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Relation between electrical compound action potential measures and speech perception in cochlear implanted children: audiological and phonological outcomes

Nada Ahmed Basiony[1], Trandil Hassan El-Mahallawi[1], Shaima Mohamed Elsayed Ahmed[1], Amani Mohammed El-Gharib[1] and Wessam Mostafa Essawy[1*]

Abstract

Purpose To study ECAP measures (threshold and amplitude growth function 'AGF') in children CI users and find the relation between these ECAP measures and speech outcomes using audiological and phonological assessment.

Subjects and method Twenty-one children were unilaterally implanted with Medel CI, and all subjects were submitted to phonological assessment, basic audiological assessment, speech recognition tests (WRS and BKB-SIN) and Medel maestro software measures (IFT, AutoART and AGF measures "thresholds and slopes" across apical, middle and basal electrodes).

Results This study demonstrated no statistically significant difference between AGF thresholds at apical, middle and basal electrodes and a statistically significant difference between AGF slopes at apical and both middle and basal electrodes. There was no statistically significant correlation between the ECAP threshold and speech perception tests. In contrast, a positive statistically significant correlation was found between the AGF slope of the apical electrode and word recognition score, and a negative statistically significant correlation between AGF slopes at apical, middle and basal electrodes and SNR loss of BKB-SIN. High sensitivity and specificity of AGF slope at apical electrode were found to differentiate between good and poor performers as regards SNR loss of BKB-SIN and language test.

Conclusions The AGF slope reflects neural survival better than the ECAP threshold. AGF slope at apical electrodes correlated with better CI performance in both phoniatric and audiological measures of speech perception and can be used as an objective tool to predict CI outcome.

Keywords Amplitude Growth Function, AGF, Bamford-Kowel-Bench speech in noise, BKB-SIN, Electrical Compound Action Potential, ECAP, Intelligent Quotient, IQ, Spiral ganglion neurons, SGNs, Cochlear implant, CI

Background

Due to a reduced capability for communication, hearing loss negatively affects emotional, social, and economic capabilities [1]. Cochlear implants (CI) are often an available option for those with severe to profound sensorineural hearing loss. In order to electrically stimulate the spiral ganglion neurons (SGNs), which in turn results in the sense of sound, the CI's electrode array is placed into the cochlea's Scala tympani [2].

*Correspondence:
Wessam Mostafa Essawy
wessamessawy@yahoo.com
[1] Department of Otorhinolaryngology, Faculty of Medicine, Vestibular Unit, Tanta University, El Nahas Street, Tanta El, Gharbia, Egypt

The integrity of the SGNs, which are the target of CI, is thought to modify the conduction of auditory impulses and have an effect on perceptual results when an implant is used. According to the research thus far, children who were deafened and implanted at a young age and adult listeners who were deafened are likely to have different SGN conditions [3].

For the CI result, it must be assumed that there is at least a healthy, significant number of SGN that is able to transmit the encoded audio information to the auditory cortex through the afferent auditory system [4].

A set of electrically triggered auditory nerve fibers produce the synchronized response known as ECAP. Threshold, amplitude, and amplitude growth function (AGF) are some of the recorded ECAP parameters [5]. AGF demonstrates the ECAP amplitude as a function of stimulation current. This linear extension of the AGF's slope is known as the AGF slope. Higher slope values (mV/A) are predicted to be associated with SGNs in better health, while lower slope values are predicted to be present at lower SGN concentrations [6].

The present study aimed to study ECAP measures in cochlear-implanted children and find the relation between these ECAP measures and speech perception outcomes.

Methods

This work was conducted in the period between February 2021 and March 2022 at Audio-vestibular Unit, ENT Department, with an ethical approval code (no. 34427/01/21).

Subjects

The study included 21 children with unilateral Medel CI with fully inserted electrodes. Their age ranged from (6 to less than 18) years. The inclusion criteria were: regular speech therapy after CI surgery for a period not less than 2 years, satisfactory aided response < 35 dB, auditory level 4–5, intelligibility 3–4-5 and IQ > 80.

Methods

All subjects were submitted to:

A. Phoniatric assessment including:

1) Clinical assessment through:

- Visual assessment of aural vocal tracts (Visual assessment of the aural and vocal tract including lips and tongue mobility, palatal mobility and vocal folds assessment using the indirect rigid laryngoscope).
- Speech assessment: Assessment of segmental (vowels, consonants) and suprasegmental aspects of speech (Tone, stress, pauses).

