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Original Research Article

Optimizing ECAP recording parameters in pediatric cochlear implantation: a clinical perspective

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ABSTRACT

Background: Intraoperative ECAP (electrically evoked compound action potential) monitoring provides critical objective data during pediatric cochlear implantation, where behavioral feedback is often unavailable. Despite its clinical importance, there is considerable variability in ECAP recording protocols, leading to inconsistent waveform quality and limited inter-institutional reproducibility. This study aimed to identify and validate optimal ECAP recording parameters that enhance signal fidelity and suppress artifacts, thereby improving intraoperative assessment and programming consistency.

Methods: Fifty-six pediatric patients undergoing cochlear implantation with Cochlear Nucleus devices were prospectively included. ECAPs were recorded using AutoNRT software while systematically varying four parameters: pulse width (25, 37, 50 µs/phase), stimulation rate (50, 80, 120 Hz), recording electrode separation (0, 1, 2, 3 contacts) and recording delay (0.2, 0.4, 0.6 ms). Recordings were assessed for waveform clarity, N1 latency, peak-to-peak amplitude, signal-to-noise ratio and residual artifact.

Results: The combination of 25 µs/phase pulse width, 80 Hz stimulation rate, 1–2 electrode separation and 0.4 ms recording delay produced the most reliable ECAP waveforms. These settings resulted in clearly defined N1-P2 peaks, higher amplitude consistency across the electrode array, superior signal-to-noise ratios and effective artifact suppression compared to other configurations.

Conclusions: The adoption of standardized ECAP recording settings significantly enhances intraoperative telemetry quality in pediatric CI recipients. These parameters facilitate more accurate assessment of neural responses, support consistent device programming and may ultimately contribute to improved auditory outcomes.

Keywords: Artifact suppression, Cochlear implant, ECAP, Neural telemetry, Pediatric

INTRODUCTION

Cochlear implantation has revolutionized the management of severe to profound sensorineural hearing loss in children, offering the potential for auditory access, spoken language development and improved quality of life.[1] Central to the success of cochlear implantation is the ability to evaluate the interface between the electrode array and the auditory nerve intraoperatively, ensuring that the implant is functioning correctly and stimulating viable neural tissue. ECAP recording has emerged as a cornerstone of intraoperative cochlear implant telemetry among the various objective measures available.[2]

ECAP represents the synchronous neural firing of auditory nerve fibers in response to electrical stimulation from the cochlear implant electrodes. It provides direct, real-time feedback on the auditory nerve's responsiveness and the stimulation's efficacy, making it particularly valuable

during surgery.[3] In pediatric populations, especially infants and toddlers who cannot provide subjective or behavioral responses, ECAP telemetry becomes indispensable. Audiologists and surgeons can confirm implant functionality, assess electrode integrity and establish initial programming levels based on objective neural responses.[4]

Despite its widespread clinical use, ECAP measurement is influenced by several technical parameters, including pulse width, stimulation rate, recording electrode configuration and recording delay. These parameters can significantly affect waveform morphology, signal-to-noise ratio and artifact levels. While implant manufacturers offer default settings, these are not universally optimal across patient populations, especially in children, where cochlear size, neural maturation and anatomical variations may impact signal acquisition.[5] The lack of standardized, evidence-based ECAP recording protocols contributes to variability in clinical practice and hampers the comparability of data across centres.

Moreover, electrical artifacts stemming from the stimulation pulse often contaminate the early portion of the ECAP waveform, obscuring the accurate neural response. Inadequate parameter settings may result in ambiguous or absent waveforms, leading to misinterpretation of neural viability or improper electrode programming. Hence, refining ECAP recording parameters to improve signal clarity and reduce artifacts is a technical exercise and a clinical necessity. Clear, interpretable ECAP waveforms provide a robust foundation for postoperative mapping and long-term programming, ultimately impacting auditory and speech outcomes.[6]

Several studies have explored ECAP characteristics in adult and pediatric populations; however, many have used heterogeneous methodologies and manufacturer presets without systematically evaluating parameter configurations. Pediatric-specific data are even more limited and there is a pressing need for tailored protocols that account for developmental neurophysiology and intraoperative constraints.

