory evoked potentials (eCAEPs) as a tool for cochlear implant (CI) verification, the relationships between the site and intensity of stimulation and the detection rates and morphologies of eCAEPs as well as investigate whether correlations exist between the morphologies of eCAEPs and speech perception in quiet and in noise, duration of hearing loss, age at implantation, whether the hearing loss bilateral or single-sided and the electrode current level required to elicit MCL stimulation. ***Methods:*** 32 adult unilateral CI users with postlingual hearing loss were enrolled. The stimuli were 1 kHz biphasic alternating pulses and were presented at either the behaviorally measured MCL or 50% of this value ($MCL_{0.5}$) via the CI fitting software. Pulses were directed to apical, medial, or basal electrodes. CAEPs were recorded from a scalp electrode placed at the vertex, low forehead, and contralateral mastoid and were evaluated by two electrophysiologists. ***Results:*** Overall, eCAEPs could be detected in 31/32 users when stimulating at MCL, and in 29/32 users when stimulating at $MCL_{0.5}$. The detection rates were 31, 31, and 28/32 for apical, medial, and basal stimulation at MCL, and 29, 29, and 26/32 at $MCL_{0.5}$. Significant differences in eCAEP amplitudes and latencies were observed across electrodes and stimulation levels. No significant correlations were found between eCAEP latencies and amplitudes and user age, duration of deafness prior to CI surgery, or with bilateral versus single-sided hearing loss, nor with the charge level required to elicit MCL, or with speech perception scores in quiet. Peak latencies correlated with speech perception scores in some configurations of speech-in-noise. ***Conclusion:*** eCAEPs can readily be elicited in the majority of adult CI users and show normal waveform characteristics at stimulation levels corresponding to MCL, as well as at basal, medial, and apical electrode stimulation sites. Neither the latencies nor amplitudes of eCAEPs are confounded by variables of age, duration of deafness prior to CI surgery, or the laterality of hearing loss. eCAEPs are a useful, objective method evaluate sound perception in CI users.

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Introduction

Cochlear implantation (CI) is the treatment of choice for rehabilitation of severe-to-profound hearing loss. CI programming traditionally relies on behavioral responses, in which the user provides feedback about the percepts elicited by electrode stimulation. This feedback is used to establish the basic programming parameters, such as the hearing threshold (T) and the most comfortable level (MCL) of stimulation. This method works well for users who are able to provide accurate and consistent feedback but is more troublesome in populations who are unable to do so, such as young children or individuals with cognitive comorbidities. This has spurred to development of objective measures of stimulation-induced hearing.

Objective measures which have been used in clinical settings include the electrically evoked compound action potential (eCAP), the electrically evoked reflex threshold (eSRT), and the electrically evoked auditory brainstem response (eABRs). Although promising results have been found, each of these methods presents its own limitations. Evoked compound action potential thresholds (Ts) do not correlate strongly with behaviorally measured Ts or MCLs [Brown et al., 1999; Gordon et al., 2004; Polak et al., 2005; Lundin et al., 2015; de.Vos et al., 2018], nor are they deemed to be good predictors of speech discrimination [Abbas and Brown, 2015]. eSRT correlates well with MCLs, both in pediatric and adult CI users [Polak et al., 2005, 2006; Walkowiak et al., 2011; Kosaner et al., 2018] but is adversely affected by middle ear abnormalities and stapedius muscle dysfunction [Spivak and Chute, 1994]. Furthermore, eSRT may not be present in all individuals, despite them having normal middle ear and auditory nerve function, and when it is present, the stimulation level required to elicit it may exceed MCL [Battmer et al., 1990; Spivak and Chute, 1994; Hodges et al., 1997; Bresnihan et al., 2001; Caner et al., 2007]. eABR also correlates poorly with behaviourally derived T and MCL [Brown et al., 1999; Gordon et al., 2004; Lundin et al., 2015].

Cortical auditory evoked potentials (CAEPs) are event-related potentials which follow the cochlear nerve, auditory brainstem, and middle-latency responses [Stapells, 2002]. Unlike the other evoked potentials mentioned above, CAEPs are measurements of auditory cortical function and are therefore more likely to represent conscious sound perception. There are multiple CAEPs, including the P1-N1-P2 complex, P300, and mismatch negativity (MMN) [Stapells, 2002]. The P1-N1-P2 complex is the most frequently used CAEP in CI research, and here, we use the term CAEP to refer to this complex.

Acoustically evoked CAEPs (aCAEPs) have been successfully used to evaluate the benefits of amplification in children and in adults [Purdy et al., 2001; Korczak et al., 2005; Sharma et al., 2005; Golding et al., 2007; Alvarenga et al., 2012; Chang et al., 2012; Glista et al., 2012]. Furthermore, CAEPs correlates well with speech perception scores and hearing thresholds in adults and pediatric CI users [Rance et al., 2002; Sharma et al., 2016; Legris et al., 2018; Mao et al., 2018]. In CI users, aCAEP thresholds (Ts) strongly correlate with behavioral Ts [Abbas and Brown, 2015; Visram et al., 2015]. Most recently, aCAEPs have been used to verify MCLs and guide MCL adjustments in adults CI users with either single-sided deafness (SSD) or bilateral deafness [Távora-Vieira et al., 2018, 2022a, 2022b] and also in children whom CI map was created through eSRT measurement [Kosaner et al., 2018].

aCAEPs have some limitations when used in CI mapping. These include a lack of electrode specificity, the requirement for masking of the contralateral ear in cases of asymmetrical hearing loss, the need for a speaker set-up and a sound booth, and the fact that responses may be influenced by factors introduced by the audio processor such as delay and reverberation.

Recently, studies have investigated the use of CAEPs evoked via direct cochlear stimulation by direct control of the CI electrode, rather than via presentation of sound to the audio processor microphone [Kranick et al., 2021; Távora-Vieira et al., 2021; Callejón-Leblic et al., 2022; Deniz et al., 2022]. This technique has come to be known as the electrically evoked CAEP (eCAEP). These studies have demonstrated that eCAEPs can be evoked in most CI users that the waveform morphology is independent of both stimulus burst duration and CI electrode position [Kranick et al., 2021] and that they have good correlation with the aCAEP waveforms [Távora-Vieira et al., 2021]. Deniz et al. [2022] compared two CI maps: one in which the MCLs were based on eSRT measures and another where the MCLs were adjusted to a level where eCAEP could be recorded. It was found that MCLs did not differ significantly between the two CI maps neither did the participants' performance, and the authors indicated that eCAEPs could be preferred option as an objective tool for establishing MCLs [Deniz et al., 2022].

