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Improved Outcomes in Auditory Brainstem Implantation with the Use of Near-Field Electrical Compound Action Potentials

Marco Mandalà, MD, PhD[1], Liliana Colletti, PhD[1], Giacomo Colletti, MD[2], and Vittorio Colletti, MD[1]

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Abstract

Objective. To compare the outcomes (auditory threshold and open-set speech perception at 48-month follow-up) of a new near-field monitoring procedure, electrical compound action potential, on positioning the auditory brainstem implant electrode array on the surface of the cochlear nuclei versus the traditional far-field electrical auditory brainstem response.

Study Design. Retrospective study.

Setting. Tertiary referral center.

Subjects and Methods. Among the 202 patients with auditory brainstem implants fitted and monitored with electrical auditory brainstem response during implant fitting, 9 also underwent electrical compound action potential recording. These subjects were matched retrospectively with a control group of 9 patients in whom only the electrical auditory brainstem response was recorded. Electrical compound action potentials were obtained using a cotton-wick recording electrode located near the surface of the cochlear nuclei and on several cranial nerves.

Results. Significantly lower potential thresholds were observed with the recording electrode located on the cochlear nuclei surface compared with the electrical auditory brainstem response (104.4 ± 32.5 vs 158.9 ± 24.2, P = .0030). Electrical brainstem response and compound action potentials identified effects on the neighboring cranial nerves on 3.2 ± 2.4 and 7.8 ± 3.2 electrodes, respectively (P = .0034). Open-set speech perception outcomes at 48-month follow-up had improved significantly in the near- versus far-field recording groups (78.9% versus 56.7%; P = .0051).

Conclusions. Electrical compound action potentials during auditory brainstem implantation significantly improved the definition of the potential threshold and the number of auditory and extra-auditory waves generated. It led to the best coupling between the electrode array and cochlear nuclei, significantly improving the overall open-set speech perception.

Keywords

auditory brainstem implant, intraoperative monitoring, electrical compound action potentials, electrical auditory brainstem response

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Auditory brainstem implantation (ABI) shows a wide range of hearing performance, from detection and some discrimination of basic and environmental sounds to open-set speech perception and mobile phone use.[1-3] The wide range of outcomes is seen within and across a variety of etiologies, including neurofibromatosis type 2 and nontumor patients (eg, cochlear nerve aplasia, cochlear ossifications, and advanced otosclerosis).[1,2] A possible theory to explain the range of ABI outcomes within cohorts is the variability of the degree of contact between the electrode array and the surface of the cochlear nucleus (CN).

The neural activity generated after ABI insertion is currently evaluated with far-field recording of the electrically evoked auditory brainstem response (EABR) and with electromyography (EMG) recordings on the neighboring cranial nerves VII, IX, X, XI, and V[4] from the corresponding innervated muscles. Evoked neural activity can also be recorded through the implant itself using neural response telemetry

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(NRT). However, NRT waveforms are very heterogeneous across and within individual patients, making it impossible to differentiate recordings associated with auditory versus nonauditory sensations. Thus, NRT is inappropriate in assisting ABI electrode placement intraoperatively or for programming.[5]

Neurophysiological intraoperative monitoring of hearing with auditory brainstem responses (ABRs) is routinely used to improve hearing preservation rates[6,7] during vestibular schwannoma surgery and microvascular decompression of VII and VIII cranial nerves. However, the ABR may disappear during ABI surgery while auditory compound nerve action potentials (CAPs) may still be preserved. The CAPs, recorded from the exposed cochlear nerve or cochlear nuclei,[8] indicate that the hearing function is not completely lost and show that CAP recordings are far more sensitive than ABR. With a stimulating electrode located on the round window and a recording electrode on the root entry zone of the cochlear nerve, neural activity may be recorded as electrical compound nerve action potentials (ECAPs) as well EABRs.