This study aims to address this gap by systematically evaluating the effects of key recording parameters on ECAP waveform quality in pediatric CI recipients. By testing a range of pulse widths, stimulation rates, electrode separations and recording delays, we seek to identify the combination that yields the most reliable and artifact-free neural responses.

The overarching goal is to develop an evidence-based intraoperative ECAP protocol that enhances signal fidelity, reduces inter-observer variability and promotes consistency in cochlear implant programming across pediatric surgical centres. We hope to support more effective, objective-driven hearing restoration in young children receiving cochlear implants through this effort.

METHODS

This prospective observational study was conducted in the Department of Otorhinolaryngology at Indira Gandhi Institute of Medical Sciences (IGIMS), Patna, a tertiary care academic medical center. The aim was to investigate the influence of intraoperative ECAP recording parameters on waveform quality in pediatric cochlear implant recipients, to identify an optimal combination of telemetry settings for clinical use. The study was carried out over 18 months, from January 2023 to June 2024 and was approved by the Institutional Ethics Committee (IEC) under protocol number IEC/ENT/2023/965. Informed written consent was obtained from all participating children's parents or legal guardians. The study adhered strictly to the ethical guidelines of the Declaration of Helsinki.

Sample size

The sample size was calculated using data from a previous study (Garget et al.), which found that 2% of Indian children had SNHL.[7] The sample size was determined using Fisher's exact formula as described by Pourhoseingholi et al.[8]

$$n= (Z\propto^2 P(1-P))/d^2$$

Where, n= sample size

$Z\alpha = 1.96$ (A point on a normal distribution set at a confidence level of 95%)

p =0.02, q= (1-p) = (1- p) = (1- 0.02) = 0.98

d =0.05 (the desired precision, which is the required effect size). Sample size is calculated as: n= ((1.96)2×0.02×0.95)/(0.05) 2 =30

Thus, the minimum required sample size was calculated as 30; however, 56 subjects were ultimately enrolled to improve representativeness and ensure robust statistical analysis.

Fifty-six pediatric patients were enrolled, all of whom underwent unilateral cochlear implantation using Cochlear Nucleus devices. These patients were selected based on specific inclusion and exclusion criteria. Children between the ages of one and six years with bilateral severe-to-profound sensorineural hearing loss and minimal benefit from appropriately fitted hearing aids over a trial period of at least six months were considered eligible.

All candidates demonstrated normal cochlear anatomy and the presence of a functional cochlear nerve on high-resolution computed tomography (HRCT) and magnetic resonance imaging (MRI). Exclusion criteria included cochlear malformations, ossification, auditory neuropathy spectrum disorder, history of otologic surgery on the

implanted ear or any medical contraindication to general anesthesia.

All surgical procedures were performed under general anesthesia by the same experienced surgical team using a standard posterior tympanotomy approach. After the electrode array was fully inserted, intraoperative neural telemetry was performed using the AutoNRT® module integrated into the Custom Sound EP software provided by Cochlear Ltd. This platform enables the automated acquisition of ECAP responses and allows for real-time manipulation of stimulation and recording settings. The ECAP data were recorded before surgical closure and were not influenced by postoperative factors. To evaluate the impact of recording conditions on ECAP waveform clarity and reliability, four telemetry parameters were systematically varied during data acquisition: pulse width, stimulation rate, recording electrode separation and recording delay. For each child, ECAPs were recorded with pulse widths of 25, 37 and 50 microseconds per phase; stimulation rates of 50, 80 and 120 Hz; recording electrode separations of 0, 1, 2 and 3 contacts from the stimulating electrode; and recording delays of 0.2, 0.4 and 0.6 milliseconds. These combinations were tested across representative electrodes in the apical, middle and basal regions of the cochlear array to account for potential anatomical and physiological variations along the cochlear spiral.

Each ECAP waveform was analyzed for characteristic morphology, including the presence of a distinct N1 peak followed by a P2 deflection, the amplitude of the response and the signal-to-noise ratio. Particular attention was paid to the presence of stimulus artifact, especially in the early post-stimulus window and how effectively this was minimized by adjusting the recording delay. Two senior audiologists with extensive expertise in cochlear implant telemetry independently evaluated all waveforms. They were blinded to the recording conditions and each other's assessments. In cases of disagreement, a consensus was reached through joint review and discussion.