2) Diagnostic aids, including:

- Language assessment: Using items of Modified Preschool Language Scale–fourth (modified PLS-4) Arabic edition [7].
- Auditory abilities: Using CAP scoring (Capacity of Auditory Performance), it gives a score from I to V based on auditory level: I: detection, II: discrimination, III: identification, IV: recognition, and V: comprehension [8].
- IQ: Intelligent-Quotient is assessed through Stanford-Binet Intelligence Scale Fifth Edition [9].
- Intelligibility: Assessed through the speech intelligibility index, which gives scores from I-V, I: unintelligible speech, II: poor intelligibility, III: fair intelligibility, IV: good intelligibility, and V: excellent intelligibility [10].

B. Audiological assessment

1) Full audiological history including the onset of hearing loss, cause of hearing loss, type of hearing aid, duration of HA use and its regularity, speech therapy, age at the time of operation, duration of CI use, side of implantation, type of device, time and numbers of programming, onset and duration of speech therapy and the use of hearing aid in the other ear.
2) Basic audiological evaluation including aided sound field thresholds, aided speech recognition threshold (SRT) using bisyllabic words for kindergarten [11] and speech recognition tests including word recognition score using monosyllabic words for kindergarten, speech recognition in noise through Arabic version of BKB-SIN using Madsen Astera (Type-1), two channels, and PC-based audiometer with multiple sound field speakers (MARTIN-AUDIO LONDON type) and connected to a laptop, BKB-SIN Arabic test material incorporated in Astera software and chosen during BKB testing.
3) Arabic BKB-SIN test developed and standardized at Tanta University hospitals, Egypt [12], it is one of the adaptive SNR tests. SNR loss in dB for each list using a formula based on Spearman-Kärber Equation. Then, interpreting the SNR loss result into: normal: (0-3 dB), mild: (> 3–7 dB), moderate: (> 7–15 dB), or severe: (> 15 dB) according to BKB manual [13].

C. Medel Maestro software measures: *Impedance measures*, *AutoART*: measuring auto ART for all electrodes through a specific range from 0 to 30 qu to ensure that all electrodes are fully inserted and functioning with no short or open circuits, then manual measurement of *AGF* of ECAP: using the following parameters: 1) Maximum amplitude: 800 CU. 2) Minimum amplitude: 0 Cu. 3) Phase duration: 40 μs. 4) Maximum charge: 32 qu 5) Iterations: 15. 6) Measurement delay: automatic 145 μs. 7) Measurement gap: 1 ms. 8) Levels: 15 levels.

Stimulating and recording electrodes: Three sets of electrodes, *E1, E6, and E12,* were used as stimulating electrodes, and their adjacent electrodes were the recording ones. "Alternating Polarity" was used as an artifact reduction paradigm per default.

Following that, the intersection of a linear extrapolation from the steepest part of the AGF and the baseline is used to calculate the ECAP threshold and slope [14].

Results

This study included 21 children.The age range of the study group was 7- 17 years with the mean of 9.9 years. They were 13 females (61.9%) and 8 males (38.1%). As regards cause of hearing loss, there was (13) Cases with unknown cause, (4) cases were hereditary non syndromic hearing loss, (3) cases caused by non meningitic fever, (1) case by trauma. There was not any correlations between the cause of hearing loss and our test findings.

Results of ECAP measures

ECAP threshold measured through AGF showed that the means and SD were (11.6 ± 4.09) (14.2 ± 4.66), and (11.9 ± 4.23) qu at E1, E6 and E12, respectively. ANOVA test was done to compare between the ECAP thresholds at E1, E6, and E12. The result revealed no statistically significant difference between ECAP thresholds at different electrodes (Table 1).

AGF slopes at E1, E6 and E12 measured through Medel maestro software revealed significantly lower slope values at electrodes in the basal region (E12 = 25.1 μV/ qu), medium values at electrodes positioned in the middle part of cochlea (E6 = 38.4 μV/ qu), and the highest slopes in the more apical region (E1 = 53.6 μV/ qu). A statistically significant difference was found between slope values at E1, and both E6 and E12 electrodes, with no statistically significant difference between slope values at E6 and E12 (Table 1) (Fig. 1).

Results of speech recognition tests:

Aided word recognition score was measured, and its values ranged from (80–96%) with a mean and SD of 88.4 ± 5.64, while the BKB-SIN test showed SNR loss ranging from (5.2–18.3 dB) with a mean and SD of 12.1 ± 3.4.

Correlation between ECAP measures and speech perception measures

This study showed no significant correlation between ECAP thresholds and speech perception tests (WRS, SNR loss in dB of BKB-SIN). However, there was a positive statistically significant correlation between the AGF slope at E1 and word recognition score, while for the BKB-SIN, there was a negative statistically significant correlation between AGF slopes at E1, E6, E12 and SNR loss in dB of BKB-SIN test, i.e., AGF slope increase with better SNR loss (Table 2).