Our experience with ECAP recording in posterior fossa surgery led us to adopt a similar near-field monitoring procedure of ECAPs to obtain a better evaluation of the electrode array position with regard to the CN. The present study aims to investigate whether ECAP recording may provide a complete evaluation of the neural activity generated by the ABI on the auditory system and on neighboring cranial nerves and so improve the definition of auditory threshold and allow better differentiation of auditory and extra-auditory generated waves. It may lead to a better coupling between the electrode array and cochlear nuclei, significantly improving the overall open-set speech perception.

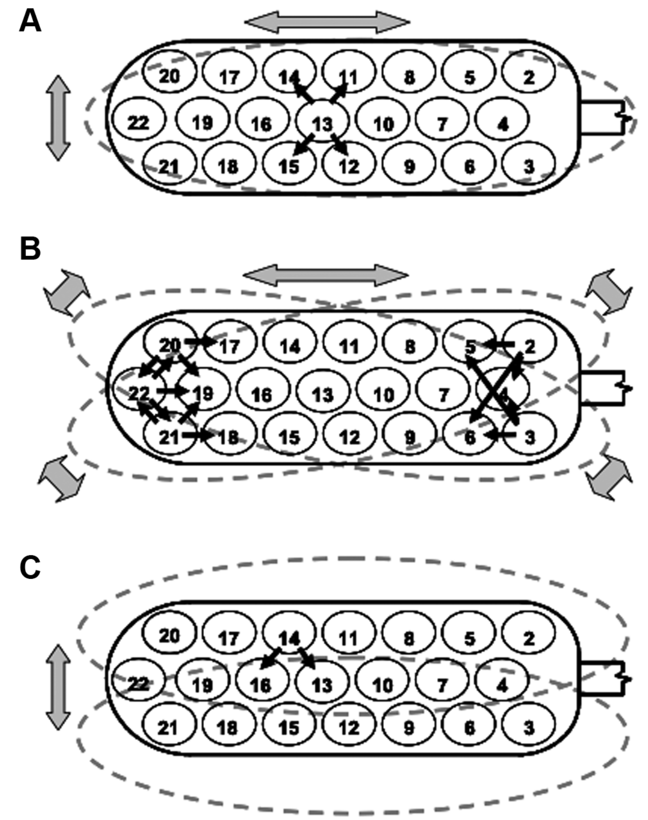

Figure 1. Site of stimulation on the auditory brainstem implantation electrode array estimating the optimal device fitting. (A) Central electrode combinations to evaluate longitudinal and transverse tilt. (B) Edge electrode combinations to evaluate rotational and transverse shift. (C) Lateral electrode combinations to evaluate longitudinal shift.

Materials and Methods

All patients were duly informed with regard to the aim and protocol of the experiment and gave their consent. Ethics approval was obtained from the University of Verona Ethics Committees.

All 202 subjects operated in Verona were monitored for EABR during ABI surgery, and 9 of them also underwent ECAP recording. The present prospective cohort study includes 9 adults fitted with ABI who were monitored during surgery with ECAP recording. The control group was composed of 9 adults who received only EABR and EMG monitoring, matched retrospectively for age at implantation, hearing loss duration, and etiology. All subjects were operated at the University of Verona Hospital (tertiary referral center) and were fitted with a Cochlear Nucleus 24 ABI device. The same protocol has been adopted in an ongoing investigation with ABI patients fitted with the Med-El device. Details of the surgical procedure are reported elsewhere.[9]

The main outcome measures were intraoperative EABRs; ECAPs using a cotton-wick recording electrode located on the foramen of Luschka and the root entry zone of the V, VII, IX, X, and XI cranial nerves; and EMG monitoring, traditionally performed on the facial, glossopharyngeal, laryngeal, and trapezoid muscle groups. The postoperative number of active electrodes and their mean auditory threshold (current level [CL]), open-set percentage of sentence recognition, and the number of electrodes with effects on neighboring cranial nerves were investigated.

The EABRs and ECAPs were acquired using Medelec Synergy (CareFusion, San Diego, California), a system to evoke potential, triggered by the nucleus evoked potential module of the NRT v3.1 software using the Portable Programming System (Cochlear, Sydney, Australia). Stimulus intensity was initially set at 190 CL with a pulse width of 25 to 100 microseconds, and a reliable waveform threshold was then identified.

