Turkish Journal of Medical Sciences

http://journals.tubitak.gov.tr/medical/

Research Article

Turk J Med Sci
(2013) 43: 174-184
© TÜBİTAK
doi:10.3906/sag-1202-88

The effects of an adaptive directional BEAM microphone on the mismatch negativity responses of cochlear implant users in noise

Asuman ERDOĞAN*, Ferda AKDAŞ
Department of Audiology Speech and Language, Marmara University, İstanbul, Turkey

Received: 28.02.2012 • **Accepted:** 28.03.2012 • **Published Online:** 18.01.2013 • **Printed:** 18.02.2013

Aim: To investigate the effects of noise on mismatch negativity (MMN) responses and the possible benefits of an adaptive directional BEAM microphone in noise during MMN recordings, and to compare the cochlear implant-evoked potential results with normal hearing subjects.

Materials and methods: /da/ and /di/ speech stimuli were used to elicit MMN responses in 11 Freedom cochlear implant users and in 11 normal hearing subjects. Speech noise was delivered at 80 dB sound pressure level (–10 dB signal-to-noise ratio). All subjects were tested in quiet and noisy conditions. To compare the microphone effects, MMN responses for the cochlear implant group were recorded with an omnidirectional and adaptive directional BEAM microphone mode in noise.

Results: The MMN responses of the cochlear implantees and the normal hearing group were remarkably similar in terms of latency, amplitude, and morphology in both quiet and noisy conditions. MMN peak latencies were significantly prolonged in the noisy conditions compared to the quiet conditions for both groups. There was a significant decrease in MMN latencies when using an adaptive directional microphone in noise.

Conclusion: MMN could be a useful tool to evaluate postoperative cortical auditory performance. BEAM technology provides an ease of discrimination similar to quiet settings for cochlear implant recipients in noisy environments (BEAM and Freedom are trademarks of Cochlear Limited).

Key words: Mismatch negativity, cochlear implant, adaptive directional BEAM microphone

1. Introduction

Cochlear implantation is a well-accepted method of treatment for severe to profoundly hearing impaired patients. Development of communication and comprehension abilities in cochlear implant (CI) recipients is the main indicator of CI success. Today, advances in CI technology enable its users to understand speech in quiet conditions, but their ability to understand speech and to communicate with others in noisy conditions is compromised. They generally experience severe degradation in understanding speech in real-life conditions. For example, in order to understand speech 50% correctly, normal hearing people need as low as a –5 dB signal-to-noise ratio (SNR) in noisy situations (1,2). This ratio is higher for CI recipients. Indeed, they need at least a +10 to a +25 dB SNR in order to understand speech in noisy situations (3).

An effective way to improve speech intelligibility in noisy situations for these recipients is to use an adaptive directional microphone system in their speech processor to increase the SNR. In the literature, the benefits of the adaptive directional system are generally evaluated in terms of the speech performance abilities of the CI recipients, using various speech materials (2–4).

Spriet et al. (4) showed that speech tests with an adaptive directional beamformer BEAM demonstrated significant improvements in the speech reception threshold (SRT) in noise. The average improvement was 5–16 dB in SRT and an average of 10%–41% in phoneme scores when compared to the standard directional microphone system.

Speech-evoked auditory cortical potentials are successfully used to evaluate the central auditory process that contributes to speech perception both in normal hearing individuals and CI recipients (5–8).

Mismatch negativity (MMN) is a cognitive event-related potential and a neurophysiological correlate of auditory discrimination. It is an objective measure of discrimination of stimulus differences and does not require conscious attention to the stimuli (9). MMN can be elicited by differences in speech when presented with a CI (7).

---

* Correspondence: asuman.erdogan@yahoo.com

Considering the fact that in the literature, CI microphone systems have never been evaluated by using electrophysiological responses, in this study the purposes of attempting to obtain MMN potential in CI recipients are: a) to examine the effects of noise on the MMN responses of CI users, b) to investigate the possible benefits of an adaptive directional BEAM microphone system in noisy situations by using recordings of MMN potential, and c) to compare the CI-evoked potential results with those of normal hearing subjects.

2. Materials and methods

2.1. Subjects

Eleven implant recipients participated in this study. The CI group consisted of 8 females and 3 males ranging in age from 14 to 47 years (mean age: 22 years). All CI recipients had received the Nucleus implant system and used the Freedom speech processor. They all had at least 1 year of CI experience (mean: 5 years, range: 1–10 years) and wore their speech processor actively every day. All subjects used the advanced combination encoders (ACE) strategy at different rates. The CI patient data are shown in Table 1. Only 1 recipient had a Freedom 22 speech processor and used a speech strategy with a rate of 250 Hz. All were healthy recipients with no medical history other than deafness. Informed consent was obtained from each subject. Eleven normal hearing subjects (5 females, 6 males) aged from 23 to 60 years (mean age: 31 years) participated in the test as a control group. All had successfully passed a transient-evoked otoacoustic emissions (TEOAE) test (Otodynamics ILO 96 analyzer) and an otoscopic examination.

2.2. Stimuli

For recording, the computer-generated syllables /da/ and /di/, which already existed within the electrophysiological test device, were used. All subjects discriminated these stimuli behaviorally. Speech stimuli were presented using an oddball paradigm where /da/ was the standard stimulus (probability of occurrence = 80%) and /di/ was the deviant stimulus (probability of occurrence = 20%). Total stimulus duration was 200 ms and the interstimulus interval was 1 s. Standard and deviant stimuli were presented in a pseudorandom sequence. They were delivered through a loudspeaker placed 1 m from the subjects at a 0° angle. The speech stimuli intensity was 70 dB sound pressure level (SPL). Subjects were instructed to watch a silent video.

Because of its wide frequency spectrum and similarity to a real-life situation, speech noise was used as the background noise. The noise stimulus intensity level was 80 dB SPL (−10 dB SNR) and was delivered through a second loudspeaker placed 1 m from the subjects at a 180° angle. A 2-channel Interacoustic AC 30 Model audiometer was used to deliver both speech and noise stimuli. All stimuli were calibrated with a Bruel & Kjaer 2235 sound level meter.