Correlation between ECAP measures and phonological assessment (IQ, auditory level, intelligibility and language assessment)

There was no significant correlation between the ECAP threshold and phonological assessment, as the threshold correlates less to neural health. On the other hand, there was a statistically significant positive correlation between AGF slope and IQ, auditory level, intelligibility and language test as AGF slope is correlated to neural health (Table 3).

Table 1 Comparison between AGF measures (thresholds and slopes) at E1, E6, E12

AGF measures	E1	E6	E12	F	*P*	Post hoc
AGF threshold (qu)						
Mean ± SD	11.6 ± 4.09	14.2 ± 4.66	11.9 ± 4.23	2.223	0.117	
Min.-Max	3.10 -18.30	7.20–21.2	2.60 –16.50			
AGF slope (μV/qu)						P1 0.05*
Mean ± SD	53.6 ± 24.36	38.4 ± 20.35	25.1 ± 16.12	10.119	< 0.001*	P2 < 0.001*
Min.-Max	20.12–110.20	9.98–95.80	4.51 – 56.0			P3 0.124

* $p \leq 0.05$ statistically significant. F: ANOVA

P1 is difference between slope values at E1 and E6

P2 is difference between slope values at E1 and E12

P3 is difference between slope values at E6 and E12

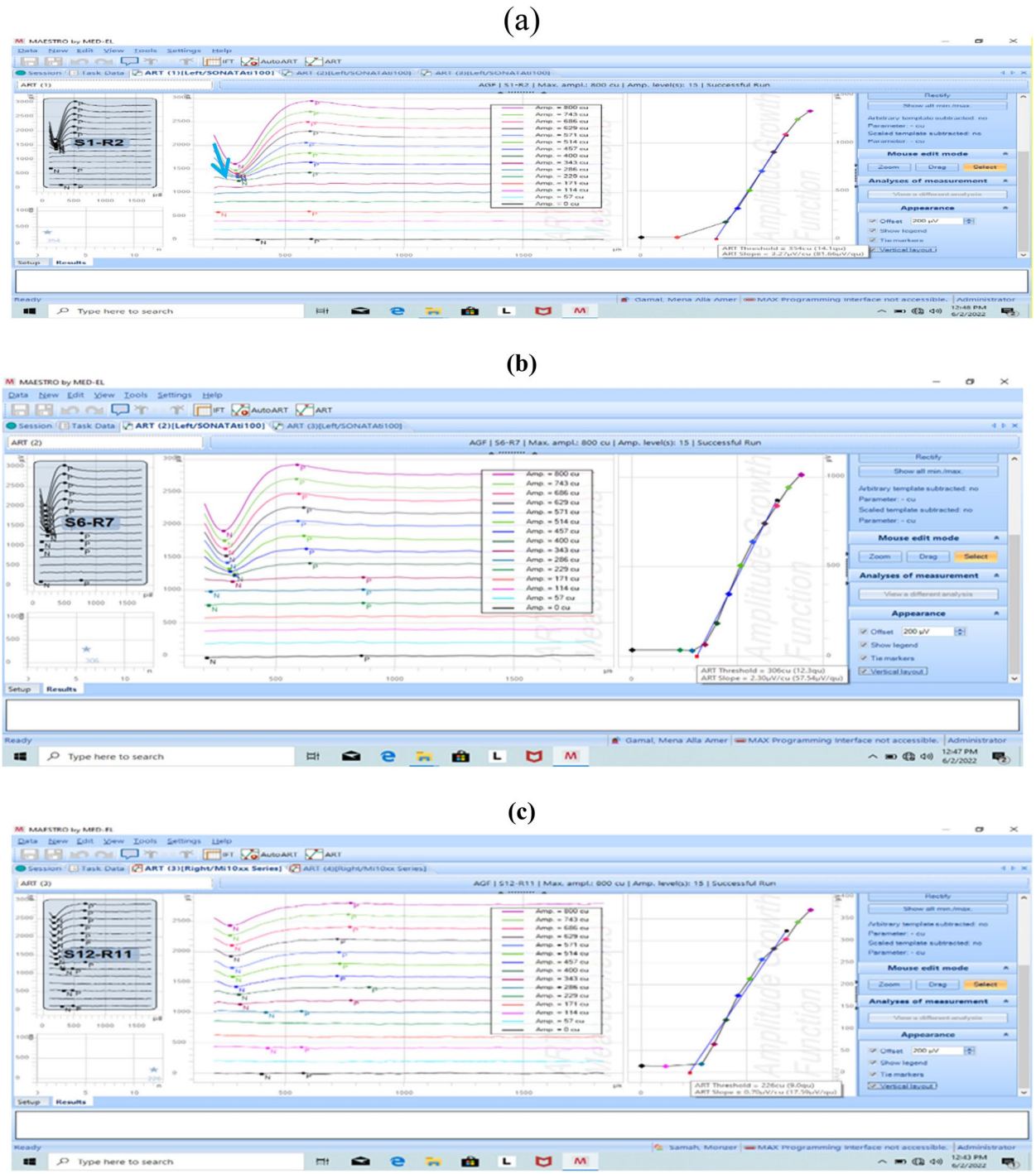

Fig. 1 One of this study case showing AGF slope and threshold. **a** at E1 ART slope = 81.66 μV/qu, ART threshold = 14.1 qu. **b** at E6 ART slope = 57.54 μV/qu, ART threshold = 12.3 qu. **c** at E12 ART slope = 17.59 μV/qu, ART threshold = 9 qu

Sensitivity and specificity of AGF slope in the detection of better speech outcome

This study group was divided into 2 groups based on the results of BKB-SIN. Group (1) included 16 children with moderate SNR loss (7–15 dB), and Group (2) included four children with severe SNR loss (> 15 dB) (One case with mild SNR loss not included).

AGF slope values were compared between the two groups. While there was no statistically substantial distinction between the two groups at slopes E6 and E12,

Table 2 Correlation between AGF measures (threshold and slope), word recognition score, and SNR loss BKB test

	AGF Threshold E1		**AGF Threshold E6**		**AGF Threshold E12**	
	r*	***P***	**r***	***P***	**r***	***P***
Word recognition score	- 0.067	0.772	0.019	0.934	0.101	0.663
SNR loss (in dB)	0.089	0.700	0.094	0.685	- 0.037	0.873
	AGF slope E1		**AGF slope E6**		**AGF slope E12**	
	r*	***P***	**r***	***P***	**r***	***P***
Word recognition score	0.557	0.006*	0.361	0.108	0.264	0.248