The EABRs and ECAPs were recorded with the Verona protocol (**Figure 1**) through stimulation of 20 different sites on the electrode array using 2 closely spaced electrodes that stimulated a small area of neural tissue. The first electrode to be stimulated was the 13th (13-11, 13-12, 13-14, 13-15), and these recordings allowed quantification of the longitudinal and transverse tilt of the electrode array by evaluating peaks, magnitudes, and thresholds, which are considered to be inversely proportional to the distance from the surface of

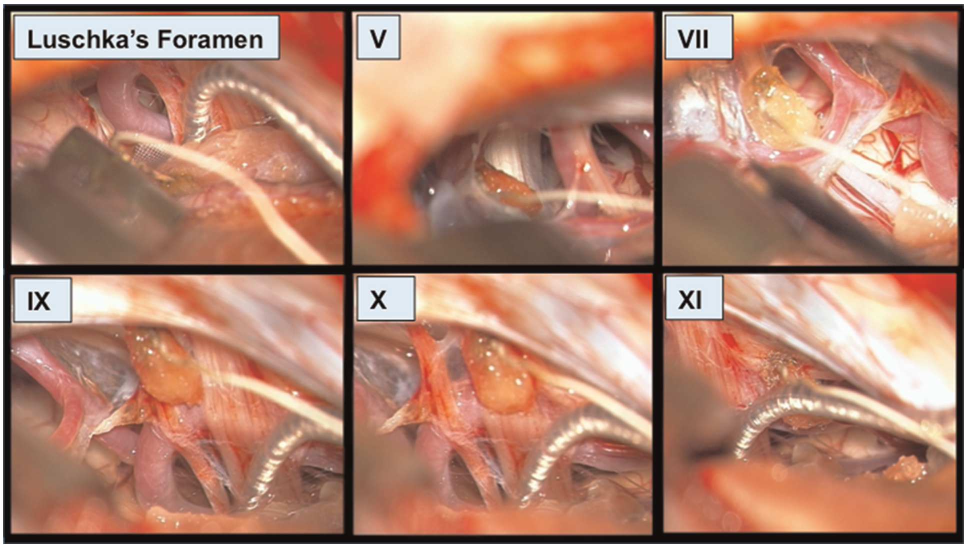

Figure 2. Recording locations of electrical compound nerve action potentials. The cotton-wick electrodes were placed on the foramen of Luschka (main location for auditory response) and on the V, VII, IX, X, and XI cranial nerves.

the CN. Then, stimulation of lateral (2-4, 2-5, 2-6), medial (20-17, 20-19, 20-22, 21-18, 21-19, 21-22, 22-19), inferior (14-16, 8-7, 8-10), and superior (15-16, 9-7, 9-10) electrodes was performed. The analysis of recorded responses can allow estimation of the rotational shift and position of the transverse axis of the electrode array with respect to the CN surface (lateral and medial electrodes) or the position of the longitudinal axis (inferior and superior electrodes). Changes in the positioning of the array were performed by the surgeon to obtain the best EABR and CAP responses in terms of number of electrodes with only auditory responses and with low threshold and high response amplitude.

Recordings were obtained from cotton-wick electrodes placed on the foramen of Luschka (the main location for auditory response); V, VII, IX, X, and XI cranial nerves (positive electrodes in ECAPs; **Figure 2**); and subdermal needle electrodes positioned on the forehead (positive in EABR), ipsilateral tragus (negative), and sternum (ground). Recording of ECAPs was performed using a Teflon-insulated silver electrode wire (Type Ag 7/10; Medwire Corporation, Mt Vernon, New York) with a small cotton wick sutured on its tip, which was uninsulated over a distance of 2 to 3 mm.

The EABR signal was filtered with a bandpass filter ranging from 100 to 3000 Hz, and 1000 sweeps were averaged to achieve a good signal-to-noise ratio with a recording window of 10 milliseconds. The ECAPs were filtered through a 3- to 3000-Hz bandpass filter and averaged over 100 responses.