2.3. Electrophysiological recordings

MMN responses were recorded using the Intelligent Hearing evoked potential system (IHS) with 10-mm gold cup surface electrodes. The midline of the top of the head (Cz) was used for the noninverting electrode placement. The inverting electrodes were placed on the mastoid or ear lobe (for CI subjects, on the opposite ear from the

Table 1. Demographic data of the CI group.

No.	Age	Sex	Ear	Dur.*	Etiology	Model	Str.**	Rate
1	16.8	F	R	1	Idiopathic	Freedom	ACE(RE)	2400
2	29.9	M	L	3	Sudden hearing loss	Freedom	ACE	1200
3	27.4	F	L	10	Meningitis	CI22	SPEAK	250
4	40	F	R	3	Sudden hearing loss	Freedom	ACE	900
5	25.9	F	R	10	Enlarged vestibular aqueduct	CI24M	ACE	900
6	47.2	F	L	3	Hereditary	Freedom	ACE	900
7	28.2	M	L	3	Physical trauma	Freedom	ACE	1800
8	22.2	M	R	2	Meningitis	Freedom	ACE	900
9	14.5	M	R	2	Idiopathic	Freedom	ACE	1800
10	24.7	F	R	10	Idiopathic	CI24M	ACE	1200
11	40.1	F	L	8	Ototoxic	Contour	ACE	1200

*Dur. = duration of implant usage in years. **Str. = programming strategy.

implanted ear). The forehead (Fpz) was used for the ground electrode placement. Eye movements were monitored on one recording channel by placing electrodes at the outer canthus and supraorbital place. The artifact rejection level for both eye movements and electroencephalograms was set at 100 µV. The analysis time window was 500 ms with a 100-ms prestimulus baseline. Bandpass filter settings of 1–40 Hz were used. The evoked responses were collected in blocks of approximately 100 standard stimuli and 25 deviant stimuli. A total of 3 blocks (300 standard and 75 deviant stimuli) were run in each stimulus condition for each subject. For the standard and deviant stimulus presentation, 3 series of recordings were collected and averaged separately for each subject. Thus, for each person, an average MMN waveform was obtained separately for quiet and noisy conditions. In addition, for both groups, a grand average waveform was obtained by averaging the individual waveforms for quiet and noisy conditions.

2.4. Protocol

To show the effects of an adaptive directional microphone in noisy conditions, a Freedom speech processor was used. Freedom has a 2-microphone adaptive beamformer BEAM that combines a directional microphone (in front of the processor) and an omnidirectional microphone (rear microphone). The beamformer discriminates between signals coming from the front and the back based on amplitude and phase differences between the outputs of the microphones. Sounds coming from the back were attenuated, while sounds coming from the front passed through (4).

MMN recordings were conducted within one session for normal hearing subjects in quiet (Quiet) and noisy conditions (Noise). For the CI group, the CI recipients' own standard programs were used to record MMN using the following protocols: a) in quiet conditions using omnidirectional microphone mode (Quiet OM), b) in noisy conditions using omnidirectional microphone mode (Noise OM), and c) in noisy conditions using adaptive directional beamforming microphone BEAM mode (Noise BEAM).

MMN difference waveforms were derived by subtracting the individual grand average responses to the standard stimulus from the response to the deviant stimulus. The MMN was identified automatically by the computer as a relative negativity following the N1, within a latency range of 150–300 ms. The morphologies of standard, deviant, and difference waveforms were examined and compared to the previously described morphology of speech-evoked MMNs (6).

Electrophysiological recordings in quiet and noisy conditions were done in a random order. CI recipients were seated on a comfortable chair in a soundproof test booth and watched a silent subtitled video. The individual test time including electrode placement and electrophysiological recordings was 30–45 min for the normal hearing group and approximately 1 h for the CI group.

2.5. Statistical analysis

Using the subjects' grand average difference waveforms, values for latency, onset, offset, peak amplitude, and P3a peak latency were analyzed. Standard and deviant P1, N1, P2, and N2 mean latency and range were also determined. For statistical analysis, nonparametric tests were used because of the small number of participants.

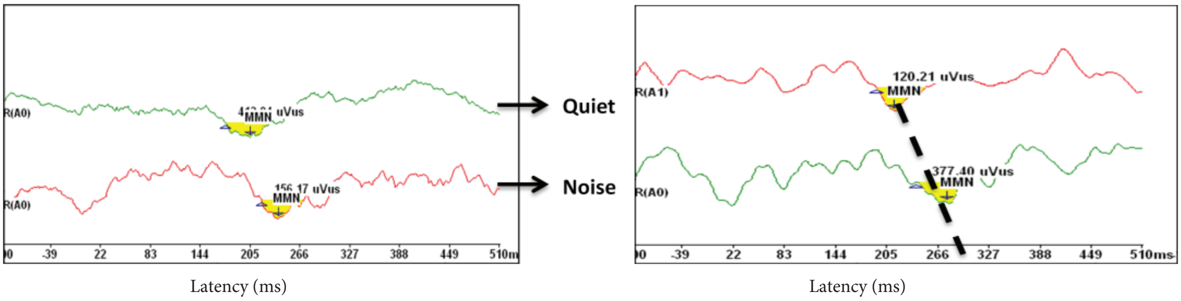
For the normal hearing group, the Wilcoxon matched pairs test was applied to analyze the MMN peak latencies, peak amplitudes, and P3a mean latencies in quiet and in noisy conditions. For the CI group, the Friedman test, a nonparametric repeated measures analysis of variance (ANOVA), was performed to determine whether MMN peak latencies, peak amplitudes, P3a peak latencies, and speech discrimination scores were different for the 3 conditions (Quiet OM, Noise OM, and Noise BEAM). If there was a difference between the 3 variables, Dunn's multiple comparison test was applied to determine which condition was significantly different from the others. Data were compared between the normal hearing and CI groups in both quiet and in noisy conditions using the Mann–Whitney U test.