As it is a relatively new technique, the literature on the use of eCAEP to investigate and optimize CI mapping is scarce, and little is known about the correlation of eCAEPs with behavioral measures. The goal of this study was to investigate the relationships between the site and intensity of stimulation and the detection rates and morphologies of eCAEPs. Stimulation was provided at two levels: at the behaviorally derived MCL and at half of this level. Stimulation was also provided at three electrode sites: basal, medial, and apical. The secondary goals of this study were to investigate whether correlations exist between the

Table 1. Patient information table

Subject ID	Age, years	Gender	Duration of deafness, years	Onset	Etiology	Prior treatments tried	Type of implant	Type of electrode	Implanted ear	Time since implant months
1	79.5	M	0.3	Sudden	ISSNHL	HA + WiFi + Baha	CONCERTO	Flexsoft	R	102
2	73.3	M	0.6	Sudden	Head trauma	None	SYNCHRONY	FLEX28	R	28
3	68.5	M	20	Sudden	MD	None	SYNCHRONY	FLEX28	R	14
4	58.6	F	41	Sudden	Mumps	HA + WiFi + Baha	SONATAti100	Standard	L	142
5	67.7	M	0.5	Sudden	Meningitis	None	SYNCHRONY	Standard	R	15
6	48.1	M	26	Gradual	Progressive SNHL	HA	SYNCHRONY	FLEX28	R	43
7	55.3	M	45	Birth	Incomplete partition	HA	SYNCHRONY	FLEX28	L	47
8	43.9	M	42	Birth	Neuropathy	HA	SYNCHRONY	FLEX28	R	20
9	71.5	F	30	Sudden	Unknown	HA	CONCERTO	Standard	R	47
10	78.0	M	35	Sudden	ME surgery	HA + WiFi + Baha	CONCERTO	FLEX24	R	99
11	70.4	M	10	Gradual	MD	HA	SYNCHRONY	FLEX28	L	56
12	49.0	F	48	Sudden	German Measles	HA	SYNCHRONY	FLEX28	L	10
13	76.3	F	20	Gradual	Progressive SNHL	HA	SYNCHRONY	FLEX24	R	32
14	71.9	M	50	Sudden	Head trauma (explosion)	HA	SYNCHRONY	FORM19	R	16
15	71.0	F	60	Gradual	Otosclerosis	HA	SYNCHRONY	FLEX28	R	11
16	33.0	F	20	Sudden	ISSNHL	none	SYNCHRONY	FLEX28	R	14
17	37.8	F	4	Sudden	ISSNHL	HA	SYNCHRONY	FLEX28	R	29
18	85.7	M	2	Sudden	ISSNHL	HA	CONCERTO	FLEX28	L	115
19	72.8	M	6.5	Sudden	Stroke	HA	SYNCHRONY	FLEX28	L	5
20	75.1	F	3	Sudden	ISSNHL	HA	SYNCHRONY	FLEX28	L	104
21	65.1	M	17	Sudden	ISSNHL	none	SYNCHRONY	FLEX28	L	80
22	83.9	M	40	Sudden	Progressive SNHL	HA	SYNCHRONY	FLEX28	L	105
23	83	M	40	Gradual	Progressive SNHL	HA	SYNCHRONY	FLEX28	R	119
24	40.2	F	32	Gradual	Progressive SNHL	HA	SYNCHRONY	FLEX28	L	102
25	86.1	M	25	Gradual	Noise exposure	HA	SYNCHRONY	FLEX28	R	74
26	39.9	F	7	Sudden	ISSNHL	None	SYNCHRONY	FLEX28	R	112
27	80.5	F	7	Sudden	ISSNHL	CROS	SYNCHRONY	FLEX24	R	92
28	85.2	M	53	Gradual	Otosclerosis	HA	SYNCHRONY	FLEX28	R	98
29	61.9	F	61.9	Birth	Congenital	HA	SYNCHRONY	FLEX28	R	121
30	93.2	F	7	Sudden	ISSNHL	CROS	SYNCHRONY	FLEX28	R	74
31	45.7	F	6	Sudden	ISSNHL	HA	SYNCHRONY	FLEX28	R	41
32	71	F	18	Gradual	Cholesteatoma	HA	SYNCHRONY	FLEX28	R	25

ISSNHL, idiopathic sudden sensorineural hearing loss; MD, meniere disease; ME, middle ear; SNHL, sensorineural hearing loss.

morphologies of eCAEPs and speech perception in quiet and in noise, as well as with the duration of hearing loss, the age at implantation, with whether the hearing loss is bilateral or single-sided and the electrode current level required to elicit MCL stimulation.

Materials and Methods

Ethics

This study was designed and conducted in accordance with the Declaration of Helsinki, and ethics approval was obtained from the South Metropolitan Health Service, Human Research Ethics

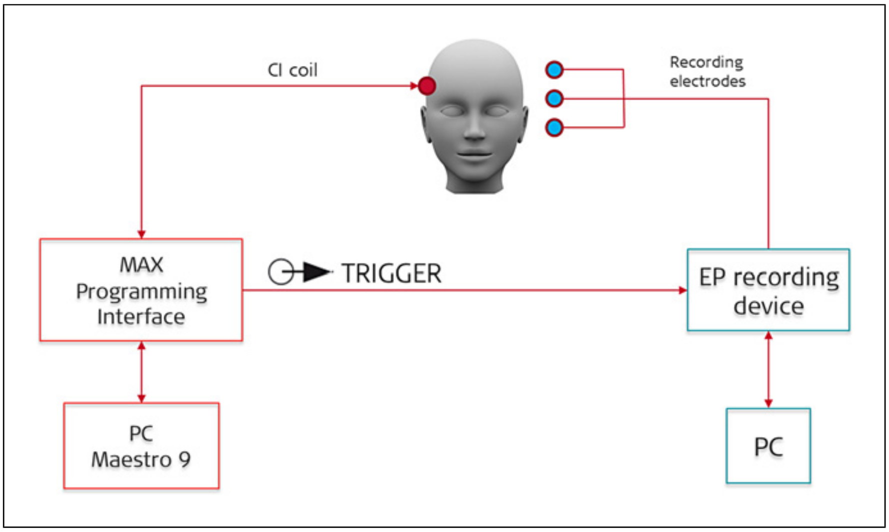

Fig. 1. eCAEP recording setup.

