Neural representation of speech in pediatric cochlear implant recipients

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Objective
Cochlear implantation (CI) is an established treatment for selected individuals with bilateral severe-to-profound sensorineural hearing loss who derive limited benefits from conventional hearing aids.

This work was designed to assess speech processing at the brainstem and the cortical level in children fitted with CIs after a variable duration of implantation and speech therapy compared with language acquisition.

Patients and methods
Thirty-one children between 4 and 5 years of age fitted with unilateral CIs of variable duration ranging from 1 to 3 years were assessed at 1 year (n=10), 2 years (n=12), and 3 years (n=9) after device activation. They underwent aided sound–field audiological evaluation, speech-evoked auditory brainstem response, and speech-evoked mismatch negativity test. The results were compared among the study groups and then correlated with language assessment and speech perception tests.

Results
Both speech-evoked auditory brainstem response and mismatch negativity test responses were significantly different among the three groups. Moreover, language development showed a significant difference among the three groups.

Conclusion
Children fitted with CI showed cortical and brainstem activation from the first year and these activity changes continue with CI use and both are highly correlated with receptive and expressive language. Thus, both electrophysiologic tests could be early and critical objective indicators of optimal speech encoding after programming of the CI device.

Keywords:
children, cochlear implants, mismatch negativity, speech-evoked auditory brainstem response, speech processing

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Introduction

The cochlear implantation (CI) has given children with severe-to-profound sensory hearing loss access to the auditory world with great success by directly stimulating the auditory nerve and thus bypassing the dysfunctioning inner ear. Nevertheless, stimulating the auditory nerve with up to 22 active electrodes cannot be compared with the stimulation by thousands of inner ear hair cells. Consequently, frequency discrimination with the CI is lower and the dynamic range smaller, even though technical innovations strive to bridge the gap. In addition to the condition of the cochlea and survival of the spiral ganglion neurons, the relative integrity or extent of degeneration of the central auditory pathway is likely to affect the benefit that can be obtained from a cochlear implant. Severe degeneration of the brain structures that normally process the sensory input from the ear is likely to limit the success of a cochlear implant in restoring hearing [1,2].

Speech-evoked auditory brainstem response (SABR) represents the precise temporal and spectral neural code of the speech within the brainstem. Complex sounds used to evoke SABR include vowels, syllables, words, and phrases. One of the most commonly studied brainstem responses to complex stimuli in recent years has been the auditory brainstem response evoked using a 40-ms synthesized consonant–vowel syllable /da/ [3–8].

A large number of studies describe language outcomes of children with a CI after several years of implant and report variable results. Nevertheless, little is known about the perceptual resources these children have during the phase of acquisition. This, however, would be crucial information as the window of

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language acquisition is finite, and implanted children are already delayed in receiving appropriate auditory input. Thus, the earlier and more we know about what an implanted child can extract from its language environment, the better and more specific therapeutic intervention can become and the better we could acknowledge possible compensatory strategies and the potential additional cognitive resources that are needed [9–16].

Taken together, there is only scarce information available on whether implanted children perceive and discriminate fine spectral differences in speech syllables at both subcortical and cortical levels. On that ground, we performed the present study to investigate the SABR and event-related potentials.

Patients and methods

Patients

The study group comprised a total number of 31 CI children operated by second and third authors (I.M.N. and H.A.A.A.K.) in three different hospitals, but further audiologic evaluation was performed in Demerdash Hospital, Ain Shams University, between October 2014 and June 2016.

Inclusion criteria

(1) Age between 4 and 5 years.
(2) Prelingual deafness.
(3) Hereditary or idiopathic hearing loss.
(4) Duration of implant use of more than 9 months.
(5) Regular speech and language therapy and at the same rate, place, and with the same phoniatrician (A.A.A.M.).
(6) Average or above average mentality.
(7) Complete cochlear electrode insertion with no flagged electrodes.

Exclusion criteria

(1) Partial electrode insertion or cochlear deformity.
(2) Presence of disabilities other than hearing loss.

On the basis of the duration of CI, the children were further subdivided into three groups:

(1) Group 1: 1 year of device use (10–12 months).
(2) Group 2: 2 years of device use (22–24 months).
(3) Group 3: 3 years of device use (34–36 months).

Informed consent was obtained from all individual participants included in the study

Equipment

(1) Computerized two-channel audiometer Madsen (model GSI 61; Grason-Stadler Inc., Eden Prairie, Minnesota, USA).
(2) Sound-treated room (IAC model 1602, USA).
(3) Cassette tape recorder with CD player.
(4) Biologic evoked potential equipment.

Phoniatric workup

This study was conducted by the fourth author (A.A.A.M.).

Language tests: language assessment was carried out using a standardized Arabic language test developed by Kotby in 1994. It includes phonology (articulation), syntax perception, syntax expression, semantics perception, semantics expression, and pragmatics.