3. Results

3.1. Normal hearing group

Standard and deviant P1, N1, P2, and N2 waves were recorded for all participants under quiet conditions. P1, N1, P2, and N2 waves were recorded for all participants, but a reliable MMN response was not obtained under noisy conditions for one participant. Thus, the MMN data from noisy conditions was analyzed for only n = 10 participants. The subjects could not cooperate easily during the noisy test sessions. In the noisy conditions, it was observed that the waveform morphology was abnormal and some waves had smaller amplitudes than those from the quiet conditions. Mean latency and amplitude data were analyzed using the Wilcoxon test. Figure 1a shows the individual MMN latencies and Figure 1b shows the mean group MMN latencies in the quiet and noisy conditions for the normal hearing group. It is apparent that MMN mean latency shows changes in the noisy conditions. Group statistical data are given in Figure 2.

MMN mean latency in the quiet conditions was 221 ms (SD: ±24.9, n = 11, range: 184–279 ms), while it was 289 ms (SD: ±41.5, n = 10, range: 236–362 ms) in the noisy conditions. The Wilcoxon test showed that the MMN mean latency of the normal hearing group was statistically prolonged under the noisy conditions compared to the quiet conditions (P = 0.002).



a. Individual MMN waveforms in Quiet (top) and in Noise (bottom) conditions.

b. Group MMN waveforms in Quiet (top) and in Noise (bottom) conditions.

Figure 1. MMN waveforms for the normal hearing subjects in quiet and noisy conditions: a) individual MMN waveforms in quiet (top) and in noise (bottom); b) group MMN mean waveforms. Both sets of waveforms show a prolongation in the MMN peak latencies in noise. Statistical analysis proved that there is a significant prolongation in MMN mean latency in the noisy conditions compared to the quiet conditions (P < 0.01).

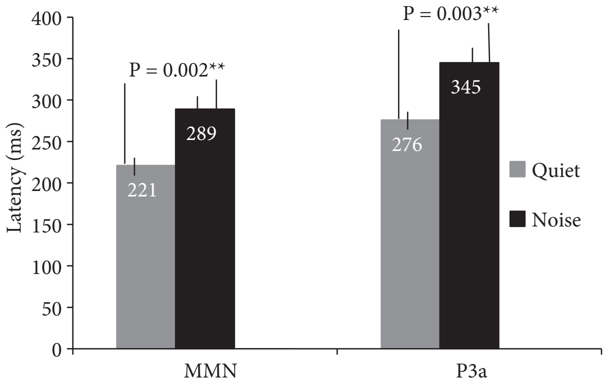


Figure 2. Statistical analysis of the normal group's MMN and P3a mean latencies in quiet and noisy conditions (quiet: SD ±24.9 for MMN mean latency, SD ±30.4 for P3a, and n = 11; noise: SD ±41.5 for MMN mean latency, SD ±42.4 for P3a, and n = 10). In noise, a significant prolongation was found for both MMN mean latency and P3a mean latency compared to mean latencies in quiet (**P < 0.01).

P3a mean latency was obtained at 276 ms (SD: ±30.4, range: 235–340 ms) in the quiet conditions and was 345 ms (SD: ±42.4, range: 266–412 ms) in the noisy conditions. Like for MMN peak latency, for normal hearing subjects there was a statistically significant prolongation in P3a mean latency in the noisy conditions compared to the quiet conditions (P = 0.0039).

MMN mean amplitude in the quiet conditions was 4.08 µV (SD: ±1.26, n = 11), and it was 4.18 µV (SD: ±1.47, n = 10) in the noisy conditions. No correlation was found between the 2 conditions for the normal hearing group in terms of MMN mean amplitudes (P = 0.999).

The group MMN on-latency mean was obtained at 196 ms in the quiet conditions and was obtained at 269 ms in the noisy conditions. The MMN off-latency mean was 244 ms in the quiet conditions and 342 ms in the noisy conditions. The group MMN duration means were 46 ms and 43 ms in the quiet and noisy conditions, respectively.

Group P1, N1, P2, and N2 mean latencies (Table 2) were also analyzed using the Wilcoxon matched pairs test. In the normal hearing group with the standard stimulus, the P1, N1, P2, and N2 group mean latencies were 56 ms (SD: ±6), 98 ms (SD: ±5), 179.6 ms (SD: ±16.5), and 225 ms (SD: ±30) in quiet conditions, respectively, and 58.5 ms (SD: ±6.7), 96.9 ms (SD: ±7), 165 ms (SD: ±12.5), and 261 ms (SD: ±27.8) in noisy conditions, respectively. There was no statistically significant relationship between the quiet and noisy conditions regarding the standard P1, N1, and P2 mean latencies (P > 0.05). The N2 mean latency was found to be significantly prolonged in the noisy conditions compared to the quiet conditions (P = 0.002).

For the deviant stimulus, the P1, N1, P2, and N2 mean latencies were obtained at 56.9 ms (SD: ±6.36), 99 ms (SD: ±6), 187.9 ms (SD: ±17), and 283 ms (SD: ±11.8) in the quiet conditions, respectively, and at 57 ms (SD: ±8.38), 98.6 ms (SD: ±8.37), 193 ms (SD: ±19), and 286 ms (SD: ±19) in the noisy conditions, respectively. The Wilcoxon matched pairs test results showed that there was no significant relationship between the quiet and noisy condition data regarding the deviant P1, N1, P2, and N2 mean latencies (P > 0.05).

3.2. Cochlear implant group

For the CI group, the CI recipients' own standard programs were used to record MMN with the following protocols: a) in quiet conditions with omnidirectional microphone mode (Quiet OM), b) in noisy conditions with omnidirectional microphone mode (Noise OM), and c) in noisy conditions with adaptive directional beamforming microphone mode (Noise BEAM).