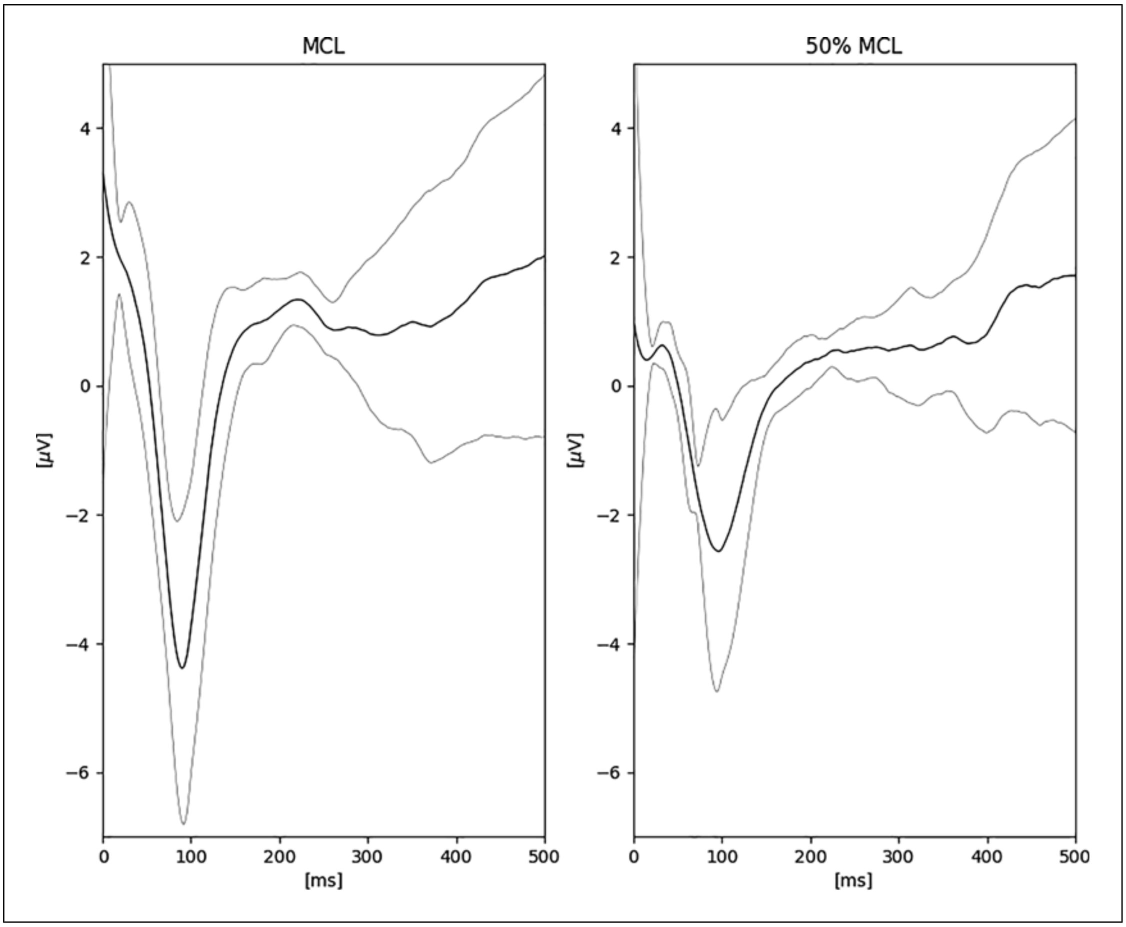

Fig. 2. eCAEP waveform averaged for the entire group at MCL and $MCL_{0.5}$.

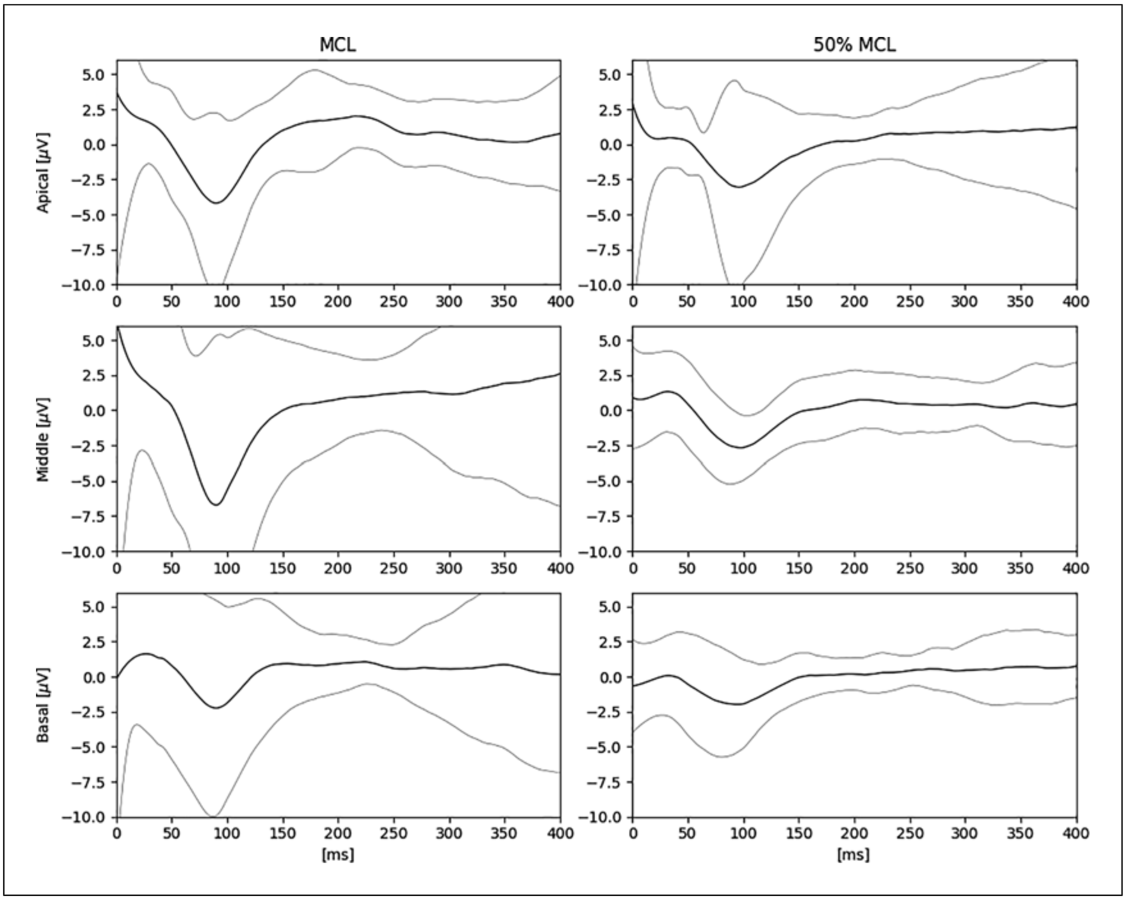

Fig. 3. eCAEP waveform averaged for the entire group per electrode at MCL and $MCL_{0.5}$.

Committee (reference number 3258). Written informed consent was obtained from all subjects.

Participants

The study included 32 adult unilateral CI users (17 male; 15 female) aged 33–93 years old (median = 73.3). 12 were CI users with SSD and 20 had bilateral hearing loss. 22 had a CI on the right ear and 10 on the left ear. All had postlingual deafness and had worn hearing aids prior to receiving a CI. Participants had CI experience of 5 months to 12 years and a duration of deafness prior to CI surgery of 4 months–62 years (median = 77 months). They all used their CIs for more than 8 h a day as per data logging. The inclusion criteria were: to be a user of MED-EL CI devices (MED-EL GmbH, Innsbruck, Austria), to have at least 6 weeks of post-activation CI usage, to be able to sit relaxed but awake for the time taken for the measurement, and to provide informed consent. See Table 1 for demographics.

eCAEP Testing

eCAEPs were recorded with the Bio-logic Navigator Pro (Natus, US), and the stimulus was presented through MAESTRO 9.0.1 using the eABR task. The signal was synchronized via a trigger cable connecting the CI Programming Interface and the Bio-Logic equipment. A three-electrode montage was used, with the ground electrode placed on the low forehead (G), the reference electrode (−) placed on the contralateral mastoid, and the active (+) electrode placed on the vertex (Fz) (shown in Fig. 1). Stimuli consisted of an electrical burst with a duration of 70 ms presented at rate of 0.9 Hz composed by a series of biphasic symmetric alternated pulses having 40 μs phase duration at 1 kHz stimulation rate. Stimuli were presented at electrode 1 or 2 (apical), electrode 5 or 6 (middle), and electrode 10 or 11 (basal). The stimuli were presented at either the behaviorally measured MCL or 50% of this value ($MCL_{0.5}$). The recording electrode impedance was kept <5 kΩ and the impedance differences between the electrodes were maintained at < 2 kΩ. Stimulation continued until 100 valid averages were taken. The signal was analog bandpass filtered from 0.3 Hz to 100 Hz, with a notch filter at 60 Hz, if required. The time window for the recording was 533 ms. The subjects were awake during the measurement and were reading or watching a silent movie. They were instructed to relax as much as possible to avoid muscle artifact.

eCAEP data were exported in txt for further analysis using Python 3.9. Peaks P1-N1-P2 on eCAEP were manually identified by two experienced electrophysiologists looking at positive (for P1 and P2) and negative (for N1) peaks at the expected latency of P1-N1-P2 and comparing MCL and $MCL_{0.5}$ responses on the same stimulating electrode. If multiple candidate response peaks were detected in the

Table 2. Latency values in ms for 100% MCL, 50% MCL and the difference between 100% MCL and 50%