SNR loss (in dB)	- 0.598	0.004*	- 0.440	0.046*	- 0.560	0.008*

* r (Pearson correlation) *$p \leq 0.05$ (Statistically significant)

Table 3 Correlation between AGF slope and phonological assessment

		AGF slope E1		**AGF slope E6**		**AGF slope E12**	
		r*	***P***	**r***	***P***	**r***	***P***
IQ		0.501	0.021*	0.446	0.043*	0.239	0.296
Auditory level		0.851	< 0.001*	0.409	0.065	0.221	0.337
Intelligibility		0.725	< 0.001*	0.279	0.220	0.126	0.586
Language test	**Receptive**	0.491	0.024*	0.204	0.375	0.034	0.885
	Expressive	0.442	0.045*	0.110	0.637	0.151	0.512
	Total	0.523	0.015*	0.193	0.401	0.118	0.612

* r (Pearson correlation) *$p \leq 0.05$ (Statistically significant)

there was a statistically significant distinction at slope E1 (Table 4) and (Fig. 2).

Then, the sensitivity and specificity of AGF slope in detecting better speech outcomes regarding SNR loss of BKB were assessed. It revealed AGF slope E1: Area under the curve (AUC) = 0.8, which means that AGF slope at E1 is suitable for differentiating between moderate and severe SNR loss, with sensitivity = 82.4%, specificity = 75% and accuracy = 80.9%). The AGF slope E6: AUC = 0.7, which means that AGF slope E6 is fair to differentiate between moderate and severe SNR loss, with sensitivity = 82.4%, specificity = 50%, and accuracy = 76.2%. The AGF slope E12: AUC = 0.6; this means that AGF slope E12 is poor in differentiating between moderate and severe SNR loss, its sensitivity = 47%, specificity = 50% and accuracy = 47.6%) (Fig. 3). So, the AGF slope at E1 is reasonable to predict better speech outcomes.

Table 4 Comparison of AGF slope within the two groups of BKB-SIN test at E1, E6 and E12 in μV/qu

Variables	**Group 1**	**Group 2**	**Test of significance**	***P***
AGF Slope E1			T 2.074	0.05*
Min. – Max	21.9 – 110.2	20.12 – 55.05		
Mean ± SD	58.6 ± 22.88	32.58 ± 13.75		
AGF Slope E6			T 1.156	0.261
Min. – Max	9.98 – 57.54	17.33 – 35		
Mean ± SD	40.84 ± 21.06	27.85 ± 7.18		
AGF Slope E12			T 1.021	0.32
Min. – Max	4.51 – 56.0	5.22 – 23.4		
Mean ± SD	30.03 ± 20.85	17.73 ± 7.35		

* r (Pearson correlation) *$p \leq 0.05$ (Statistically significant)

Also, this study group was divided into two groups based on the results of the language test: Group (1) included 14 children with less than the ceiling age for language tests (less than 7 years and 3 months), and Group (2) included 7 children with language ages equal to 7 years and 3 months.