Audiological workup

This was carried out by the first author (T.T.A.R.).

(1) Programming of CI:
    By setting behavioral map, most comfortable (M in MED El, Maestro with Opus 2 speech processor (Austria) and C in Oticon Neurelec, Digisonic, EVO speech processor (France)) levels and the threshold levels were set to 10% as per recommendation from MED-EL. With the microphone active, all M levels were increased until consistent responses to sound were obtained. Loud sounds were used to ensure there was no loudness discomfort. Over 8 weeks the profile was adjusted on the basis of detection of pure tones and discrimination of acoustic patterns (Ling's detection and aided testing) as well as determining 'blinking' levels for each ear individually.
(2) Full history taking.
(3) Aided warble tone response: it was performed through sound–field using warble tone at 0.25, 0.5, 1, 2, 4, 6, and 8 kHz.
(4) Word discrimination in quiet [17].
(5) Arabic version of the word in noise test [18].
(6) SABR and mismatch negativity (MMN) testing: this test was applied using loudspeakers at a distance of 1 m in front of the patient at 0 azimuth in a sound-treated room, with the child sitting on the bed with a parent (usually the mother) during the whole assessment in the room. To keep the child's head constant in place, he/she was instructed to watch cartoon video from a tablet placed on his/her legs.

Electrode montage

An active electrode was placed at Cz sites referenced to a mastoid electrode M1 of the nonimplanted ear. The ground electrode was placed at FPz according to the 10–20 electrode system using Ag/AgCl electrodes. The electrode impendence was kept below 5 kΩ.

Stimulus parameters

(1) For SABR assessment, alternating polarity, synthetic, 40 ms /da/ stimuli were presented to either ear at a stimulus rate of 10.9 Hz at 80 dBSPL. Responses were band-pass online filtered from 100 to 2000 Hz and recorded over 62 ms poststimulus time period. Artifact rejection was set at ±31 mV to reject epochs that contained myogenic artifacts. Three thousand repetitions were collected for each stimulus polarity (condensation and rarefaction).
(2) MMN test: the stimulus condition applied for recording MMN was a typical odd-ball paradigm. The probability of the rare stimulus was 0.2 and the probability of the frequent stimulus was 0.8. 200 ms /Ba/ speech syllable served as frequent stimulus, whereas deviant (rare) was the 200 ms /Ga/ speech stimulus. The presentation level at the position of the patient's ears was ~80 dBSPL. Recording was carried out while the child was looking into a tablet (nonattentive state) and was asked not to pay attention to the sounds.

Recording parameters

(1) SABR: recording of acoustically evoked SABR was very challenging and difficult due to the electrical activity generated from the implanted electrode array. Moreover, the speech processors do not encode the phase of the incoming acoustic stimulus. This approach would also require the temporal synchronization of the external acoustic stimulus, the pulse train delivered by the processor, and the sampling clock of the recording system. This is an achievable goal using specialized hardware and software. Moreover, an electrode jumper was connected to the preamplifier and it provided a great help in eliminating most of the artifacts. Recent research studies had concluded that 23 ms signal is the lower limit of duration for speech stimuli to skip an artifact in the time region of interest.
(2) Responses were band-pass online filtered from 100 to 2000 Hz and recorded over 62 ms poststimulus time period. Artifact rejection was set at ±31 mV to reject epochs that contained myogenic artifacts. Three thousand repetitions were collected for each stimulus polarity (condensation and rarefaction). Two runs were collected for each ear. An onset response to the speech stimulus /da/ includes a positive peak (wave V), followed immediately by a negative trough (wave A). The frequency following response follows the onset response, a series of negative peaks (C, D, E, and F). The offset response is represented by wave O. Waves C and O represent the envelope boundaries of the frequency following response. The peak latencies for all waves and VA slope were measured.
(3) MMN: a CI stimulation artifact will last for at least the duration of the stimulus. Given that the amplitude of the artifact can 5–10 times larger than the averaged evoked response, the artifact will mask a biologic response of interest that occurs within the time frame of the stimulus duration. We have used a 200 ms speech sound /ba/ to elicit the Cortical Auditory Evoked Potential (CAEP) in implant patients [19].
(4) The band-pass filter settings of the recording system were 0.1 and 30 Hz. The number of sweeps was 40 with a sweep time of 600 ms. The analysis period was 500 ms with 100 ms prestimulus recording. The measurement was repeated once more and the results were averaged. The MMN response was determined after subtracting the response of the frequent stimuli from the response of the deviant stimuli. The total time of recording was about 30–40 min. MMN was identified as a prominent first negative peak in the domain of N1 (100–250 ms). Latency was measured from the stimulus onset to the maximum negative peak of the MMN. Amplitude was measured between the baseline and the following negative trough. It is measured relative to a baseline calculated as the mean amplitude over the 100 ms preceding the stimulus.