	MCL				50% MCL				MCL – 50%	
	presence of response		latency [ms]		presence of response		latency [ms]		latency difference [ms]	
	n	%			*n*	%				
			mean	Std			mean	Std	mean	Std
Apical										
P1	29	91	45.27	22.57	27	84	44.64	13.41	−10.44	20.36
N1	31	97	98.12	25.71	29	91	114.17	26.45	−21.97	32.84
P2	31	97	192.61	30.41	29	91	197.41	36.39	−6.02	47.10
Mid										
P1	28	88	39.71	19.09	28	88	38.51	8.29	−3.99	11.30
N1	31	97	91.27	16.07	29	91	103.00	11.50	−14.63	14.28
P2	31	97	184.03	32.14	29	91	187.48	29.37	−2.42	43.79
Basal										
P1	26	81	48.84	22.44	25	78	45.48	17.24	0.02	25.52
N1	27	84	99.24	22.59	26	81	103.21	25.22	−8.54	27.27
P2	28	88	182.21	35.30	26	81	192.62	32.94	−11.5	39.49

Table 3. Amplitude values in μV for MCL, 50% MCL and the difference between MCL and 50% MCL

	MCL				50%				MCL-50%			
	P1-N1		N1-P2		P1-N1		N1-P2		P1-N1		N1-P2	
	mean	Std	mean	Std	mean	Std	mean	Std	mean	Std	mean	Std
Apical	4.44	2.10	5.77	2.33	2.89	1.65	3.46	1.74	−1.66	2.30	2.42	2.26
Mid	4.71	2.07	5.58	2.56	5.00	3.50	4.36	2.10	−0.01	3.31	1.46	2.91
Basal	4.38	2.65	4.90	2.40	2.98	2.15	3.43	2.20	−1.10	2.11	1.35	1.51

expected range, the assignation of the response was given to the one with the greater amplitude, or, in cases where peaks all had the same amplitude, to the one with the shortest latency.

Speech Perception in Quiet and in Noise

A single speaker setup in free field was used, with the speaker placed at 1 m distance from the subject and at 0° azimuth. The Consonant-nucleus-consonant (CNC) monosyllabic word test (Peterson et al., 1962) was used to measure speech perception in quiet. Words were presented at 65 dB SPL. Speech perception in noise testing was performed using the Bamford-Kowal-Bench Adaptive speech-in-noise (BKB-SIN) test [Bench et al., 1979], which evaluates the signal-to-noise ratio (dB SNR) needed to achieve a score of 50% of the words correct. The spatial configuration S_0/N_0 was used for testing with speech and noise presented from the front. Speech perception scores in quiet and in noise were obtained immediately before CAEP measurement and acutely on the same day of the eCAEP recording. Preoperative speech perception scores were obtained from medical records.

Statistical Analyses

Statistical analyses were performed using python statistical functions module scipy.stats v 1.7.3. A resulting *p* value of ≤0.05 was considered statistically significant and, for multiple comparisons, Bonferroni correction was used.

Results

eCAEP Detection Rates

eCAEP responses were averaged across participants and stimulating electrodes. Figure 2 shows the mean of all

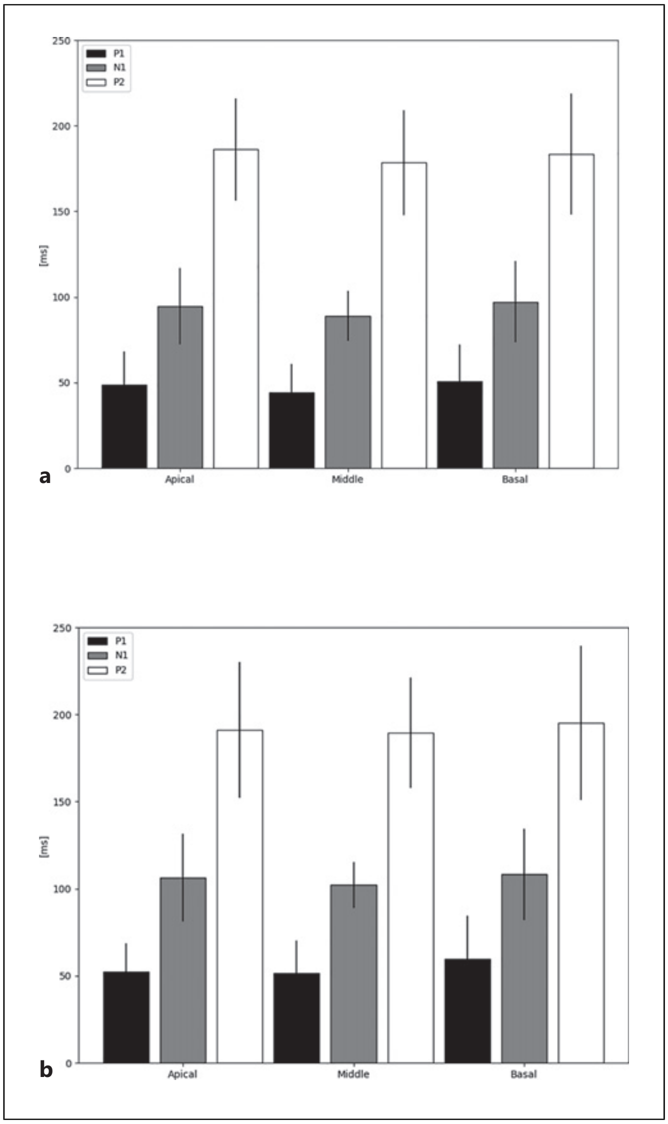

Fig. 4. eCAEP wave latencies by stimulation electrode at MCL (**a**) and at $MCL_{0.5}$ (**b**).

eCAEP (black line) with standard deviation (grey line) for all participants at each stimulation level. Figure 3 depicts averaged eCAEP morphologies by stimulating electrode.

In 31 out of 32 participants (97%), it was possible to identify N1 and P2 peaks when stimulating the apical and middle electrodes at MCL. The N1 and P2 peaks were also the most commonly recorded at $MCL_{0.5}$. The occurrence of the complex P1-N1-P2 and the mean and standard deviation of latency and amplitude of each single peak are detailed in Tables 2 and 3, respectively.

Latency Characteristics

Stimulating electrodes had no significant effect on P1-N1-P2 latency at MCL and $MCL_{0.5}$ (shown in Fig. 4).