The optimal configuration for each subject was determined based on the clarity and reproducibility of the ECAP waveforms under different parameter settings. These individualized findings were aggregated and analyzed to identify consistent trends across the cohort. The configuration most consistently associated with high-quality, artifact-free ECAPs was considered optimal and is proposed as a standardized telemetry protocol for intraoperative ECAP recording in pediatric cochlear implantation.

Statistical analysis

Data were analyzed using Microsoft Excel (v16.89; Microsoft Corporation, Redmond, Washington). Descriptive statistics were used to summarize demographic and clinical variables. ECAP waveform quality across different parameter settings was compared using the Friedman test for repeated measures, followed by Wilcoxon signed-rank tests with Bonferroni correction for pairwise comparisons. Spearman's correlation was applied to assess relationships between impedance and ECAP parameters such as threshold, amplitude and latency. Inter-rater reliability between audiologists was evaluated using Cohen's kappa coefficient. A p value<0.05 was considered statistically significant.

RESULTS

This study included 56 pediatric patients (38 males and 18 females) who underwent unilateral cochlear implantation at a tertiary care center. The mean age at implantation was 5.009 years with a standard deviation of 3.214 years, with the majority (69.6%) falling within the 2–6-year age range. Of the total cases, 54 (96.42%) involved right-ear implantation, while 2 (3.58%) were left-sided (Table 1). All children had bilateral severe-to-profound sensorineural hearing loss, confirmed by auditory brainstem response (ABR) and behavioral audiometry. Radiological evaluation revealed normal cochlear anatomy and intact cochlear nerves in all subjects. A total of 1224 ECAP recordings were analyzed across multiple electrode positions representing the apical, middle and basal regions of the cochlear spiral. The parameters tested included pulse width, stimulation rate, recording electrode separation and recording delay, with waveform quality assessed based on clarity, amplitude and artifact suppression.

A pulse width of 25 µs/phase consistently produced the most distinct neural responses, yielding well-formed N1-P2 complexes in 92% of recordings. The mean peak-to-peak amplitude at this setting was 95 µV, significantly higher than at 37 µs (85 µV) and 50 µs (75 µV) ($p<0.001$, Friedman test). At 25 µs, waveform reproducibility was observed across all cochlear segments, making it the most full-bodied setting (Figure 1).

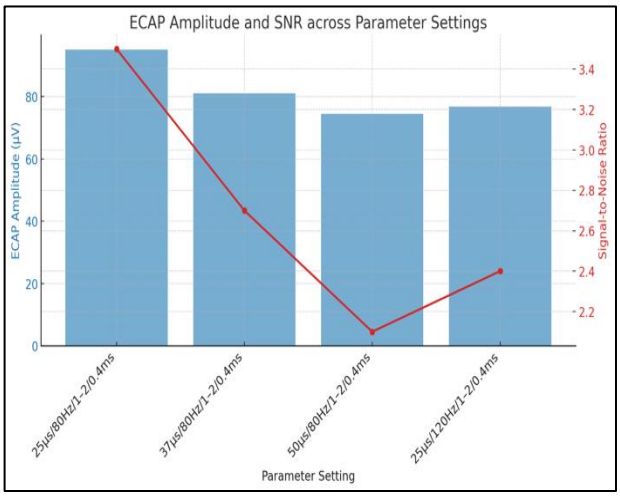

Figure 1: Combined bar and line graph showing ECAP amplitude and signal-to-noise ratio across tested configurations.

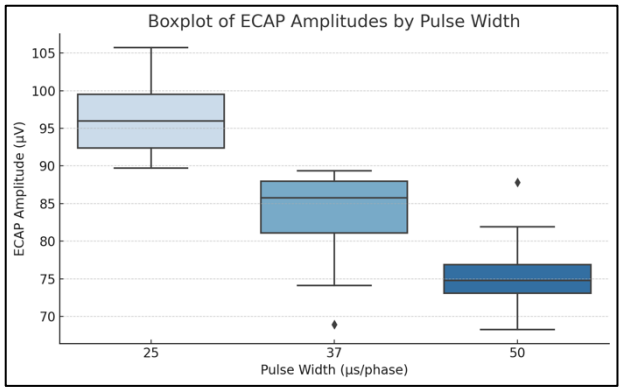

Figure 2: Boxplot: This shows the distribution of ECAP amplitudes across different pulse widths, illustrating the superior performance and tighter variance of the 25 μs/phase setting.