Statistical analysis

Student's *t*-test and analysis of variance test were used to compare the distribution of parametric, quantitative data when comparing the study groups. A *P* value of less than or equal to 0.05 indicated statistical significance. The computer program used was SPSS (release 24.0; SPSS Inc., Chicago, Illinois, USA). Pearson's correlation was used to measure correlation between different variables.

Results

Table 1 presents the demographic data of the three study groups. Figure 1 shows sex distribution of the three study group.

Table 2 presents the audiogram in the study groups; no significant differences were detected among groups as regards aided pure-tone hearing thresholds.

Table 3 presents the speech perception in the study groups; significant differences were detected among groups 2 and 3 in discrimination in noise test only. Group 1 did not have enough language to perform the speech tests.

Table 1 Demographic and clinical data of the three study groups

	N	Mean	SD	Minimum	Maximum
Age (ears)					
Group 1	10	4.133	0.4924	4.0	5.0
Group 2	12	4.633	0.3892	4.33	5.0
Group 3	9	4.800	0.2200	4.5	5.0
Age at implantation (months)					
Group 1	10	30.42	1.240	33	24
Group 2	12	25.67	1.775	23	30
Group 3	9	18.47	1.033	16	20

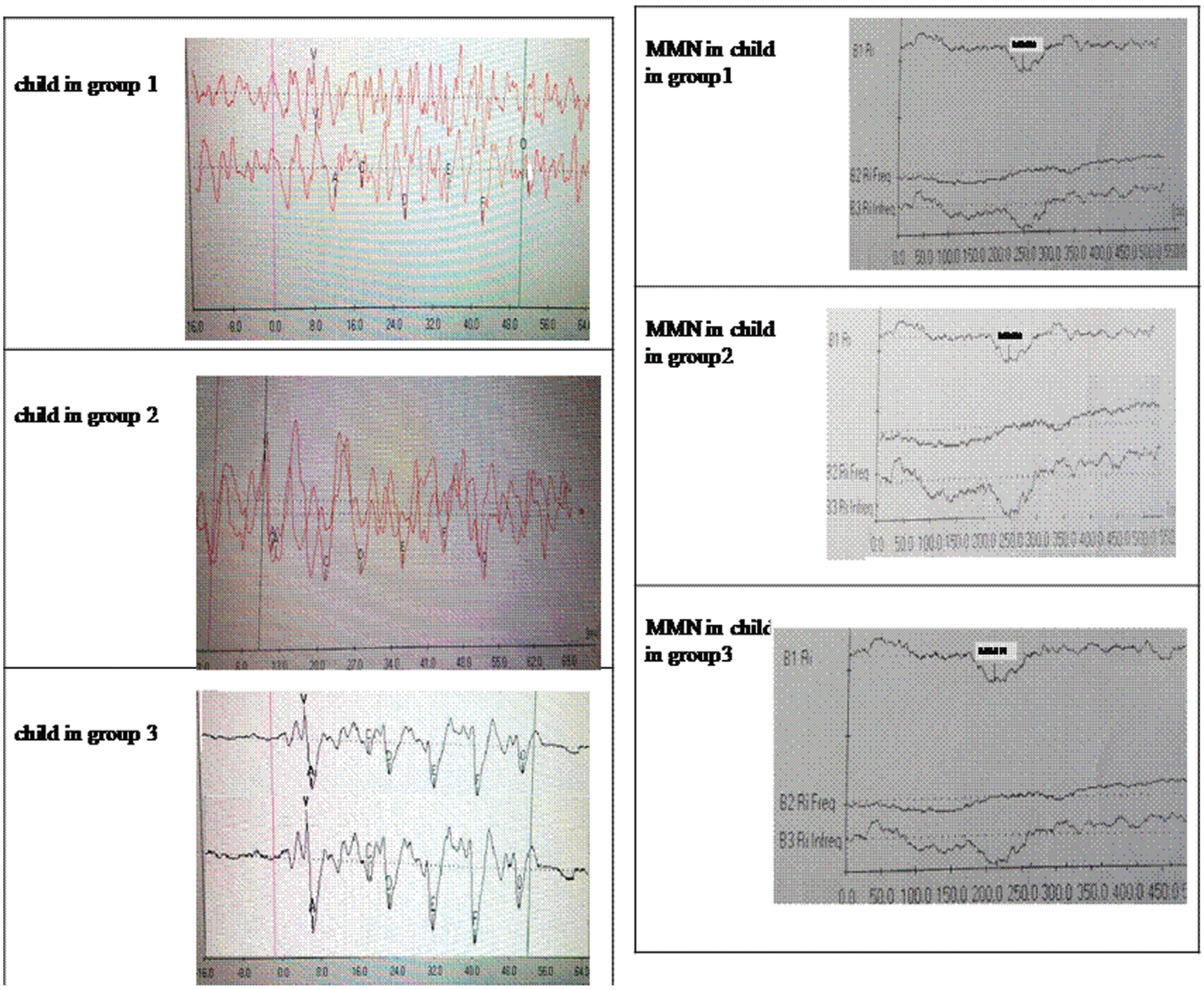
Tables 4–6 show the following:

(1) Waves V and F latency values differed significantly between groups 1 and 3. Moreover, they differed significantly between groups 2 and 3. However, they did not differ significantly between groups 1 and 2.
(2) Waves A and O latency values differed significantly between groups 1 and 3. However, they did not differ significantly, neither between groups 1 and 2 nor between groups 2 and 3.
(3) Wave C latency values differed significantly between groups 1 and 3. Moreover, they differed significantly between groups 1 and 2. However, they did not differ significantly between groups 3 and 2.