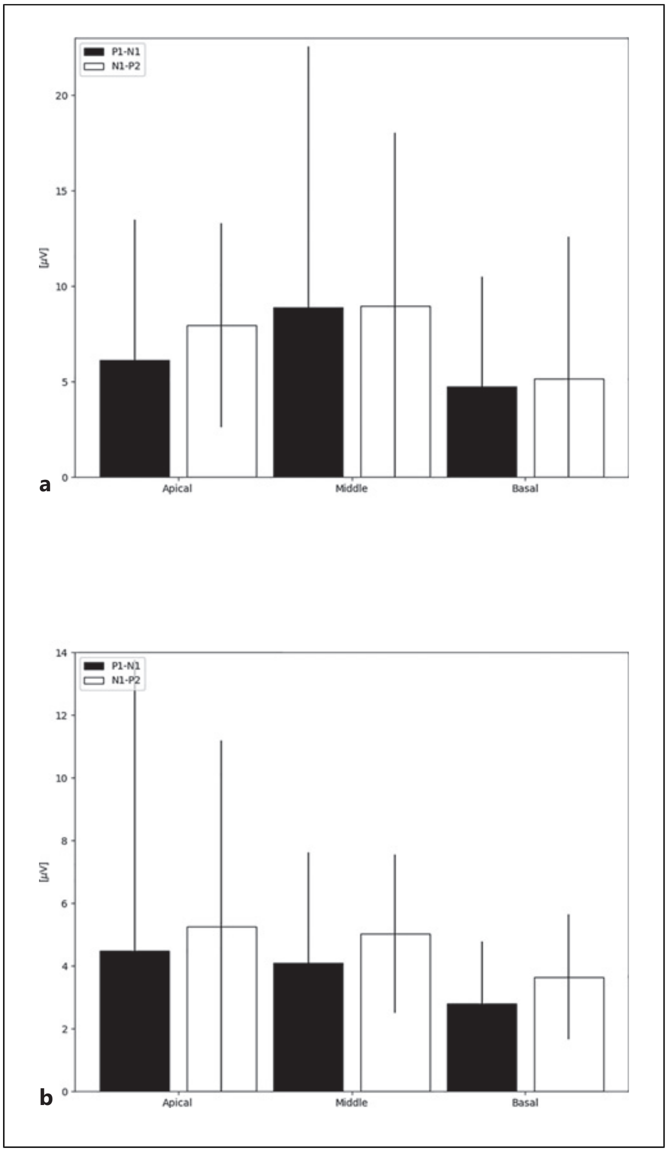

Fig. 5. eCAEP peak amplitudes by stimulation electrode at MCL (**a**) and $MCL_{0.5}$ (**b**).

However, there was a significant difference between MCL and $MCL_{0.5}$ for N1 latency in apical and middle electrode. When analyzing all electrodes together, there was a significant difference in latency between MCL and $MCL_{0.5}$ for P1 and N1 but not for P2 latency.

Amplitude Characteristics

Stimulating electrode had a significant effect on amplitude when stimulating at MCL (shown in Fig. 5a). There was a significant difference on P1-N1 between middle and basal electrode ($p = 0.005$), and N1-P2 amplitude between middle and basal electrode ($p = 0.010$)

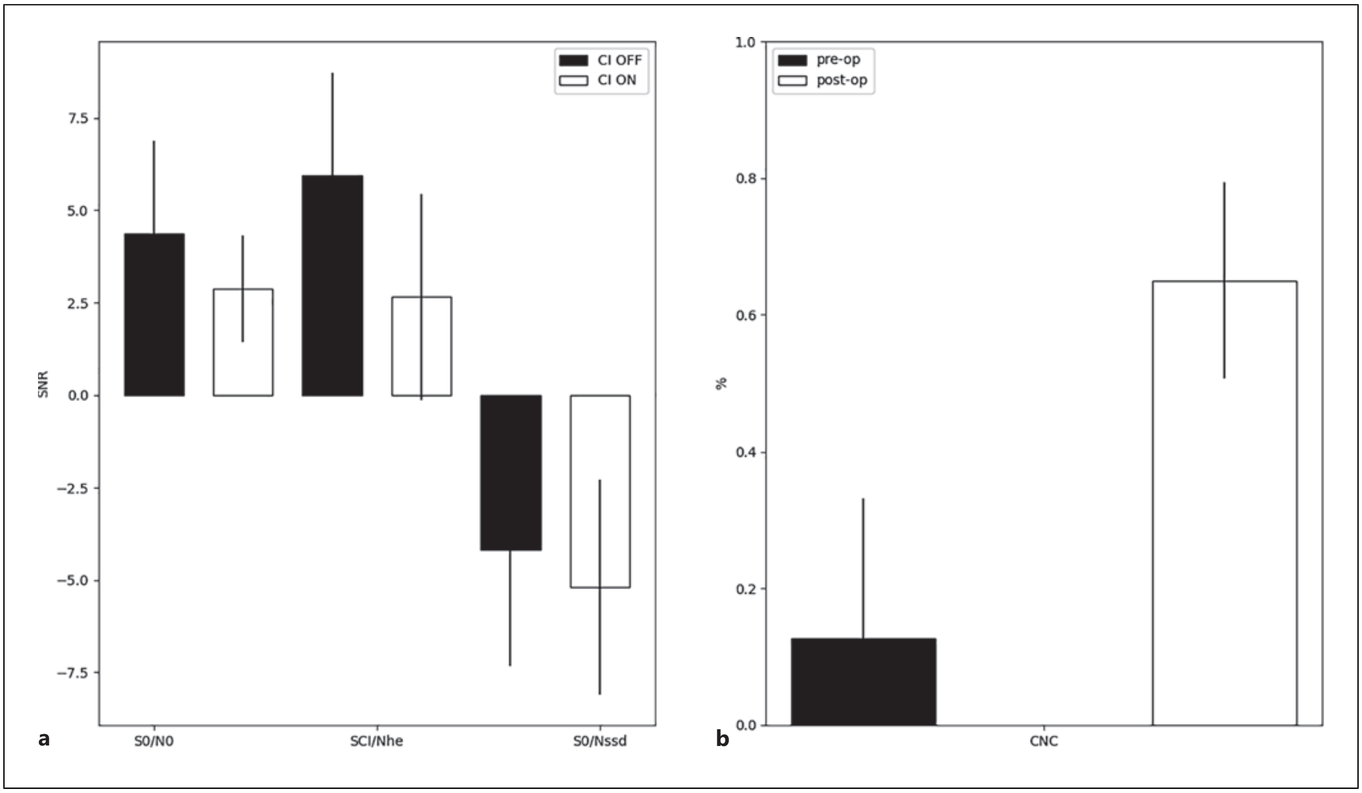

Fig. 6. a Speech perception in noise in all three spatial configurations in CI on and CI off conditions. **b** Speech in quiet (CNC words) score (%) pre-op and post-op.

and N1-P2 amplitude between apical and basal electrode ($p = 0.025$). When stimulating at $MCL_{0.5}$, the only significant difference observed was for N1-P2 between middle and basal electrode ($p = 0.040$) (shown in Fig. 5b).

A comparison between MCL and $MCL_{0.5}$ showed that amplitude was significantly different for P1-N1 at apical ($p = 0.010$) and middle electrode (0.047) and for N1-P2 at all three electrode positions (apical – $p < 0.001$; middle – $p = 0.001$; basal – $p = 0.016$). P1-N1 amplitude did not significantly differ for the basal electrode ($p = 0.069$). Furthermore, when taking all electrodes together, a comparison between MCL and $MCL_{0.5}$ showed a significant difference for P1-N1 ($p < 0.001$) and N1-P2 ($p < 0.001$) amplitudes.

Effects of Stimulation Charge (MCL)

There was no correlation between eCAEP latency and MCL charge for any electrode, or for all electrodes taken together. However, a significant difference was calculated for P1 latency ($p = 0.010$) when MCL charge >600 cu versus MCL charge <600 cu (this cutoff was determined by the fact that the median MCL charge was 600 cu). As for amplitude, a significant difference was present for P1-N1 apical ($p = 0.020$) and middle ($p = 0.010$) electrode, as well as for all electrodes together ($p < 0.001$).

Effects of Age and of Duration of Deafness

eCAEP latency did not correlate with age at implantation. Only a positive trend on P2 latency in the apical electrode ($R = 0.3$, $p = 0.1$) was observed. Additionally, no correlation was observed between eCAEP latency and duration of deafness.

Median duration of deafness for the 32 participants was 72 months. When the participants were separated into two groups according to duration of deafness – greater than and less than 72 months – no significant difference was obtained for eCAEP latency and amplitude between the groups. However, Mann-Whitney U test revealed a significant difference between longer and shorter duration of deafness for amplitude of P1-N1 apical ($p < 0.001$) and basal electrode ($p < 0.001$), and N1-P2 middle electrode ($p < 0.001$) as well as P1-N1 ($p < 0.001$) and N1-P2 ($p < 0.001$) for all electrodes together.