A comparison of AGF slope values was made between the two groups. There was a statistically significant difference in slope E1 values between the two groups, while no statistically significant difference was found in slope E6 and E12 between the two groups (Table 5) and (Fig. 4). This means that children with better language assessment results showed a steeper slope at the apical electrode.

AGF slope at E1: AUC = 0.7; this means that AGF slope E1 is fair to differentiate between the two groups, with sensitivity = 85.7%, specificity = 71.4% and accuracy = 76.2%. AGF slope E6: AUC = 0.6; this means that AGF slope E6 is poor to differentiate between the two groups; its sensitivity = 71.4%, specificity = 35.7% and accuracy = 47.6%. AGF slope E12: AUC) = 0.6; this means that AGF slope E12 is poor to differentiate between the two groups, its sensitivity = 71.4%, specificity = 42.9% and accuracy = 52.4% (Fig. 5).

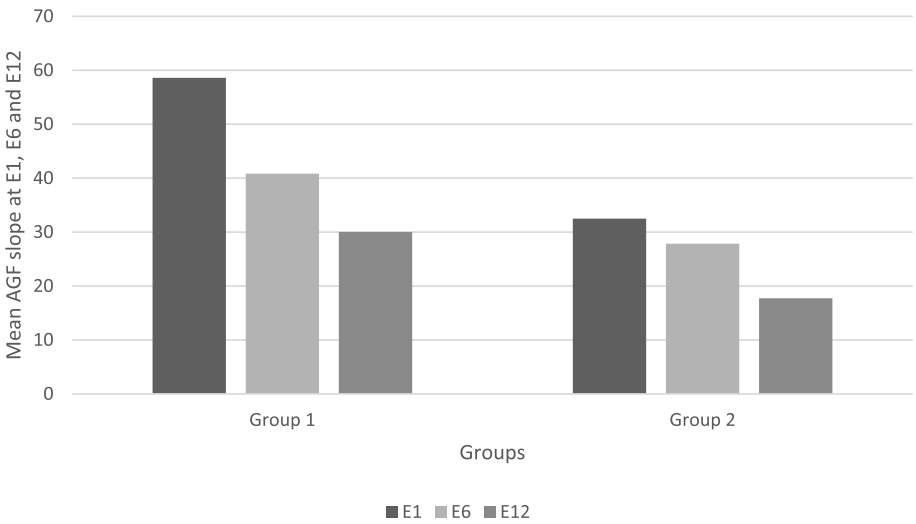

Fig. 2 Comparison mean of AGF slope E1, E6, E12 between the two groups of SNR loss of BKB-SIN test