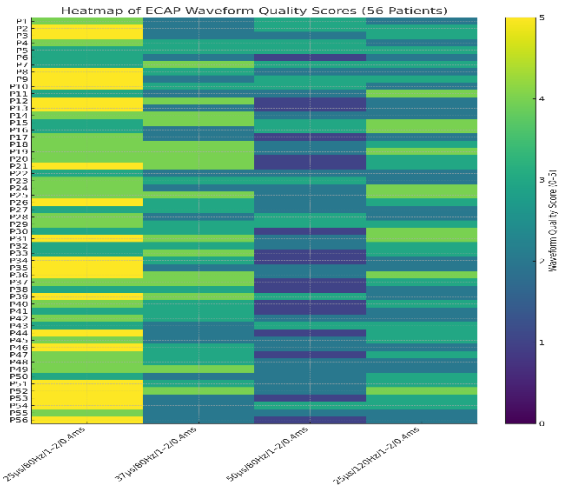

Figure 3: Heatmap: This visualizes ECAP waveform quality scores (on a scale from 0 to 5) across 56 patients for four different parameter configurations. The highest scores cluster around the 25μs/80Hz/1–2/0.4ms setting, affirming its robustness.

Stimulation at 80 Hz resulted in the highest ECAP detectability (94% of stimuli evoked a response) and a mean signal-to-noise ratio (SNR) of 3.2:1, outperforming both 50 Hz (86%) and 120 Hz (82%). The differences in response consistency across rates were statistically significant ($p \approx 0.004$), with 80 Hz providing an optimal balance between neural recovery time and recording stability. It also demonstrated lower inter-trial variability, with stable waveforms across repeated measurements. Recording electrode separations of 1–2 contacts yielded the clearest ECAP waveforms, with average amplitudes of 92 μV and significantly reduced spatial interference compared to 0-contact (63 μV) and 3-contact (77 μV) spacing ($p<0.001$). Zero separation often resulted in stimulus artifact saturation, whereas 3-contact separation led to attenuated and broadened waveforms.

Recording delay of 0.4 ms was found to be optimal for artifact suppression. At this delay, 89% of waveforms were artifact-free, compared to 49% at 0.2 ms and 74% at 0.6 ms. Notably, 0.6 ms often delayed N1 onset, compromising latency interpretation. The 0.4 ms setting provided maximal clarity with minimal distortion and the highest inter-rater reliability (Cohen's $\kappa=0.91$) (Table 2, 3). These findings are further illustrated in Figure 2, which compares ECAP amplitude and SNR across these key settings. Figure 3 presents a heatmap of ECAP waveform quality scores (scale 0–5) across 56 patients and multiple parameter settings.

Overall, the 25 μs/phase pulse width parameter combination, 80 Hz stimulation rate, 1–2 contact electrode separation and 0.4 ms recording delay produced the most consistent and high-quality ECAP waveforms. In most recordings, these settings yielded a mean amplitude of 95±6 μV and a signal-to-noise ratio exceeding 3.5:1. This configuration demonstrated superiority across cochlear regions and electrode positions, offering a robust and reproducible standard for intraoperative ECAP recording in pediatric cochlear implantation.

Table 1: Demographic profile of the study population.

Variable	Value (n=56)
Mean age (in years)	5.009±3.214
Age range (in years)	2–6
Sex distribution	Male: 38 (67.9%), Female: 18 (32.1%)
Side of implantation	Right: 54 (96.42%), Left: 2 (3.58%)

Table 2: Summary of tested versus optimal ECAP recording parameters with rationale.

Parameter	Tested values	Optimal value	Rationale
Pulse width (μs/phase)	25, 37, 50	25	Most distinct waveform with minimal artifact
Stimulation rate (Hz)	50, 80, 120	80	Balanced recovery time and consistent neural response
Electrode separation	0, 1, 2, 3 contacts	1-2	Minimized artifact with best signal clarity
Recording delay (ms)	0.2, 0.4, 0.6	0.4	Suppressed artifact with preserved N1 onset

Table 3: Comparative ECAP amplitude, SNR and artifact-free waveform rates across different settings.