Correlation with Speech Perception in Quiet and in Noise

There was a significant improvement on speech performance in noise from CI off to CI on condition in S_0/N_0 ($p = 0.032$), S_{CI}/N_{HE} ($p = 0.002$), S_0/N_{SSD} ($p = 0.026$) (shown in Fig. 6a). Significant improvement was also

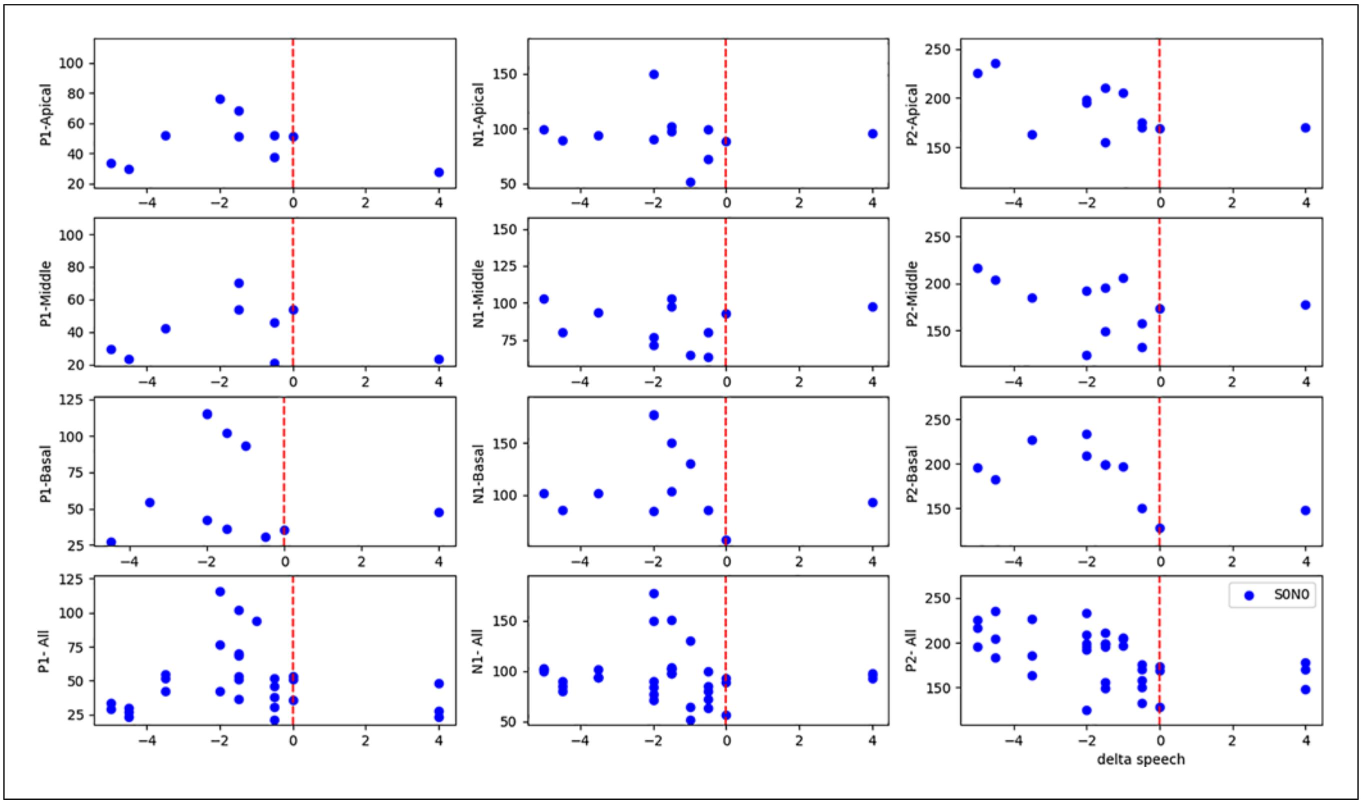

Fig. 7. Peak latency at apical, middle, basal, and all electrodes versus SNR at BKB-SIN configuration S0/N0.

observed in speech in quiet from pre- to post-CI ($p < 0.001$) (shown in Fig. 6b).

eCAEP latency did not correlate with speech in quiet outcomes post-CI, nor with delta speech (difference in speech outcomes between post-CI and pre-CI). However, there was a negative correlation between P2 latency for the apical electrode ($R = -0.57$, $p = 0.05$), as well as P2 for all electrodes together ($R = -0.49$, $p = 0.000$) and the improvement (CI on – CI off) in speech perception in noise for the S_0/N_0 spatial configuration (shown in Fig. 7).

For the spatial configuration S_{CI}/N_{HE}, a positive correlation was observed for P1 latency when all electrodes were together with speech perception scores ($R = 0.41$, $p = 0.04$) (shown in Fig. 8). eCAEP P1 latency in the apical electrode ($R = 0.84$, $p = 0.04$) and P2 in basal electrode ($R = 0.8$, $p = 0.03$) and P1 ($R = 0.53$, $p = 0.02$) and P2 latency ($R = 0.47$, $p = 0.02$) when all electrodes were considered together correlated positively with speech scores in the S_0/N_{SSD} (shown in Fig. 9).

There were no significant differences between SSD and CI users with bilateral hearing loss for eCAEP latency or amplitude. All correlations values are presented in Table 4.

Discussion

CAEPs have long been used as a tool in psychoacoustic research to investigate the properties of the hearing system, in both normal-hearing and hearing-impaired individuals [Stapells, 2002]. In clinical audiology, CAEPs are used as an objective measure to evaluate hearing outcomes in users of amplification with hearing aids and with cochlear implants. There has also been a move toward using CAEPs to guide CI programming. Few clinical studies have investigated the stimulation parameters necessary to elicit eCAEPs [Kranick et al., 2021; Callejón-Leblic et al., 2022; Deniz et al., 2022] and to compare their characteristics to that of aCAEPs [Távora-Vieira et al., 2021]. However, the literature on eCAEP is still scarce and little known about the variable that can have an effect on its characteristics.

In this study, we added to the literature by investigating (1) the eCAEPs generated by stimulation at the behaviorally measured MCL, as well as at half of this level, (2) the effects upon eCAEP morphology of stimulation at different electrode positions, and (3) whether correlations exist between eCAEP latency and amplitude and speech performance, age