The standard and deviant P1, N1, P2, and N2 mean latencies; MMN mean latencies; P3a; MMN mean amplitudes; and MMN on- and off-latencies were analyzed in both quiet and noisy conditions with the different microphone modes.

Table 2. Analysis of P1, N1, P2, and N2 mean latencies in the quiet and noisy conditions for the normal hearing group (**P < 0.01).

			Standard				Deviant			
			P1	N1	P2	N2	P1	N1	P2	N2
Quiet	(n = 11)	Mean (ms)	56	98	179.6	225	56.9	99	187.9	283
		SD	6	5	16.5	30	6.36	6	17	11.8
		n	11	11	11	11	11	11	11	11
Noise	(n = 10)	Mean (ms)	58.5	96.9	165	261	57	98.6	193	286
		SD	6.7	7	12.5	27.8	8.38	8.37	19	19
		n	11	11	11	11	11	11	11	11
		P	0.35	0.43	0.06	**0.002****	0.83	0.62	0.32	0.48

SD = standard deviation.

In the Quiet OM and Noise BEAM conditions, all standard and deviant P1, N1, P2, N2, and MMN responses were observed in every subject. In the Noise OM conditions, the standard and deviant P1, N1, P2, and N2 waves were obtained from 10 subjects.

For 2 participants, while the P1, N1, P2, and N2 waveforms were obtained, a reliable MMN response was not seen. Also, in one user, the P1, N1, P2, and N2 waveforms were not observed. Thus, for the Noise OM condition, the statistical analysis was done with only 8 subjects. As with the normal hearing group, it was obvious that all users could easily cooperate in Quiet OM and Noise BEAM conditions, but in the Noise OM condition, all had difficulties in cooperating with the test. Regarding this condition, it was observed that wave latencies were prolonged, wave amplitudes were decreased, and waveform morphology was poor when compared to the Quiet OM and Noise BEAM waveforms. Figure 3 shows the individual MMN waveforms, and Figure 4 shows the grand average MMN waveforms obtained in the Quiet OM, Noise OM, and Noise BEAM conditions of the CI group.

In the Noise OM conditions, reliable MMN waveforms were not obtained for 3 subjects. Standard and deviant P1, N1, P2, and N2 waveforms were recorded for 2 of the 3 subjects (Figure 5). In the Quiet OM and Noise BEAM conditions, reliable MMN responses were also obtained from these 3 subjects.

For the CI group, the MMN response mean latencies, the number of subjects statistically analyzed, and the ranges for the 3 different listening conditions are given in Table 3.

The Friedman (nonparametric repeated measures ANOVA) test was applied to determine whether the mean latencies were different in Quiet OM, Noise OM, and Noise BEAM conditions.

When a statistically significant difference was found between conditions, post hoc comparisons were done

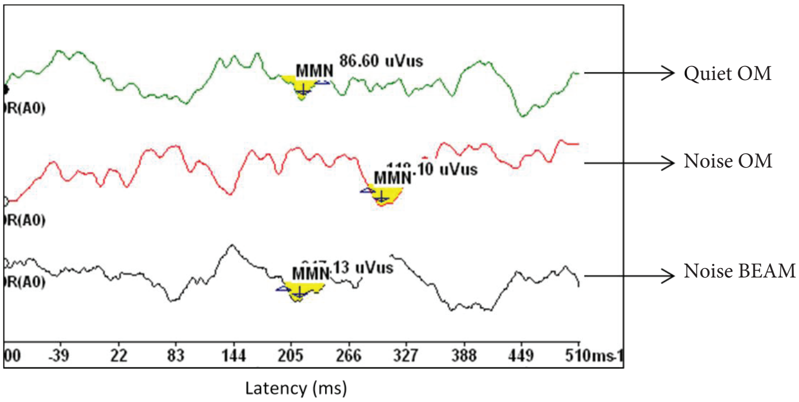


Figure 3. Individual MMN waveforms obtained in Quiet OM, Noise OM, and Noise BEAM conditions for the CI group.

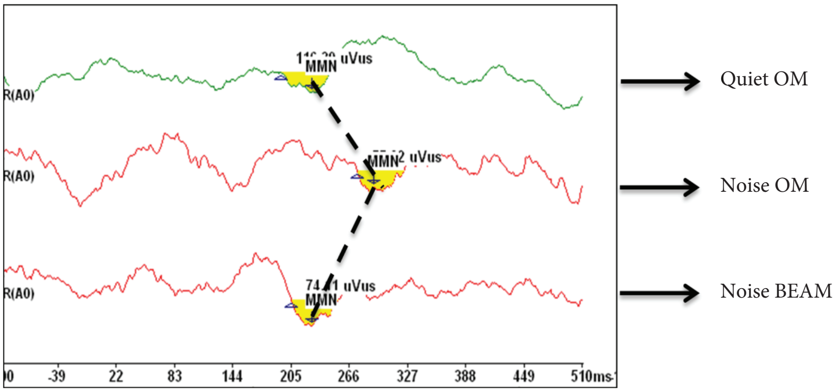


Figure 4. Grand average MMN waveforms obtained in Quiet OM, Noise OM, and Noise BEAM conditions for the CI group. Group MMN mean latency was prolonged in Noise OM compared to Quiet OM and Noise BEAM.