Tables 7 and 8 show the following:

(1) MMN wave latency differed significantly among all groups.

Figure 1



Sex distribution of the three study groups.

Table 2 Aided sound–field pure-tone threshold in the three study groups and the analysis of variance test of significance among them

	N	Mean	SD	Minimum	Maximum	*P* (ANOVA)
250 Hz						
Group 1	10	30.00	4.082	25	35	0.531
Group 2	12	31.25	2.261	30	35	
Group 3	9	30.00	0.000	30	30	
500 Hz						
Group 1	10	28.50	4.116	25	35	0.358
Group 2	12	26.67	2.462	25	30	
Group 3	9	28.33	2.582	25	30	
1000 Hz						
Group 1	10	26.50	5.798	20	35	0.128
Group 2	12	25.00	0.000	25	25	
Group 3	9	20.00	0.000	30	30	
2000 Hz						
Group 1	10	24.50	2.838	20	30	0.099
Group 2	12	23.33	2.462	20	25	
Group 3	9	26.67	2.582	25	30	
4000 Hz						
Group 1	10	22.17	1.528	20	25	0.102
Group 2	12	21.50	1.883	20	25	
Group 3	9	23.00	0.000	25	25	

ANOVA, analysis of variance.

Table 3 Aided word discrimination scores in quiet and in noise (word in noise)

	Mean	SD	Minimum	Maximum	*F*	*P*
WDQ						
Group 2	72.33	3.985	68	80	0.102	0.923
Group 3	77.33	5.465	72	84		
WIN						
Group 2	49.33	7.101	40	56	21.740	0.000
Group 3	65.33	5.465	60	72		

WDQ, word discrimination scores in quiet; WIN, word in noise.

(2) Both MMN amplitude and duration did not differ significantly among all groups.

Figures 2 and 3 and Table 9 show that the only significant difference found between right side implants and left side implants was in MMN results.

Table 10 shows that there was no significant difference between the two types of implants as regards electrophysiologic tests, speech perception tests, and language assessment.

Tables 11 and 12 show that receptive language and receptive language equivalent and expressive language equivalent differed significantly between groups 1 and 3. Moreover, they differed significantly between groups 2 and 3. However, they did not differ significantly between groups 1 and 2.

Table 13 reveals the following:

(1) The duration of CI use is highly correlated with wave V and O latencies. However, the age at CI is highly correlated with MMN parameters.
(2) Speech perception in quiet is highly correlated with age at CI. Moreover, speech perception in noise is highly correlated with age at CI, duration of CI, wave A and C latencies, and all MMN wave parameters.

Discussion

Auditory neurophysiologic investigations are presently used successfully in CI patients to confirm the diagnosis of profound hearing loss before CI. Short latency potentials such as auditory brainstem responses and middle latency responses have proved most valuable in this regard. Although very effective in evaluating the peripheral nerves and device, these potentials are incapable of assessing the status of the

Table 4 Aided speech-evoked auditory brainstem response wave latencies in the three study groups and the analysis of variance test of significance among them

	Mean	SD	Minimum	Maximum
V				
Group 1	9.35	0.588	9	10
Group 2	8.65	0.160	9	9
Group 3	7.27	0.628	7	8
A				
Group 1	10.68	0.770	10	11
Group 2	9.86	0.112	10	10
Group 3	9.20	1.676	8	12
C				
Group 1	14.04	1.994	12	16
Group 2	13.00	0.887	12	14
Group 3	15.30	2.181	12	17
D				
Group 1	20.50	1.069	20	22
Group 2	20.31	0.789	20	21
Group 3	22.20	4.533	17	29
E				
Group 1	26.67	1.865	25	28
Group 2	25.13	2.977	22	28
Group 3	24.18	4.104	26	37
F				
Group 1	38.00	0.001	38	38
Group 2	39.00	0.001	39	39
Group 3	39.86	2.895	35	42
O				
Group 1	46.38	3.889	45	56
Group 2	52.00	0.001	52	52
Group 3	45.72	3.383	42	52

Table 5 Comparison among the three study groups as regards speech-evoked auditory brainstem response results

ANOVA among groups	*F*	*P*
V	4.019	0.035*
A	6.660	0.007**
C	10.442	0.000**
D	1.980	0.155
E	0.260	0.853
F	6.597	0.004**
O	4.515	0.017*

ANOVA, analysis of variance. *The mean difference is significant at the 0.05 level. **The mean difference is significant at the 0.01 level.

central nervous systems, primarily the auditory cortex. However, they are also used to evaluate the integrity of the implant device and facilitate its programming after implantation [20].