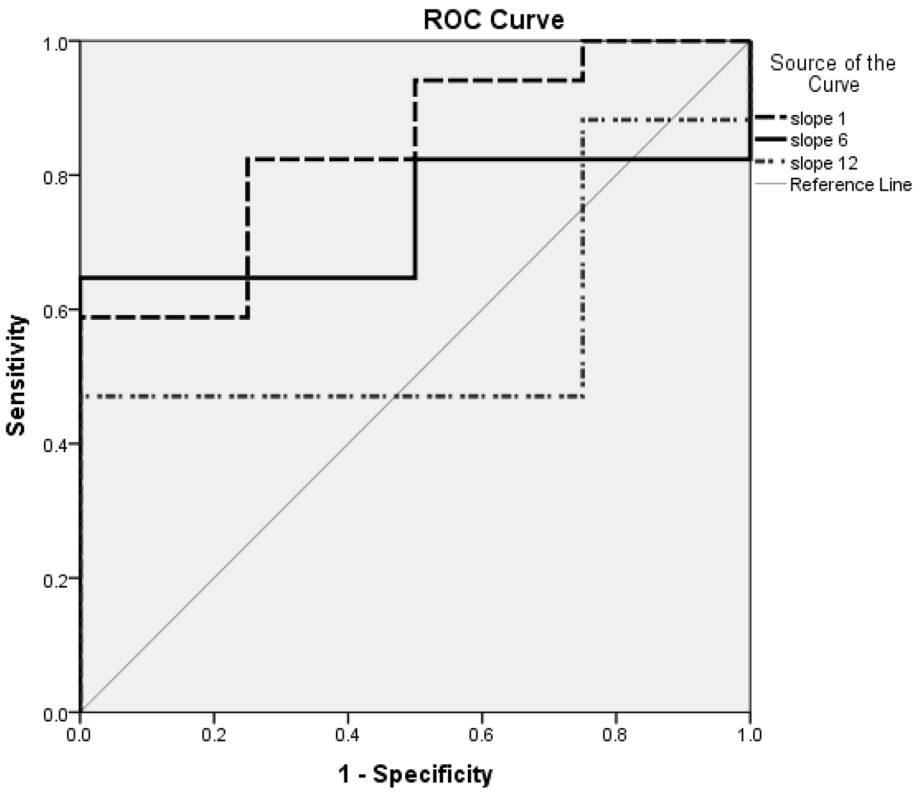

Fig. 3 ROC curve representation of AGF slope E1, E6, E12 to differentiate between the two groups of SNR loss of BKB-SIN test

Correlation between ECAP AGF threshold and age, duration of HI and duration of CI use

This study demonstrated no statistically significant correlation between age, duration of hearing loss and duration of CI use and AGF slope E1, E6 and E12.

Discussion

Since SGNs are the target cells for CI stimulation, measuring the ECAP has grown in importance as a method for confirming the functionality of these cells [15].

Table 5 Comparison of AGF slope values between the two groups of language test at E1, E6, E12 in μV/qu

Variables	Group 1	Group 2	Test of significance	*P*
AGF Slope E1			T 2.486	0.022*
Min. – Max	20.12 – 81.66	29.75 – 110.2		
Mean ± SD	45.3 ± 20.22	70.3 ± 24.62		
AGF Slope E6			T 0.983	0.358
Min. – Max	9.98 – 57.54	14.3 – 95.8		
Mean ± SD	34.4 ± 12.51	46.2 ± 30.55		
AGF Slope E12			T 0.834	0.414
Min. – Max	4.51 – 56.0	14.12 – 51.30		
Mean ± SD	23.0 ± 16.67	29.3 ± 15.29		

* r (Pearson correlation) *$p \leq 0.05$ (Statistically significant)

This research aimed to study ECAP thresholds and AGF in cochlear-implanted children and to find the relation between ECAP measures and speech perception measures.

ECAP AGF thresholds mean and SD were found to be at E1, E6 and E12 (11.6 ± 4.09) (14.2 ± 4.66) and (11.9 ± 4.23) qu, respectively, with no statistically significant difference between them. These results agreed with the results reported by van de Heyning et al. [16] and Walkowiak et al. [17]. This could be explained as the ECAP threshold being a less reliable correlator of neural health as low SGN counts in guinea pigs were associated with low amplitude and lower slope values, but ECAP threshold did not differ as a function of SGN [18]. Gordon et al. [19] observed that ECAP thresholds were much greater for the middle and basal electrodes than for apical ones. They interpreted this as a consequence of either improved neuronal survival or closer proximity between the electrodes and activated neurons in the apex [20].

In the current study, the ECAP AGF slope exhibited much lower slope values for electrodes in the basal area, medium values at the middle part of the cochlea and the highest in the more apical region. These results agreed with Gartner et al. [15] who studied AGF slope in children with Medel CIs and reported that the lowest slope values were at the basal electrodes and the highest at the apical electrodes. Two possible causes for decreasing the AGF slope from apex to base, the first is the SGN density, and the second is the electrode nerve distance [15].

As regards SGNs density, ganglion cell densities were found to be greater at the apex than the base by histological analysis of temporal bone in animals [21]. So, the discovery of greater slopes at apical electrodes and reduced slopes in the basal area may be connected to lower residual SGN numbers in the base and higher residual SGN numbers in the apex [15]. Another factor of steeper AGF at the apex is related to the electrode-nerve distance, which relates to the variety of peripheral variables, such as electrode location, bone and tissue development, and the health of the auditory neurons, that may affect the stimulation of the auditory nerve [22].

DeVries et al. [22] used estimates from CT imaging to analyze the relationship between ECAP metrics and other electrode-neuron interface metrics. They discovered that electrodes located far from the modiolus were not linked to smaller ECAP amplitudes, concluding that ECAP amplitude and AGF are more sensitive to the neural conditions than electrode position.