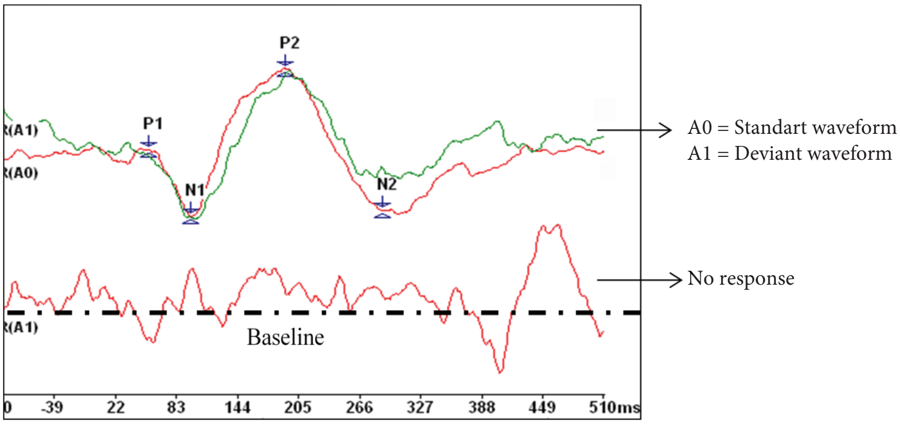


Figure 5. No MMN response. While deviant and standard waveforms were being recorded, no MMN response was obtained for 3 subjects by subtracting the standard waveform from the deviant waveform in Noise OM conditions.

Table 3. MMN response parameters in the Quiet OM, Noise OM, and Noise BEAM conditions for the CI group.

Latency (ms)	MMN peak latency	On-latency	Off-latency	Duration	P3a
Quiet OM (n = 11)	227	205	247	42	286
Noise OM (n = 8)	298	271	314	44	345
Noise BEAM (n = 11)	245	229	271	42	314
Quiet OM ranges	176–276	161–257	186–307	25–60	83–157
Noise OM ranges	249–342	190–323	260–362	32–70	278–370
Noise BEAM ranges	214–316	191–293	231–341	17–66	273–383

using Dunn's multiple comparison test. The group data analysis included comparison of MMN mean latencies, MMN mean amplitudes, and P3a mean latencies in Quiet OM, Noise OM, and Noise BEAM conditions (Figure 6).

MMN mean latencies were 223 ms (SD: ±22.6) in Quiet OM, were prolonged to 298 ms (SD: ±34.37) in Noise OM, and were 245 ms (SD: ±40.35) in Noise BEAM conditions. The Friedman test results indicated that there was a significant difference between the measurements obtained in Quiet OM, Noise OM, and Noise BEAM conditions (P = 0.0009). A post hoc analysis showed that:

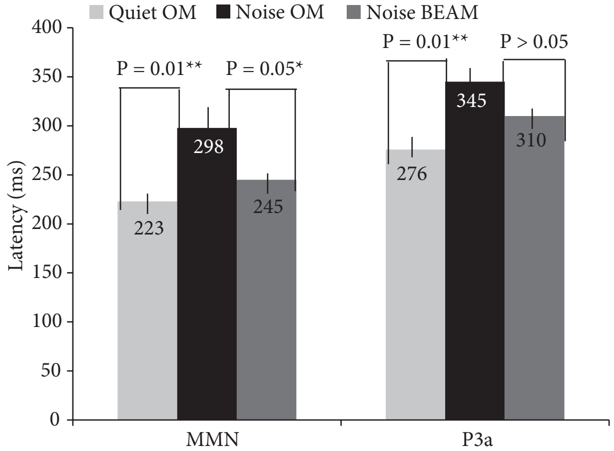


Figure 6. Statistically significant conditions in the CI group for MMN and P3a mean latencies. Standard deviation values for MMN mean latencies are SD ±31.32 in Quiet OM, SD ±38.84 in Noise OM, and SD ±37.78 in Noise BEAM. Values for P3a mean latencies are SD ±31 in Quiet OM, SD ±38.84 in Noise OM, and SD ±37.78 in Noise BEAM (*P = 0.05, **P < 0.01). In Noise OM conditions, MMN mean latencies were significantly prolonged when compared to those obtained in the Quiet OM and Noise BEAM conditions. P3a mean latency was only significantly prolonged in the Noise OM condition when compared to those in the Quiet OM condition.

a. Compared to that of the Quiet OM condition, the MMN mean latency was significantly prolonged in the Noise OM condition (P < 0.01).
b. The MMN mean latency obtained in the Noise BEAM condition was significantly shorter than that of the Noise OM condition (P < 0.05).
c. No statistical difference was found between measurements obtained in the Quiet OM and Noise BEAM conditions (P > 0.05).

P3a mean latencies were 286 ms (SD: ±31) in Quiet OM, 345 ms (SD: ±38.84) in Noise OM, and 314 ms (SD: ±37.78) in Noise BEAM conditions. The Friedman test results indicated that there were significant differences between measurements obtained in the Quiet OM, Noise OM, and Noise BEAM conditions (P = 0.004). Dunn's multiple comparison post hoc analysis showed that:

a. Compared to that of the Quiet OM condition, the P3a mean latency was statistically prolonged in the Noise OM condition (P < 0.01).
b. The P3a mean latency obtained in the Noise BEAM condition was not significantly different than that of the Noise OM condition (P > 0.05).
c. No statistically significant differences were found between the P3a latencies obtained in the Quiet OM and Noise BEAM conditions (P > 0.05).

MMN mean amplitudes were 4.92 nm (SD: ±1.63) in Quiet OM, 4.36 nm (SD: ±7.7) in Noise OM, and 4.83 nm (SD: ±6.5) in Noise BEAM conditions. There was no statistically significant difference between the 3 conditions (P > 0.967).

Table 4 shows the statistical analysis of the standard P1, N1, P2, and N2 mean latencies and Table 5 shows the statistical analysis of the deviant P1, N1, P2, and N2 mean latencies.

Table 4. Statistical analysis of the standard P1, N1, P2, and N2 mean latencies (*P < 0.05, ***P ≤ 0.001).

		Standard			
		P1	N1	P2	N2
Quiet OM	Mean (ms)	65.8	105	167	227
	SD (±)	17	20	15	19.9
	n	10	10	10	10
Noise OM	Mean (ms)	92.7	134	202	277
	SD (±)	28.5	22.9	21.6	26.7
	n	10	10	10	10
Noise BEAM	Mean (ms)	66	106.7	179.5	241
	SD (±)	11.5	17.7	28.9	36
	n	10	10	10	10
	P	=0.09	<0.05*	=0.001***	<0.0001***

Table 5. Statistical analysis of the deviant P1, N1, P2, and N2 mean latencies (**P < 0.01).