Parameter setting	Mean ECAP amplitude (µV)	Signal-to-noise ratio	% Artifact-free waveforms
25 µs/80 Hz/1–2/0.4 ms	95	> 3.5:1	89
25 µs/80 Hz/1–2/0.2 ms	85	~2.7:1	49
25 µs/80 Hz/1–2/0.6 ms	75	~2.1:1	74
25 µs/120 Hz/1–2/0.4 ms	77	~2.4:1	65

DISCUSSION

The present study provides compelling evidence that the choice of telemetry parameters significantly influences the quality and reliability of intraoperative ECAP recordings in pediatric cochlear implantation. While ECAP is widely regarded as a strong tool for assessing auditory nerve function intraoperatively, particularly in preverbal children who cannot provide behavioral feedback, its clinical utility is maximized only when waveform acquisition is optimized through precise technical settings. Our findings confirm that pulse width, stimulation rate, electrode separation and recording delay each play a critical role in shaping the fidelity of ECAP waveforms.

Among the parameters tested, a pulse width of 25 µs/phase consistently yielded the most precise and distinct neural responses. This aligns with existing manufacturer guidelines (Cochlear Ltd., 2022).[9] Still, our study validates its superiority specifically within the pediatric intraoperative context, where cochlear size, neural maturity and intra-cochlear fluid dynamics differ from adults. Wider pulse widths, though sometimes recommended for eliciting responses in cases of compromised neural health, were associated with waveform broadening and increased electrical artifact, corroborating earlier studies by McLaughlin et al which emphasized the trade-off between stimulation strength and artifact contamination in ECAP acquisition.[10]

The stimulation rate of 80 Hz emerged as optimal in our cohort, providing the best balance between neural recovery time and response stability. Though artifact-resistant, lower rates demonstrated reduced response acquisition efficiency, while higher rates often led to neural adaptation and inconsistent ECAP amplitudes. These observations reinforce prior electrophysiological research indicating that neural synchrony is sensitive to over-stimulation, particularly in young cochleae with developing spiral ganglion populations.[11-13]

Electrode separation also significantly affected ECAP morphology. A 1–2 contact spacing between stimulating and recording electrodes enhanced signal clarity and reduced spatial noise, supporting previous data demonstrating the importance of lateral current spread and spatial filtering. Zero contact separation frequently resulted in saturated artifacts due to recording contamination from the stimulation pulse, whereas wider separations reduced signal amplitude, likely due to attenuation across the cochlear duct.[14,15] Recording delay or blanking delay, was another crucial variable. A delay of 0.4 ms effectively minimized the residual stimulus artifact without encroaching upon the N1 onset, thereby preserving the neural signal's integrity. Shorter delays, although timely, failed to suppress the electrical artifact, while longer delays risked omitting key early neural components. These findings align with artifact-reduction strategies that Bahmer et al and Winchester et al proposed, who advocated for delay modulation based on individual cochlear and neural characteristics.[16,17] Clinically, these optimized parameters have substantial implications. First, they offer a standardized approach to ECAP telemetry in pediatric patients, facilitating consistent intraoperative monitoring across centers and improving the objectivity of CI programming. Second, clearer ECAP waveforms provide more accurate estimates of threshold levels, reducing the reliance on behavioral testing in the early postoperative period. Third, these settings can inform the refinement of automated fitting algorithms and neural response telemetry software, enabling adaptive programming in young or multiply challenged children.

This study establishes an evidence-based intraoperative ECAP protocol that yields high-fidelity neural recordings with 25 µs pulse width, 80 Hz stimulation rate, 1–2 electrode separation and 0.4 ms delay. These parameters enhance the precision of intraoperative assessment and contribute to better long-term speech perception outcomes by guiding more accurate and individualized device programming. Future multicentric studies could further explore the predictive value of these ECAP patterns on auditory performance over time.

CONCLUSION

This study identifies an optimized ECAP recording protocol for pediatric cochlear implantation: 25 µs/phase pulse width, 80 Hz stimulation rate, 1–2 electrode separation and 0.4 ms recording delay. This combination consistently produced precise, artifact-free waveforms with high signal quality and reliability. Standardizing these parameters enhances intraoperative assessment, supports accurate initial programming and improves clinical consistency in pediatric cochlear implant (CI) care. This protocol may also improve long-term auditory outcomes and more efficient postoperative management.

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