As regards BKB-SIN results in this study, the mean value of BKB SNR loss was 12.1 ± 3.45 dB. This agreed

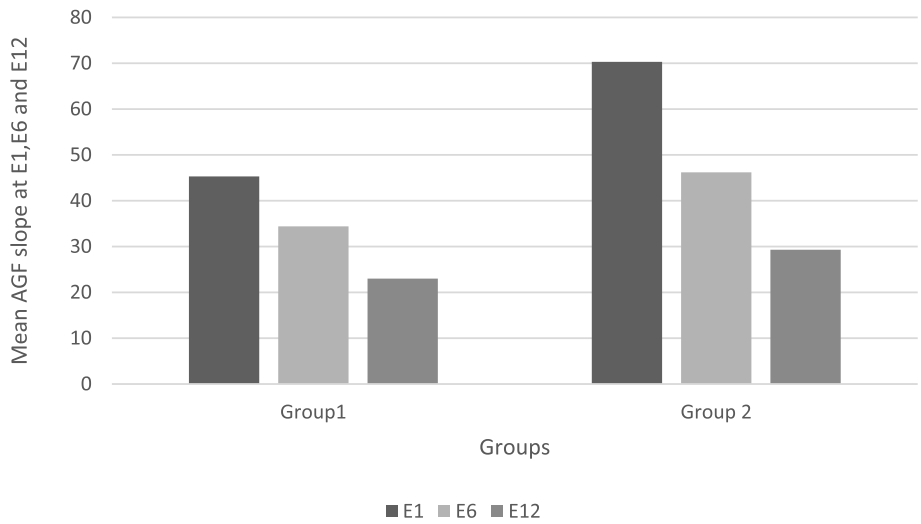

Fig. 4 Comparison mean of AGF slope E1, E6, E12 between the two groups of SNR loss of BKB-SIN test

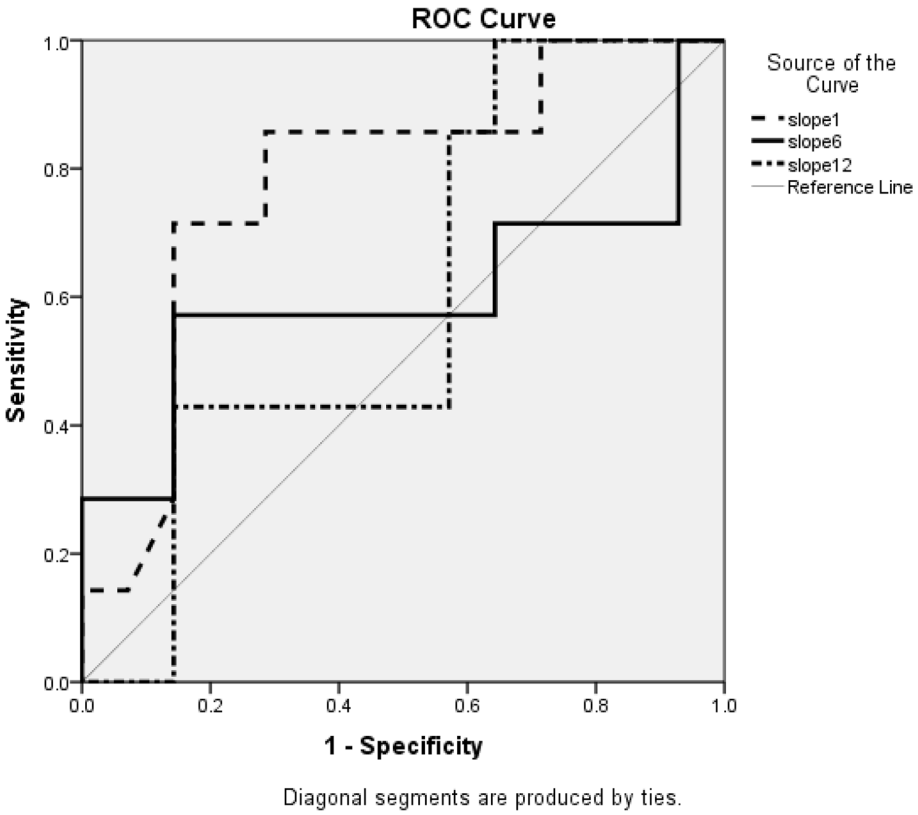

Fig. 5 ROC curve representation of AGF slope E1, E6, E12 to differentiate between the two groups of language test

with Miranda et al. [23], Donaldson et al. [24], and Gifford et al. [25] who found that the average BKB SNR loss in their studies in CI users was 11.9 dB, 11.4 dB and 12 dB, respectively.

Amer et al. [12] found that the value of average SNR loss is (0–3 dB), in comparison to the average SNR loss of CI children in this study of (12.1 dB). This means that CI users struggle in noisy situations. This is due to the limitations of the processing techniques used in CIs, which are created to provide the auditory system with spectrally broad signals. Broadened filters do not adequately represent a spectral structure that is phonologically related. Therefore, it is challenging to distinguish that spectral structure from ambient noise [26].