		Deviant			
		P1	N1	P2	N2
Quiet OM	Mean (ms)	79	116.8	117	225
	SD (±)	20.7	26.45	27	27.61
	N	10	10	10	10
Noise OM	Mean (ms)	92.7	137.2	207	274
	SD (±)	29	29.99	26.25	34.92
	N	10	10	10	10
Noise BEAM	Mean (ms)	71	114.7	188.5	255
	SD (±)	13.91	17.97	23	43
	N	10	10	10	10
	P	=0.445	=0.4656	**=0.0038****	**=0.0016****

In the CI group, MMN and P3a mean latencies were significantly prolonged in the noisy condition using the omnidirectional microphone mode compared to those of the quiet condition using the omnidirectional microphone mode. It was obvious that the waveform morphology was poor in the noisy condition with OM mode.

Significant decreases were obtained in MMN and P3a mean latencies in the noisy condition using the adaptive directional BEAM microphone system compared to those in the noisy condition using the omnidirectional microphone mode. There was no significant difference between responses recorded in the quiet condition and the noisy condition with BEAM. Furthermore, the waveform morphology was good in the BEAM condition.

3.3. Comparison between the CI group and the normal hearing group

The MMN waveforms of the CI group were remarkably similar to those obtained from the normal hearing listeners (control group). A Mann–Whitney U test was performed for the MMN and P3a mean latencies and the MMN mean amplitudes in Quiet OM and Noise OM.

In the Quiet OM condition, MMN mean latency was 221 ms (SD: ±24.92) for the control group and 227 ms (SD: ±25.30) for the CI group. The Mann–Whitney U test showed no statistically significant differences between the 2 groups (P = 0.293). P3a mean latencies were 276 ms (SD: ±30.45) for the normal hearing group and 286 ms (SD: ±32.18) for the CI group. There was no statistically significant difference between the 2 groups with regard to P3a mean latency (P > 0.561). MMN mean amplitudes were 4.08 µV (SD: ±1.5) in the control group and 4.97 µV (SD: ±1.83) in the CI group. There was no significant difference between the 2 groups (P > 0.05).

In the Noise OM condition, MMN mean latency was 289 ms (SD: ±41.55) for the control group and 298 ms (SD: ±34.37) for the CI group. The Mann–Whitney U test showed no significant differences in MMN mean latency between the 2 groups. P3a mean latencies were 345 ms (SD: ±42.44) in the control group and 345 ms (SD: ±32.18) in the CI group. There were no statistically significant differences between the 2 groups with regard to P3a mean latency (P = 0.561). MMN mean amplitude was 4.18 ms (SD: ±6) for the control group, whereas it was 4.36 ms (SD: ±7.8) for the CI group. No statistically significant differences were obtained between the 2 groups in the noisy condition (P > 0.05).

4. Discussion

Cortical MMN potential measurements provide very useful information in the processing of auditory information. Acquiring P1-N1-P2 responses with both standard and deviant (rare) stimuli shows that auditory stimulation activates the auditory cortex (10). In other words, the existence of P1-N1-P2 responses shows that the auditory cortex “detects” auditory stimuli. Moreover, acquiring MMN potential is an indicator that the auditory cortex can automatically discriminate the difference between 2 different auditory stimuli at a preconscious level (11). In particular, using speech stimuli for MMN measurements enables us to get information on how central auditory perception, memory, and attention processing work at the preconscious level (12). Korczak et al. (13) reported that N1, N2, P3, and MMN potentials could easily be recorded using hearing aids in subjects with severe and profound hearing loss. Moreover, recording cortical auditory potentials in CI users can be used to evaluate the auditory detection and discrimination abilities of implantees and the effect of hearing loss on speech processing at the higher cortex level in order to evaluate the users' hearing–speech abilities and performance with the CI. Recording MMN responses in CI recipients gives an indication of the central auditory system's capability of differentiation (14).

The central auditory system can be evaluated with different speech stimuli and different SNRs for clinical purposes. Evaluation of the central auditory system with MMN in noisy conditions offers the opportunity to examine the whole hearing system at a preconscious level. Research on how noise affects MMN auditory cortical potential can lead to improved speech performance in noisy environments for CI users who have low speech discrimination.

This study sought to: a) examine the effects of noise on the MMN responses of cochlear implantees, b) investigate the possible benefits of using an adaptive directional (BEAM) microphone system in noisy situations based on MMN potential recordings, and c) compare the CI-evoked potential results with those of normal hearing subjects.

In the present study, clear MMN potentials were successfully recorded in both the normal hearing and the CI groups in quiet conditions. We found that MMN peak latency was 221 ms in the normal hearing group and 227 ms in the CI group, which is in accordance with the literature (6).

Androulidakis and Jones (15) examined the effects of broadband and narrow-band noises on P1 and N1 wave latencies. They mentioned that at high SNR levels, P1 and N1 waveforms disappeared. When they changed the modulation of the amplitude of the noise stimulus, the P1 and N1 waveforms reappeared, but they reported that the P1 and N1 wave latencies were longer in noisy conditions than in quiet conditions. This showed that the audibility of the stimulus could affect the P1 and N1 waveforms. In our study, there was no statistically significant change in the P1, N1, and N2 latencies between quiet and noisy conditions for both the control and CI groups. We thought that the SNR level used in this study did not significantly affect the P1 and N1 detection potentials. Obtaining similar P1 and N1 wave latencies in quiet and in noisy conditions with regard to SNR level shows us that the central auditory cortex processes speech signals in a similar way in the quiet and noisy environments, dependent on the audibility of the speech signals. However, for one participant, the P1, N1, P2, and N2 waveforms were not observed in the noisy situation because of nonaudibility of the speech signals. For 2 other users, the P1, N1, P2, and N2 waveforms were recorded easily, but we could not record reliable MMN waveforms from these 3 patients. These findings show that the auditory automatic discrimination process is mostly affected by noise dependent on the SNR.