In the present study, we studied the brainstem and cortical encoding of speech in recently implanted CI children and the effect of duration of deafness and CI use on the speech representation at both levels. In the field of CIs, behavioral methods are the primary tools used at

Table 6 Post-hoc tests (least significant difference test) among the three groups as regards waves V, A, C, F, and O, which showed a significant difference using the analysis of variance test

Dependent variables	Groups		*P*
V	1	2	0.754
		3	0.005**
	2	1	0.754
		3	0.013*
	3	1	0.005**
		2	0.013*
A	1	2	0.147
		3	0.002**
	2	1	0.147
		3	0.177
	3	2	0.177
		1	0.002**
C	1	2	0.016*
		3	0.014*
	2	1	0.016*
		3	0.264
	3	1	0.014
		2	0.264
F	1	2	1.000
		3	0.021*
	2	1	1.000
		3	0.004**
	3	1	0.021*
		2	0.004**
O	1	2	0.208
		3	0.004**
	2	1	0.208
		3	0.825
	3	1	0.004**
		2	0.825

*The mean difference is significant at the 0.05 level. **The mean difference is significant at the 0.01 level.

Table 7 Comparison among the three study groups as regards mismatch negativity test results

	F	*P*
MMN latency	21.965	0.000
MMN amplitude	0.527	0.602
MMN duration	0.837	0.402

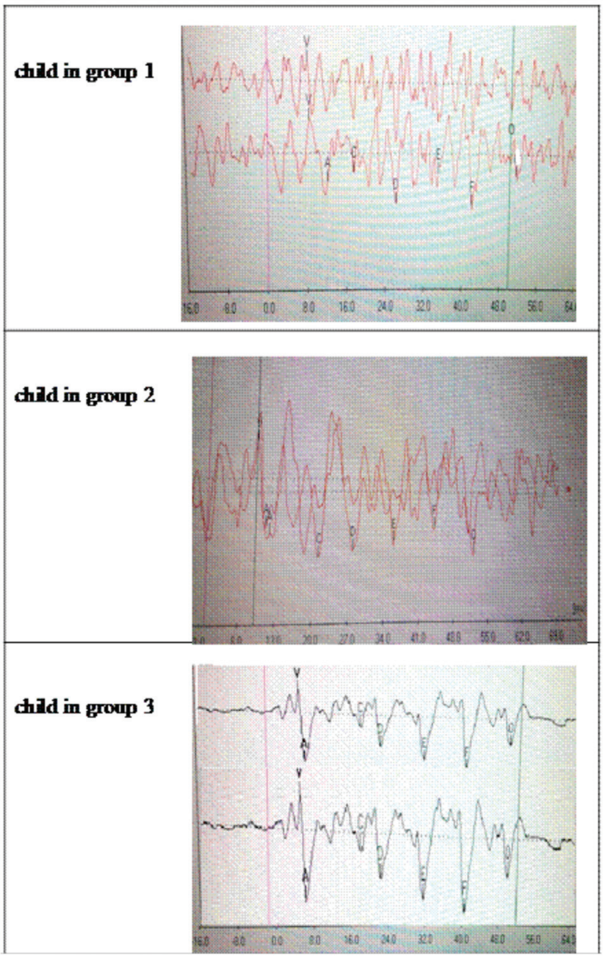
MMN, mismatch negativity.

Table 8 Post-hoc tests (least significant difference test) among the three groups as regards waves V, A, C, F, and O, which showed a significant difference using the analysis of variance test

Dependent variables	I duration of CI	J duration of CI)	*P*
MMN latency	Group 1	Group 2	0.001**
		Group 3	0.000**
	Group 2	Group 1	0.001**
		Group 3	0.005**
	Group 3	Group 1	0.000**
		Group 2	0.005**