As regards the relation between ECAP threshold and speech perception tests, there was no correlation between ECAP threshold and speech perception in this study. This agreed with Cosetti et al. [27] and Sobhy et al. [28], who found no significant correlation between ECAP threshold and speech perception performance. Also, He et al. [3] reported that threshold was not related to vowel recognition scores in their sample of participants. This is due to the ECAP threshold being less reliable correlated to neural health.

Whereas there was a significant positive correlation between AGF slope values at the apical electrode (E1) and the results of word recognition score and a significant negative correlation between slope values at apical (E1), middle (E6), basal (E12) electrodes and SNR loss of BKB-SIN which means that: the steeper (higher) AGF slope, the more increase in word recognition score and the decrease in SNR loss of BKB (better speech performance).

These results are in accordance with Kim et al. [4], who concluded that the slope values strongly correlated with how well they did on the CNC words and the BKB-SIN test. Performance was connected with steeper sloped ECAP growth functions. They concluded that AGF slope is correlated to SGNs and neural survival, which are essential factors in determining CI outcome (better speech perception). Feng et al. [29] reported that neural health affects speech outcomes.

However, Jahn et al. [30] found no correlation between the ECAP responses for AGF slope, amplitude, or threshold and vowel recognition scores. Also, Sobhy et al. [28] in their study on Medel AB CI children, found no significant correlation between AGF slope and performance in monosyllabic phonetically balanced kindergarten

(PB-KG2) speech test, Bisyllabic phonetically balanced kindergarten (PB-KG1) or word intelligibility by picture identification (WIPI). Finally, they stated that there are other elements, such as cognitive capacities, that affect speech perception results, as described by [31–33], in addition to the condition of the SGNs.

As regards the correlation between AGF slope and IQ, IQ reflects central cognitive factors such as auditory memory, attention, and problem-solving used to finish difficult jobs [34]. This study showed a significant positive relationship between slope values at apical (E1) and middle (E6) electrodes and IQ test. This agreed with Malpas et al. [35], who studied the variation of IQ compared to MRI results and indicated that higher intelligence is associated with higher neural connectivity between diffuse cortical regions.

The current study found a correlation between AGF slope and phonological assessment (intelligibility, auditory level and language test) in the form of a significant positive correlation between slope values at the E1 electrode and intelligibility level. Kleine et al. [36] assessed speech intelligibility function while the map of the CI simulation was held constant; they stated that reducing the number of auditory nerve cells leads to decreased speech recognition performance hence the intelligibility. A significant positive correlation was found between slope values at the apical (E1) electrode and auditory level. Schery et al. [37] reported that a higher auditory level means a higher ability to discriminate one sound from another (pattern perception), to identify the sounds or words heard, and finally, to comprehend the stimulus using an audition.

Peelle et al. [38] studied the effect of hearing loss on neural systems and found that the auditory level was affected by a systematic downregulation of neuronal activity during the interpretation of higher-level components of speech brought on by decreases in peripheral auditory acuity. This may also be a factor in the loss of grey matter volume in the primary auditory cortex.

Also, a significant positive correlation was found between AGF slope at E1 values and total, receptive and expressive age of language test. Researchers in the domains of clinical audiology and auditory neuroscience were aware of the neurological effects of hearing deprivation. They also know that early implantation means that healthy neurons present to enable the auditory system's synaptogenesis to take place, hence better language development [39].

The sensitivity and specificity of AGF slope showed that apical electrode slope provides a sensitive measurement as an indicator of better speech understanding in noise and better language test performers. The low specificity could be explained as language test not only assess linguistic skills in the areas of semantics, morphology, syntax, integrative language skills (e.g., categorizing, defining words) but also skills in the areas of preverbal behaviors (communication skills, such as eye contact, attention to speech, vocal behavior, and gestural communication) [40].

Conclusions

The AGF slope is better than the ECAP threshold for detecting neural survival. Therefore, apical AGF slope correlated with better CI performance in both phoniatric and audiological assessment measures.

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None.

Authors' contributions
NAB for clinical cases and writing manuscript, WE for clinical cases interpretation, data analysis. THE for study concept and design. SMEA for clinical evaluation and follow up of speech therapy for patients and AME for interpretation and writing manuscript. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The research approved by The Research Ethics Committee. approval code No. 34427/01/21). Ethical committee Tanta University, Egypt. An informed written consent to participate in the study was provided by all participants and informed written consent from parents/guardians of patients under 16 years old.

Consent for publication
Not applicable.

Competing interests
No Conflict of interest.

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