Martin et al. (16) reported that broadband noise in normal hearing listeners causes prolongation in MMN wave latencies. Similarly, Kaplan-Neeman et al. (17) recorded P3 waveforms by using /da/ and /ga/ speech signals at SNR levels of +15, +3, 0, −3, and −6 dB. They mentioned that as the noise amplitude level increases, there is a prolongation in the P3 wave latencies. In accordance with the literature, our MMN study showed that MMN and P3a wave latencies were significantly prolonged in noise conditions compared to those obtained in quiet conditions for both the normal hearing group and the CI group. There was no significant change in terms of the wave amplitudes for quiet and noisy conditions.

As we mentioned before, MMN reflects automatic auditory discrimination at the cortex level. In our study, it confirms that there is a prolongation of MMN and P3a mean latencies in noise conditions rather than quiet conditions, and normal hearing people have difficulty discriminating speech signals in a noisy environment.

In the present study, the P1, N1, and P2 mean latencies showed no significant differences between Quiet OM, Noise OM, and Noise BEAM conditions in the CI group, similar to the normal hearing group. This situation shows that depending on the SNR level, CI users, like normal hearing people, do not have difficulty detecting the speech signals in noisy environments. On the other hand, the MMN and P3a mean latencies in Noise OM conditions were significantly prolonged compared to the mean latencies in Quiet OM conditions. MMN potential is an indicator of the auditory systems' discrimination ability. This situation shows that CI users have difficulty discriminating speech signals with omnidirectional microphone systems in a noisy environment.

In the CI group, when we compared the MMN and P3a mean latencies in the Noise OM conditions, significant decreases were obtained in the Noise BEAM conditions. In addition, no significant differences were found in the MMN and P3a mean latencies between the Quiet OM and Noise BEAM conditions. When we compared the waveform morphology, poor waveform morphology was observed in the Noise OM conditions, but in the Noise BEAM conditions, waveform morphology was ameliorated. These findings show that with an adaptive BEAM microphone system, CI users can easily discriminate speech signals in noisy environments.

The prolongation of MMN wave latencies in Noise OM conditions is related to the omnidirectional microphone mechanism. This kind of microphone system collects the sounds coming from all sides. In our study, the noise coming from behind the user was transmitted to the inner system of the speech processor with speech signals so that CI users with the omnidirectional microphone system had difficulty understanding speech signals in noisy conditions. On the other hand, the adaptive BEAM is a dual microphone system in which the front microphone collects all sounds coming from the front side, and the rear microphone filters the stimulus from the back and sends it to the processor. In the present study, noise stimulus was given to the subjects at a 180° angle. Using the adaptive BEAM microphone system enabled speech stimuli to be differentiated more easily by suppressing the noise coming from the back. In this situation, depending on the improvement in SNR, as in the quiet conditions, MMN peak latencies in the noise conditions again shortened and wave morphology improved.

In the present study MMN responses were prolonged in the noisy conditions compared to the quiet conditions for both the normal hearing group and the CI group. Noise has detrimental effects on normal hearing people as well as CI users. It is thought that this is caused by the effect of the noise on the peripheral hearing system. The existence of noise basically induces elevation in the hearing threshold. This threshold change causes a decrease in speech understanding (18). In a noisy environment, the normal hearing system uses spectral and temporal cues for speech discrimination (19). Especially as hearing loss increases, depending on the level of decrease of audibility in the noisy environment, people with hearing loss cannot properly use these cues and have difficulty understanding speech. In our study, the P1 and N1 latencies did not show any significant change in the noisy conditions compared to the quiet conditions, depending on the SNR, which shows that auditory stimuli are audible and noticeable in noise. However, the MMN potentials recorded from higher levels of the auditory systems are prolonged in noisy conditions compared to quiet conditions, which shows that differentiation of auditory stimuli decreases with noise. In this situation, noise not only unfavorably affects the peripheral auditory system, but also the central auditory system. Moreover, in noisy conditions, when the audibility of stimuli is not markedly affected, at the same SNR, differentiation of stimuli is much more affected by the existence of noise. This situation shows that the noise affects the central auditory system more than the peripheral auditory system. Salo et al. (20) reported a significant decrease in MMN amplitudes when an ipsilateral and contralateral mask was used. Shtyrov et al. (21), in a magnetic MMN (MMNm) study, examined how noise affects hemispheric lateralization. They recorded MMNm responses to speech stimuli, especially in the left hemisphere, in quiet conditions. However, they reported that when the speech stimulus and noise were given at the same time, the MMNm response amplitude decreased in the left hemisphere but increased in the right hemisphere. This situation shows that the existence of noise can cause restructuring in the right and left hemispheres. In noisy environments, top–down speech processing increases the activation of brain structures, but especially in the left hemisphere, down–top processing related with the phonetic characteristics of the speech is suppressed.

The characteristics of the stimuli used in MMN studies affect the response parameters. There are studies that show prolongation in cortical auditory latencies as the differences between stimuli decrease, because they become more difficult to differentiate (5–22). Groenen et al. (23), by using /ba/–/da/, /ba/–/pa/, and /i/–/a/ stimuli, compared 9 postlingual adult CI user responses with 9 normal hearing group responses. In the control group, the highest amplitude and shortest latency for P300 responses were acquired by tonal stimulus. They reported that when /ba/–/da/ and /ba/–/pa/ stimuli pairs were used, they recorded longer P300 latencies. They concluded that differentiation of consonants is more difficult than differentiation of tonal and vowel sounds. In our preliminary study, we recorded MMN responses by using the /ba/–/da/ stimuli pair. It has been subjectively observed that users have difficulty differentiating these 2 stimuli, especially in a noisy environment, and so for this study we used the /da/–/di/ stimuli pair, which can be differentiated more easily. It is thought that there is a big spectral difference between these stimuli, which facilitated the obtaining of MMN responses in the noisy conditions.