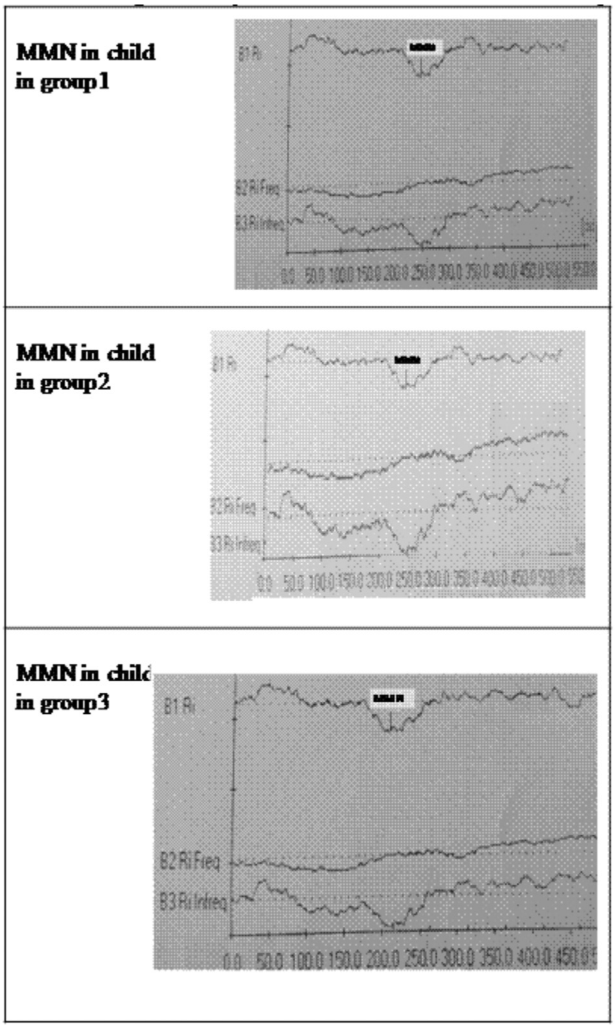
CI, cochlear implant; MMN, mismatch negativity. **The mean difference is significant at the 0.01 level.

Figure 2



Speech-evoked auditory brainstem response data in the three study groups.

Figure 3



Speech-evoked mismatch negativity (MMN) test data in the three study groups.

present to assess and predict the outcome of implantation in adults and children. The recent decline in the age of implantation with a strong trend toward early implantation has subsequently requested the development of a more objective tool to predict future outcome after CI. To the best of authors' knowledge, no published research studies were conducted to evaluate the effect of CI use on SABR and MMN. We analyzed speech audiometric comparison data as well as speech perception tests and electrophysiologic data.

As regards the aided behavioral data of the children, Table 2 shows that the aided sound–field threshold was comparable in all study groups. However, Table 3 shows that speech discrimination in noise (but not quiet scores) was significantly different among the study groups.

Electrophysiological measures have provided an important addition to the battery of tests used to manage children with CIs. As regards SABR, Table 5 shows that wave V, A, C, F, and O latency values differed significantly between groups 1 and 3, reflecting a gradual reorganization of the inferior colliculus neurons with auditory experience. Moreover, wave V and F latencies differed significantly between groups 2 and 3 but they did not differ significantly between groups 1 and 2, reflecting that maximum changes occur during the second year after implantation and not the first year. However, wave C latency differed significantly between groups 1 and 2, reflecting maximum improvement in the perception of voicing pattern of speech in the first year. However, they did not differ significantly between groups 3 and 2 and may reflect slower progress after the first year of implantation. Many electrophysiological studies examined the functional consequences of chronic electrical stimulation of the auditory nerve on neuronal responses in the central auditory system. Experiments have shown that stimulation delivered by a CI can result in significant changes both in the spatial selectivity of activation and in temporal processing within the auditory midbrain (inferior colliculus) [21]. Onset and offset responses reflect processing of both segmental and

Table 9 Comparison between right and left implant results

Implant sides	*N*	Mean	SD	*P* (*t*-test)
SRT				
RT	25	28.75	2.261	0.201
LT	6	27.50	2.739	
WDQ				
RT	25	69.00	6.282	0.532
LT	6	78.00	4.899	
WIN				
RT	25	49.50	8.626	0.879
LT	6	62.00	8.295	
V				
RT	25	8.75	0.960	0.711
LT	6	7.78	0.567	
A				
RT	25	10.16	0.759	0.091
LT	6	9.39	0.948	
C				
RT	25	13.58	1.548	0.076
LT	6	15.46	2.412	
D				
RT	25	21.37	2.930	0.613
LT	6	21.43	3.272	
E				
RT	25	27.09	4.456	0.686
LT	6	31.76	4.402	
F				
RT	25	38.88	1.269	0.227
LT	6	38.83	2.652	
O				
RT	25	48.65	3.872	0.371
LT	6	46.86	4.743	
MMN latency				
RT	25	250.00	0.002	0.013
LT	6	310.67	46.992	
MMN amplitude				
RT	25	8.44	0.532	0.017
LT	6	9.13	0.000	
MMN duration				
RT	25	81.67	10.328	0.063
LT	6	85.00	0.009	
Receptive				
RT	25	26.94	3.296	0.410
LT	6	30.00	1.866	
Receptive EQ				
RT	25	26.82	4.866	0.361
LT	6	28.80	9.418	
Expressive				
RT	25	26.08	1.558	0.318
LT	6	26.00	2.449	
Expressive EQ				
RT	25	22.88	2.112	0.281
LT	6	22.80	3.271	
Total language				
RT	25	55.08	6.928	0.237
LT	6	55.80	10.710	

The only significant difference found between right side implants and left side implants was in MMN results. EQ, equivalent; LT, left; MMN, mismatch negativity; RT, right; SRT, speech reception threshold; WDQ, word discrimination scores in quiet; WIN, word in noise.