Two replications of each recording condition were collected and analyzed. Criteria for the presence of EABR and ECAP responses were the following: (1) visual inspection of morphology, (2) good visual correlation between the 2 replications, (3) significantly high response-to-noise ratio, (4) when reversing the stimulus polarity: inversion of the electrical artifact but no polarity change of an early latency neural response.[10]

The effects on neighboring cranial nerves were investigated in the ABI-ECAP groups with retrograde compound nerve action potential recorded with cotton-wick electrodes placed on the VII, IX, X, and XI nerves and with EMG monitoring of the VII, IX, X, and XI nerves in the ABI-EABR group. Details of EMG monitoring procedures are reported elsewhere.[4]

Performance was measured on a variety of closed-set and open-set speech measures, but only results from open-set sentence recognition will be presented here.

Simple sentences were presented in random order in a sound field at a comfortable listening level. Listeners were instructed to repeat whatever they heard, and sentences with each word correctly repeated were scored.

Comparison of outcomes in the 2 groups was performed using the Wilcoxon Mann-Whitney test and Fisher exact test as appropriate. Statistical significance was set at $P < .05$.

Results

The mean ages at implantation for the EABR and ECAP groups with 9 adults in each group were 51.9 ± 18.3 years and 47.3 ± 11.4 years, respectively ($P > .05$). The male-female ratio did not differ significantly between the 2 groups ($P > .05$). The onset of hearing loss in both groups was about 10 years before ABI surgery, and the difference was not statistically significant ($P > .05$). The etiology of hearing loss in the 2 cohorts was homogenous and related to advanced otosclerosis, meningitis, or trauma (**Table 1**).

The mean follow-up time was 56 ± 6.8 months.

Intraoperative Electrophysiological Outcomes

The number of electrodes with intraoperatively recorded auditory responses was statistically significantly higher in the near-field monitored group (16.2 versus 12.1; $P = .0079$). Furthermore, statistically significant differences

Table 1. Demographic Data and Outcomes for the 2 Populations Investigated.

	ABI-EABR	ABI-ECAP	Statistical Analysis
Age at implantation, y	51.9 ± 18.3	47.3 ± 11.4	$P > .05$[a]
Sex, M/F	5/4	4/5	$P > .05$[b]
No. of years since the onset of hearing loss	9.2 ± 7.1	11.4 ± 5.9	$P > .05$[a]
Etiology	3 advanced otosclerosis 4 meningitis 2 trauma	4 advanced otosclerosis 3 meningitis 2 trauma	
Intraoperative recordings			
Electrodes with auditory potentials, n	12.1 ± 2.9	16.2 ± 2.3	$P = .0079$[a]
Mean auditory threshold (CL)	158.9 ± 24.2	104.4 ± 32.5	$P = .0030$[a]
Electrodes with effects on neighboring cranial nerves at 190 CL, n	3.2 ± 2.4	7.8 ± 3.2	$P = .0034$[a]
Percentage of neighboring cranial nerves where monitoring is not reliable	44.4 (EMG)	0 (ECAP)	—
Postoperative outcomes			
Active electrodes, n	13.1 ± 3.8	17.2 ± 2.1	$P = .0210$[a]
Mean auditory threshold (CL)	173.3 ± 29.2	132.2 ± 29.5	$P = .0085$[a]
Number of electrodes with stimulation below 150 CL, n	2 ± 1.7	11.3 ± 3.3	$P < .001$[a]
Electrodes with extra-auditory effects, n	6.1 ± 1.9	1.9 ± 1.5	$P = .0004$[a]
48-Month follow-up			
Percentage of open-set sentence recognition	56.7 ± 15	78.9 ± 10.5	$P = .0051$[a]

Abbreviations: ABI, auditory brainstem implantation; CL, current level; EABR, evoked auditory brainstem response; ECAP, electrical compound nerve action potential; EMG, electromyography.
[a]Wilcoxon Mann-Whitney test.
[b]Fisher exact test.

emerged between groups when comparing the mean auditory threshold in terms of CL, with ABI-ECAP subjects always showing lower CL values to evoke auditory responses (P = .0030; **Figure 3**). The ECAP identified a statistically significantly higher number of electrodes that produced activation on neighboring cranial nerves at a CL of 190 CL (7.8 versus 3.2; P = .0034). Among the subjects who received EMG monitoring to investigate extra-auditory effects of ABI stimulation on other cranial nerves, EMG could be conducted properly only in 6 of 9 subjects because of curarization.