This study is the first to evaluate an adaptive BEAM microphone system with MMN auditory cortical potentials. Using an adaptive directional BEAM microphone system in a noisy environment improves the SNR and enables the subject to differentiate auditory stimulus at the preconscious level. Implant users, even when in a noisy environment, differentiate speech stimuli exactly as in a quiet environment. The finding that the directional microphone system is a useful tool to increase speech understanding in a noisy environment basically shows the necessity of using this system in the CI speech processors. However, this technology is not currently used in many existing processor models. In the next steps of development, CI companies should integrate a directional microphone system into the default program of all processor models that do not have this type of technology.

Cortical auditory evoked potentials reflect performance after cochlear implantation and provide an objective way to evaluate postoperative cortical auditory performance in both quiet and noisy environments. The adaptive directional BEAM microphone system improved speech understanding and cortical responses in noisy situations. Manufacturers should improve BEAM technology and integrate it into the standard program with automatic adaptive directionality as in digital hearing aids.

References

1. Plomp R, Mimpen AM. Speech-reception threshold for sentences as a function of age and noise level. J Acoust Soc Am 1979; 66: 1333–42.
2. Versfeld NJ, Daalder L, Festen JM, Houtgast T. Method for the selection of sentence materials for efficient measurements of the reception threshold. J Acoust Soc Am 2000; 107: 1671–84.
3. Wouters J, Vanden Berghe J. Speech recognition in noise for cochlear implantees with a two-microphone monaural adaptive noise reduction system. Ear Hear 2001; 22: 420–30.
4. Spriet A, Van Deun L, Eftaxiadis K, Laneau J, Moonen M, van Dijk B et al. Speech understanding in background noise with the two-microphone adaptive beamformer (BEAM) in the Nucleus Freedom Cochlear Implant System. Ear Hear 2007; 28: 62–72.
5. Kileny PR, Boerst A, Zwolan T. Cognitive evoked potentials to speech and tonal stimuli in children with implants. Otolaryngol Head Neck Surg 1997; 117: 161–9.
6. Kraus N, McGee T, Sharma A, Carrell T, Nicol T. Mismatch negativity event-related potential elicited by speech stimuli. Ear Hear 1992; 13: 158–64.
7. Kraus N, Micco A, Koch DB, McGee T, Carrell T, Sharma A et al. The mismatch negativity cortical evoked potential elicited by speech in cochlear-implant users. Hear Res 1993; 65: 118–24.
8. Micco A, Kraus N, Koch DB, McGee TJ, Carrell TD, Sharma A et al. Speech-evoked cognitive P300 potentials in cochlear implant recipients. Am J Otol 1995; 16: 514–20.
9. Ponton CW, Eggermont JJ, Don M, Waring MD, Kwong B, Cunningham J et al. Maturation of the mismatch negativity: effects of profound deafness and cochlear implant use. Audiol Neurootol 2000; 5: 167–85.
10. Kileny PR. Use of electrophysiologic measures in the management of children with cochlear implants: brainstem, middle latency and cognitive (P300) responses. Am J Otol 1991; 12: 37–42.
11. Näätänen R. Paavilainen P, Rinne T, Alho K. The mismatch negativity (MMN) in basic research of central auditory processing: a review. Clin Neurophysiol 2007; 118: 2544–90.
12. Näätänen R, Sams M, Alho K. Mismatch negativity: the ERP sign of a cerebral mismatch process. Electroencephalogr Clin Neurophysiol 1986; 38: 172–7.
13. Korczak PA, Kurtzberg D, Stapells DR. Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioral measures of speech-sound processing. Ear Hear 2005; 26: 165–85.
14. Roman S, Canévet G, Marquis P, Triglia JM, Liégeois-Chauvel C. Relationship between auditory perception skills and mismatch negativity recorded in free field in cochlear-implant users. Hear Res 2005; 201: 10–20.
15. Androulidakis AG, Jones SJ. Detection of signals in modulated and unmodulated noise observed using auditory evoked potentials. Clin Neurophysiol 2006; 117: 1783–93.
16. Martin BA, Kurtzberg D, Stapells DR. The effects of decreased audibility produced by high-pass noise masking on N1 and the mismatch negativity to speech sounds /ba/ and /da/. J Speech Lang Hear Res 1999; 42: 271–86.
17. Kaplan-Neeman R, Kishon-Rabin L, Henkin Y, Muchnik C. Identification of syllables in noise: electrophysiological and behavioral correlates. J Acoust Soc Am 2006; 120: 926–33.
18. Kozou H, Kujula T, Shtyrov Y, Toppila E, Starck J, Alku P et al. The effect of different noise types on the speech and non-speech elicited mismatch negativity. Hear Res 2005; 199: 31–9.
19. Peters RW, Moore BC, Baer T. Speech reception thresholds in noise with and without spectral and temporal dips for hearing-impaired and normally hearing people. J Acoust Soc Am 1998; 103: 577–87.
20. Salo SK, Lang AH, Salmivalli AJ. Effect of contralateral white noise masking on the mismatch negativity. Scand Audiol 1995; 24: 165–73.
21. Shtyrov Y, Kujula T, Ahveninen J, Tervaniemi M, Alku P, Ilmoniemi RJ et al. Background acoustic noise and the hemispheric lateralization of speech processing in the human brain: magnetic mismatch negativity study. Neurosci Lett 1998; 251: 141–4.
22. Okusa M, Shiraishi T, Kubo T, Nageishi Y. Effects of discrimination difficulty on cognitive event-related brain potentials in patients with cochlear implants. Otolaryngol Head Neck Surg 1995; 121: 610–5.
23. Groenen PA, Beynon AJ, Snik AF, van den Broek P. Speech-evoked cortical potentials and speech recognition in cochlear implant users. Scand Audiol 2001; 30: 31–40.