Table 10 Comparison between the two brands of implants

Implant types	*N*	Mean	SD	*P* (*t*-test)
SRT				
MED-EL	22	28.08	2.532	0.102
Neurelec	9	29.00	2.236	
WDQ				
MED-EL	22	71.06	8.066	0.632
Neurelec	9	72.80	1.789	
WIN				
MED-EL	22	52.71	1.422	0.179
Neurelec	9	53.60	3.578	
V				
MED-EL	22	8.56	1.099	0.241
Neurelec	9	8.40	0.224	
A				
MED-EL	22	10.08	1.178	0.069
Neurelec	9	9.75	0.000	
C				
MED-EL	22	14.16	2.102	0.086
Neurelec	9	13.46	0.818	
D				
MED-EL	22	22.05	2.989	0.613
Neurelec	9	19.12	1.006	
E				
MED-EL	22	28.33	5.445	0.686
Neurelec	9	27.54	0.818	
F				
MED-EL	22	39.08	1.516	0.625
Neurelec	9	38.17	1.865	
O				
MED-EL	22	47.71	3.917	0.667
Neurelec	9	50.06	4.338	
MMN				
MED-EL	22	295.50	48.642	0.073
Neurelec	9	293.60	38.642	
AMPL				
MED-EL	22	8.62	0.551	0.053
Neurelec	9	7.62	0.851	
Duration				
MED-EL	22	85.00	10.690	0.103
Neurelec	9	85.00	10.690	
Receptive				
MED-EL	22	28.13	6.612	0.410
Neurelec	9	31.00	2.612	
Receptive EQ				
MED-EL	22	27.00	5.876	0.646
Neurelec	9	28.67	5.774	
Expressive				
MED-EL	22	26.08	1.824	0.058
Neurelec	9	26.00	0.000	
Expressive EQ				
MED-EL	22	22.84	2.461	0.078
Neurelec	9	23.00	0.000	
Total language				
MED-EL	22	55.48	7.912	0.353
Neurelec	9	53.50	4.041	

AMPL, amplitude; EQ, equivalent; MMN, mismatch negativity; SRT, speech reception threshold; WDQ, word discrimination scores in quiet; WIN, word in noise.

Table 11 Comparison among the three study groups as regards language tests (language age in months)

	Mean	SD	*F*	*P*
Receptive				
Group 1	26.43	3.155	6.956	0.006
Group 2	24.70	2.214		
Group 3	38.00	13.856		
Receptive EQ				
Group 1	25.29	4.608	5.08	0.018
Group 2	23.00	3.162		
Group 3	34.00	11.547		
Expressive				
Group 1	25.43	1.397	2.7	0.093
Group 2	26.00	0.003		
Group 3	27.50	2.887		
Expressive EQ				
Group 1	22.00	1.915	5.569	0.013
Group 2	23.00	0.002		
Group 3	24.50	4.041		

EQ, equivalent.

Table 12 Post-hoc tests (least significant difference test) among the three groups as regards language tests

	Groups		*P*
Receptive language	Group 1	Group 2	0.575
		Group 3	0.008
	Group 2	Group 1	0.575
		Group 3	0.002
	Group 3	Group 1	0.008
		Group 2	0.002
Receptive language EQ	Group 1	Group 2	0.439
		Group 3	0.029
	Group 2	Group 1	0.439
		Group 3	0.005
	Group 3	Group 1	0.029
		Group 2	0.005
Expressive language equivalent	Group 1	Group 2	0.427
		Group 3	0.033
	Group 2	Group 1	0.427
		Group 3	0.093
	Group 3	Group 1	0.033
		Group 2	0.093

EQ, equivalent.

suprasegmental information within the speech and, subsequently, prepare its processing at higher levels of the auditory system.

MMN method is an objective tool that provides a measure of automatic stimuli discrimination. As discussed here, Table 7 shows that MMN latencies differed significantly among the study groups, reflecting a great reduction in neural conduction time and an increase in the speed of cortical speech processing throughout the first 3 years after implantation. It is best to use these tests in a battery including behavioral measures in much the same way as similar electrophysiological measures are used with behavioral tests to diagnose and characterize hearing loss, and electrophysiologic studies can be used to monitor the neurophysiologic function of CI individuals.