Electrophysiologic Outcomes at Activation

At activation, the ABI-ECAP group showed a statistically significantly higher number of active electrodes compared with the control group (17.2 versus 13.1; P = .0210). When comparing the mean CL necessary to evoke a subjective auditory sensation postoperatively, the study group showed consistently lower CL values, with about 11 electrodes below 150 CL against only 2 in the control group ($P < .001$; **Table 1**). The number of electrodes with extra-auditory effects at activation was significantly higher in the EABR group (P = .0004). The number of intraoperative electrodes with auditory effects was correlated in both groups with the number of active auditory electrodes at activation ($P < .001$, Fisher exact test). The probability of obtaining auditory responses at activation on electrodes that showed intraoperative EABRs and ECAPs was, respectively, .92 and .94.

Speech Perception Outcomes

Open-set speech perception outcomes at 48-month follow-up had significantly improved in the ABI-ECAP group compared with the EABR subjects (78.9% versus 56.7%; P = .0051).

Intraoperative outcomes of EABR and ECAPs in the study group are presented in **Table 2**. The ECAPs demonstrated consistently improved intraoperative outcomes with respect to EABR in every subject ($P < .05$).

Safety

No complications were observed during surgery or during the 48-month follow-up of the 2 cohorts of ABI subjects examined.

Discussion

Electrical compound nerve action potential was demonstrated to be an effective tool that could improve the correct intraoperative placement of the ABI electrode array compared with traditional EABR (higher number of usable electrodes and reduced amount of electrical charge needed to activate these electrodes), replace EMG monitoring for extra-auditory effects (not affected by curarization), and improve the overall open-set speech perception.

The adoption of a complete range of near- and far-field evoked potential measurements offers the opportunity to evaluate the best coupling between the electrode array and the CN. Despite the fact that EABRs and EMG are effective

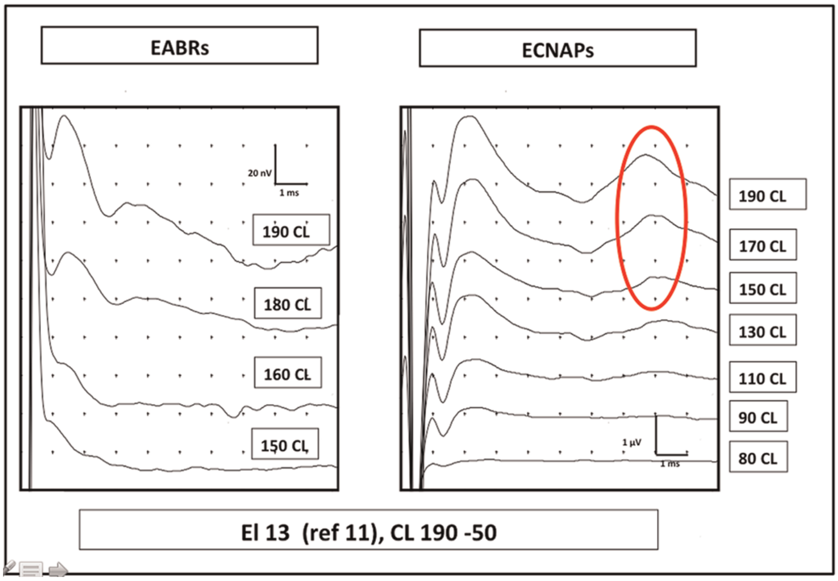

Figure 3. Evoked auditory brainstem response and electrical compound nerve action potential recordings obtained in 2 auditory brainstem implantation subjects with stimulation of electrode 13 from 190 current level (CL) to 50 CL. The red circle indicates the presence of a myogenic response at high CL stimulation.