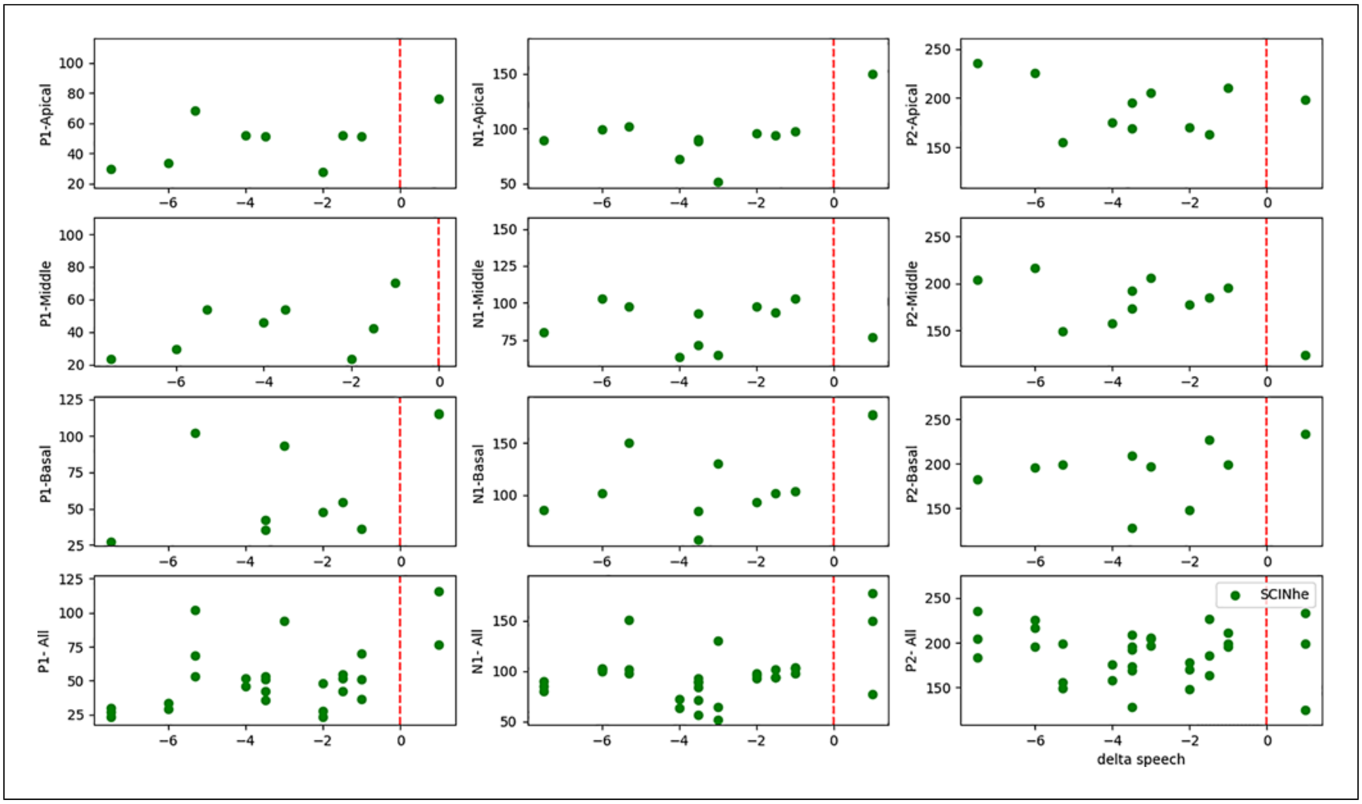

Fig. 8. Peak latency at apical, middle, basal, and all electrodes versus SNR at BKB-SIN configuration Sci/Nhe.

of implantation, duration of deafness, whether deafness was single-sided or bilateral, and stimulation charge.

We found that clear eCAEP responses can be elicited at both MCL and MCL_{50} in almost all users (97%). This compares positively to the results of 71% success rate reported by Callejón-Leblic et al. [2022]. In addition, eCAEP amplitudes were greater at the higher stimulation level. This is expected, as both aCAEPs and eCAEPs are an intensity-dependent response. This is thought to be explained by the number of neurons being activated by a higher stimulation level [Pickles, 2013; Visram et al., 2015]. This is similar to the findings reported by Kranick et al. [2021] which demonstrated a significantly higher N1-P2 amplitude for higher levels of stimulation.

In this study, it was observed that stimulation at basal (high frequency) electrode sites produced waveforms of somewhat lower reproducibility compared to medial and apical sites. Moreover, the amplitudes of P1-N1 and N1-P2 peaks were often smaller when stimulating the basal electrodes compared to the medial and apical electrodes. This is in line with previous literature [Visram et al., 2015; Liebscher et al., 2018; Távora-Vieira et al., 2021; Callejón-Leblic et al., 2022] with multiple explanations suggested. Lower charge levels are often applied to basal electrodes due to discomfort and a low tolerance to high frequency stimulation, perhaps offering a reason for lower amplitudes of eCAEP responses seen at basal electrodes [Visram et al., 2015]. However, Callejón-Leblic et al. [2022] reported lower N1-P2 amplitudes at basal electrodes even when stimulated at higher levels. This could be due to the lower number of residual functional auditory neurons at the basal region due to increased duration of deafness [Visram et al., 2015; Liebscher et al., 2018]. Acoustic CAEP in a group of 108 CI users has demonstrated aCAEP elicited by a high frequency speech token (/s/) was absent for more than 50% of those who had their CI map adjusted based on aCAEP presence/absence. In addition, it was also observed that the poorest aCAEP morphology was obtained for /s/ [Távora-Vieira et al., 2022a, 2022b]. These findings may serve as encouragement for clinicians to be more vigilant when setting basal MCLs to avoid suboptimal electrical stimulation. Furthermore, it indicates that eCAEPs may be particularly useful as an objective tool in this area.

We found no significant correlations between eCAEP amplitude or latency and user age, duration of deafness

DOI: 10.1159/000529797

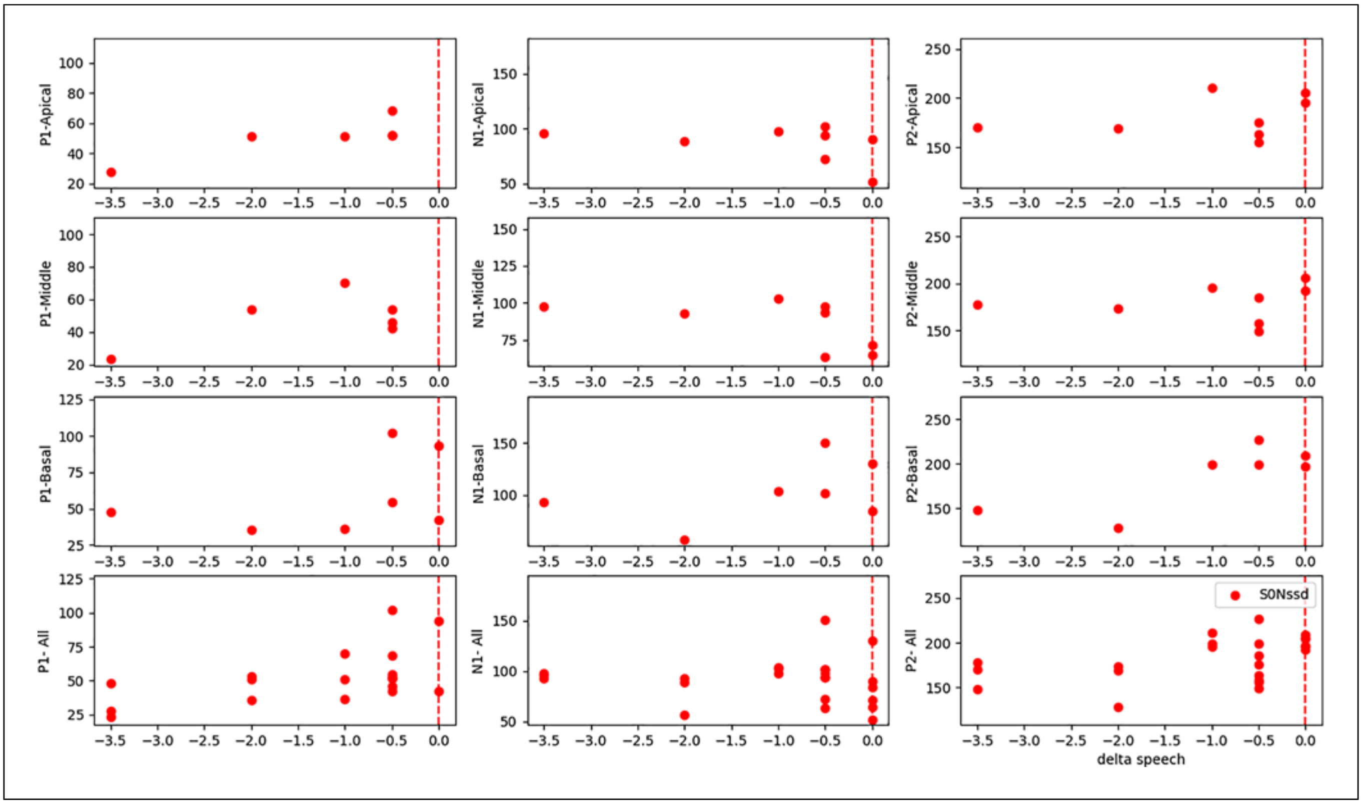

Fig. 9. Peak latency at apical, middle, basal, and all electrodes versus SNR at BKB-SIN configuration S_0/N_{SSD}.