These results indicated that the developing central auditory system is capable of substantial plasticity. The initially restricted area excited by the stimulated cochlear neurons expands over time as the central auditory system adapts to the only available afferent input. However, this expansion actually represents a significant degradation in the cochleotopic organization (frequency selectivity) of the central auditory system. It is important to note that chronic stimulation on two adjacent bipolar intracochlear channels of the CI can be effective in maintaining more normal selectivity of the central representations of stimulated cochlear sectors. Thus, competing inputs elicited by means of electrical stimulation on adjacent channels may prevent the expansion and degradation of frequency selectivity seen after single-channel stimulation [21].

Table 9 shows that there was no difference between right side and left side CI. The only significant difference found between right side implants and left side implants was in MMN results. This may be attributed to the alternative neural strategies that permit speech comprehension mainly in the various speech-processing left hemisphere regions after CI. As regards the performance with the two brands of CI devices, Table 10 shows that there was no significant difference between the two types of implants as regards electrophysiologic tests, speech perception tests, and language assessment.

Listening and speech skills do not emerge spontaneously as a result of children receiving CIs and then being exposed to conversation in their everyday environments. A concerted, deliberate rehabilitation effort is required before they learn to utilize the electrical signal from the CI for the purpose of speech recognition and speech and language acquisition. Both receptive and expressive language scores differed significantly between groups 1 and 3 (Table 11). Moreover, they differed significantly between groups 2 and 3. However, they did not differ significantly between groups 1 and 2. These findings are in agreement with most studies, which also reported maximum language acquisition during the second year after CI.

The duration of CI use is highly correlated with wave V, A, O, and C latencies and all MMN wave parameters and speech perception in noise (Table 13). However, the age at CI was highly correlated with

Table 13 Correlation among demographic, behavioral, and electrophysiologic data

	Duration of CI	Age at cochlear implantation	WIN	WDQ	Receptive EQ	Expressive EQ
Duration of CI						
r	1	−0.967	0.728*	−0.968*	0.140	0.371
P		0.026	0.022	0.032	0.860	0.629
Age at cochlear implantation						
r	−0.967	1	−0.980*	0.607	0.485	0.593
P	0.026		0.020	0.393	0.515	0.407
WIN						
r	0.728*	0.980*	1	0.608	0.442	0.589
P	0.022	0.020		0.392	0.558	0.411
WDQ						
r	−0.968*	0.607	0.505	1	0.259	0.475
P	0.032	0.393	0.495		0.741	0.525
V						
r	0.954*	−0.306	−0.488	−0.249	0.015	−0.215
P	0.046	0.694	0.512	0.751	0.985	0.785
A						
r	−0.826	−0.937	−0.988*	−0.592	−0.395	−0.568
P	0.174	0.063	0.012	0.408	0.605	0.432
C						
r	0.821	0.940	0.989*	0.593	0.398	0.570
P	0.179	0.060	0.011	0.407	0.602	0.430
D						
r	0.563	−0.350	−0.158	−0.15	−0.331	−0.175
P	0.437	0.650	0.842	0.849	0.669	0.825
E						
r	0.989*	0.453	0.620	0.333	0.067	0.300
P	0.011	0.547	0.380	0.667	0.933	0.700
F						
r	0.333	−0.577	−0.404	−0.29	−0.420	−0.314
P	0.667	0.423	0.596	0.704	0.580	0.686
O						
r	−0.968*	−0.762	−0.876	−0.50	−0.259	−0.475
P	0.032	0.238	0.124	0.495	0.741	0.525
MMN						
r	−0.577	1.0**	−0.980*	−0.60	−0.485	−0.593
P	0.423	0.000	0.020	0.393	0.515	0.407
AMPL						
r	0.577	−1.00**	0.980*	0.607	0.485	0.593
P	0.423	0.000	0.020	0.393	0.515	0.407
Duration						
r	0.577	−10.000**	0.980*	0.607	0.485	0.593
P	0.423	0.000	0.020	0.393	0.515	0.407

AMPL, amplitude; CI, cochlear implant; EQ, equivalent; MMN, mismatch negativity; WDQ, word discrimination scores in quiet; WIN, word in noise. *Correlation is significant at the 0.05 level (two-tailed). **Correlation is significant at the 0.01 level (two-tailed).

MMN parameters and speech perception in quiet and noise. Similarly, Owens [22] reported that, in most cases of early implantation, the expectation for language acquisition will follow the normal pattern. However, even a child implanted at 18 months of age has experienced a substantial delay in the commencement of the process of spoken language acquisition. Although parents may be able to facilitate their child's language acquisition, the overall rate of progress may not match that of hearing peers. The clinician must be aware of this aspect of the child's development to ensure that, through listening, the child is acquiring a sufficiently rich and sophisticated language system to allow for the communication of a range of concepts with a range of people [22].

Conclusion

Children fitted with CI showed cortical and brainstem activation from the first year and these activity changes continue with CI use and both are highly correlated with receptive and expressive language. Thus, both electrophysiologic tests could be early and critical objective indicators of optimal speech encoding after programming of the CI device.

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Conflicts of interest

There are no conflicts of interest.

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