Table 2. Intraoperative Outcomes of EABR and ECAPs in the Study Group.

	ABI-ECAP Group		Statistical Analysis (Wilcoxon Mann-Whitney Test)
	EABR	ECAP	
Electrodes with auditory potentials, n	11.4 ± 3.6	16.2 ± 2.3	*P* = .0089
Mean auditory threshold (CL)	151.1 ± 27.6	104.4 ± 32.5	*P* = .0071
Electrodes with effects on neighboring cranial nerves at 190 CL, n	4.1 ± 2.1	7.8 ± 3.2	*P* = .0154
Monitoring of neighboring cranial nerves not reliable because of curarization, %	29 (EMG)	0 (ECAP)	—

Abbreviations: ABI, auditory brainstem implantation; CL, current level; EABR, evoked auditory brainstem response; ECAP, electrical compound nerve action potential; EMG, electromyography.

tools for the correct placement of the electrode array, the ECAPs showed an improved evaluation of response threshold and ABI effects of neighboring cranial nerves. The ECAPs, as a near-field procedure, offer more precise evaluation of auditory threshold compared with far-field recordings (EABR). The ECAPs appeared to suffer a similar amount of electrical artifacts and saturation effects as EABRs but provided a better signal-to-noise ratio because of the larger amplitude of responses.

Electrical compound nerve action potentials, through more complete information with regard to the exact auditory and extra-auditory effects thresholds, allowed the surgeon to define the rotational, transverse, and longitudinal shifts and tilts of the array with accuracy and apply minimum correction to its positioning.

The information provided by the ECAPs was helpful in the initial fitting of the implant, and its use during implantation significantly improved overall open-set speech perception.

Intraoperative EABR monitoring is widely adopted for coupling of the array with the surface of the CN, despite there not being a general agreement on the correlation between electrodes with EABR responses and those producing only an auditory sensation at behavioral fitting. Some authors have indicated that fewer than half of the electrodes producing EABRs offer auditory sensations.[4,11] The EABR results in the present study are in agreement with recent papers in which EABR intraoperative monitoring is advocated as a useful tool in ABI surgery[12-14] and show a very good correlation with the number of auditory-only electrodes at the time of activation.[13]

Greater accuracy obtained in the coupling of the array with the CN through ECAPs was demonstrated by the higher number of usable electrodes and the reduced amount of electrical charge needed to activate those electrodes compared with the EABR subjects. The lower the charge required, the closer the ABI is to the CN surface. In particular, evaluation of the threshold for inducing extra-auditory effects with ECAPs on the lower cranial nerves allowed a more precise selection of the active electrodes to be used in the fitting process.

The higher electrode positioning accuracy obtained by ECAPs recorded with monopolar electrodes on the VII, IX, X, and IX cranial nerves could replace EMG monitoring, giving the surgeon immediate feedback on which electrodes induce myogenic responses. Furthermore, as demonstrated in the present study, ECAPs are not affected by curarization, but EMG monitoring is. In addition, a significant reduction in time was observed in the preparation of the patient compared with the traditional monitoring procedure with EMG.

The main limitations of this preliminary investigation are the limited number of patients, the short-term follow-up in terms of auditory outcomes, and the absence of tumoral[4,14] subjects and children[15] as comparative groups. However, to the best of our knowledge, the present study reports the largest population of ABI patients who underwent intraoperative ECAP monitoring in comparison with the traditional EABR monitoring.

In conclusion, ECAP monitoring is a very promising tool that can improve the correct intraoperative placement of the ABI electrode array, replace EMG monitoring for extra-auditory effects, provide important information at the time of ABI fitting, and improve the overall outcome of ABI surgery.

Author Contributions

Marco Mandalà, conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, revising the article, final approval; **Liliana Colletti**, conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, revising the article, final approval; **Giacomo Colletti**, conception and design of the study, analysis and interpretation of data, drafting the article, revising the article, final approval; **Vittorio Colletti**, conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, revising the article, final approval.

Disclosures

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