prior to CI surgery, whether the hearing loss was bilateral or single-sided, nor with the charge level required to elicit MCL. There is no previous literature that has investigated the correlation of eCAEP characteristics and demographic variables, and therefore, comparison cannot be made. However, these findings suggest that none of these variables confound the ability to use eCAEPs as a diagnostic of sound perception and it could, therefore, be more broadly used in CI optimization and verification.

We found that peak latencies correlated with speech perception scores in some spatial configurations of speech-in-noise. Specifically, there was a negative correlation between speech perception in noise scores and the latency of P2 in the S_0/N_0 spatial configuration for the apical electrodes and all electrodes combined. Liebscher et al. [2018] have also reported P2 latency at the apical electrodes correlated negatively with word recognition in quiet scores, suggesting that shorter processing time (shorter P2 latency) indicates better speech perception in noise scores. In contrast, a positive correlation between the latency of P1 in the S_{CI}/N_{HE} configuration and a positive correlation between the latency of both P1 and P2 in the S_0/N_{SSD} configuration were obtained. For S_{CI}/N_{HE} and S_0/N_{SSD}, longer peak latencies correlated with higher speech perception scores. This is an unexpected finding and is not in line with previous reports. For instance, using an oddball paradigm, Finke et al. [2016] showed that shorter N1 latencies were related to enhanced speech intelligibility. However, it is important to note that, Finke et al. [2016] used speech stimulus while this study used tone burst. It is possible that the presentation of two sounds from spatially separated sources disrupts the normal relationship between peak latency and speech perception. It is also important to note that the speech perception scores in these two spatial configurations were obtained only for SSD participants, and therefore, the small sample size might have affected the results.

The findings presented here, along with a growing body of existing research, demonstrate the feasibility of using eCAEPs as a technique to evaluate hearing perception in CI users and to verify the device programming parameters. Direct electrical elicitation of CAEPs has also been used to investigate sound perception in users of auditory brainstem implants [He et al., 2015]. It is unclear whether CAEPs represent conscious sound perception, conscious sound perception and sound recognition, or an unconscious process of sound reception. The fact that CAEPs can

Table 4. Correlation analyses between eCAEP waveforms and electrode position, charge, and speech recognition scores

Latencies					
		apical	medial	basal	all
	P1	335, 0.36	298, 0.13	252, 0.17	2,646.5, 0.03**
	N1	314.5, 0.046**	180.5, <0.001**	252, 0.08*	2,299.5, <0.001**
	P2	417, 0.64	356, 0.17	316.5, 0.42	3,300, 0.15
Amplitudes					
		apical-medial	medial-basal	apical-basal	
MCL	P1-N1	183, 0.20	81, <0.01**	128, 0.09*	
	N1-P2	231, 0.74	90, 0.01**	105, 0.02**	
$MCL_{0.5}$	P1-N1	172, 0.33	138, 0.34	161, 0.50	
	N1-P2	175, 0.36	95, 0.04**	142, 0.26	
		apical-medial	medial-basal	apical-basal	all
	P1-N1	99, 0.01**	116, 0.04**	86, 0.07*	893, <0.01**
	N1-P2	58, <0.01**	65, <0.01**	67, 0.02**	558, <0.01**
By charge					
		< 600 cu versus > 600 cu			
Latency	P1	1,010, 0.01**			
	N1	780.5, 0.46			
	P2	915, 0.61			
Amplitude	P1-N1	1,333, 0.01**			
Speech recognition scores					
		apical	medial	basal	all
	P1	−0.08, 0.82	−0.01, 0.99	−0.03, 0.93	−0.02, 0.92
	N1	−0.12, 0.72	−0.03, 0.93	−0.11, 0.74	−0.09, 0.6
	P2	−0.57, 0.05**	−0.35, 0.26	−0.57, 0.06*	−0.49, 0.01**

For latencies, values represent the Mann-Whitney U test, followed by the *p* value. For amplitudes, values represent the Wilcoxon singed-rank test, followed by the *p* value. For speech-in-noise perception (S_0N_0), the values represent Pearson's *r* correlation, followed by the *p* value.

generally be elicited only at supra-threshold presentation levels tends to favor one of the former two [Ross et al., 1999]. Cortical potentials must already be of sufficient magnitude to be detected via scalp electrodes. This being the case, it would imply that CAEP-derived thresholds would correlate strongly with perceptual thresholds, but systemically overestimate them. Based on findings with acoustically elicited CAEPs, it has been suggested that the electrophysiologic method overestimates the hearing threshold by 4–10 dB [Ross et al., 1999]. It remains to be investigated whether the same tendency toward overestimation also holds true for the MCL and if the eCAEP elicited by direct stimulation may provide a more precise set-up for threshold and MCL estimation.

A limitation of the CAEP approach is that the detection thresholds will vary based on sensitivity of the EEG recording equipment used. Recent advances may help in this regard; it has been shown that CAEPs can be measured directly from the implant electrodes themselves [Somers et al., 2021; Bauernfeind et al., 2022]. Implant electrodes, being situated within the skull, should in principle give superior signal quality and lower artefacts. Although this method is still in its earliest stages of development at the time of writing, it points the way toward a future application in which CAEPs can be elicited and measured without the need for external EEG recording hardware. CAEP detection thresholds may also vary based on statistical and/or morphological criteria used to define the presence of a CAEP. It may become necessary to define a consensus methodology for eCAEP detection during cochlear implant programming.

Conclusion

Electrically evoked P1–N1–P2 recordings can be made at stimulation levels corresponding to the MCL, and at basal, medial, and apical electrode stimulation sites. Detection rates, amplitudes, and latencies are not affected by the variables of age, duration of deafness prior to CI surgery, or whether of hearing loss is bilateral or single-sided. Some peak latencies correlated with speech perception scores in some configurations of speech-in-noise. As such, eCAEPs may be a useful objective method for fitting and sound perception evaluation in CI users.

Acknowledgments

We would like to thank the CI users who participated in this study. We also thank Giacomo Mandruzzato for helping with data analysis and Patrick Connolly for editing a version of this manuscript.

Statement of Ethics

This study was designed and conducted in accordance with the Declaration of Helsinki, and ethics approval was obtained from the South Metropolitan Health Service, Human Research Ethics Committee (reference number 3258). Written informed consent was obtained from all subjects.

Conflict of Interest Statement

The authors have no conflict of interest to declare.

Funding Sources

Dayse Távora-Vieira holds a research fellowship grant from Rayne Medical Research Foundation. The authors have no conflicts of interest to declare.

Author Contributions

Dayse Tavora-Vieira: drafting, design, data collection, interpretation, and final approval. Ellen Ffoulkes: drafting, data collection, and final approval.

Data Availability Statement

Data can be made available upon request sent to the corresponding author.

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