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Electrical Impedance Changes InPediatric Cochlear Implant Recipients Among Three Different Cochlear Implant Manufacturers

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Abstract
Background: *Electrical impedance is a key objective parameter reflecting the electrode–tissue interface in cochlear implant (CI) recipients. Its temporal variation provides important insights into device performance and intracochlear biological responses, particularly in paediatric populations.*
Objective: *To evaluate and compare electrical impedance changes over time among paediatric cochlear implant recipients using three different CI manufacturers.*
Methods: *This prospective observational study included 30 paediatric patients (aged 2–8 years) with bilateral profound sensory-neural hearing loss that underwent cochlear implantation at a tertiary care centre. Patients were equally distributed into three groups (n=10 each) based on implant manufacturer (Company A, B, and C). Impedance measurements were recorded at four time points: intraoperative, switch-on, 3 months, and 6 months post-implantation. Statistical analysis was performed using paired t-tests and ANOVA.*
Results: *Intraoperative and early postoperative impedance values showed no statistically significant inter-group differences (p>0.05). However, a trend toward divergence was observed at 3 months, becoming statistically significant at 6 months (p=0.006), with Company A demonstrating higher impedance values compared to Company B. Within-group analysis revealed stable impedance in Company A, significant early increases followed by stabilization in Company B, and a marked immediate postoperative rise with subsequent plateau in Company C.*
Conclusion: *While early impedance values are comparable across implant systems, significant differences emerge over time, reflecting device-specific electrode characteristics and biological interactions. These findings highlight the importance of individualized device monitoring and programming in paediatric cochlear implant recipients.*
Keywords:*Cochlear implant; Electrical impedance; Paediatric hearing loss; Electrode–tissue interface; Impedance telemetry; Sensory-neural hearing loss; Cochlear implant manufacturers; Postoperative monitoring; Auditory rehabilitation; Implant programming*

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I. Introduction

Cochlear implantation has emerged as a highly effective and widely accepted intervention for individuals with profound sensory neural hearing loss, particularly in the paediatric population. With appropriate patient selection, meticulous preoperative evaluation, and standardized surgical techniques, cochlear implants (CIs) have demonstrated consistently high success rates in restoring auditory perception and facilitating speech development.

The functional efficacy of a cochlear implant depends on the complex interaction between the implanted electrode array and the residual neural elements within the cochlea. Each electrode establishes a unique interface with the surrounding neural tissue, and this interaction is influenced by several factors, including electrode position within the scale tympani, the extent of current spread, intracochlear fluid composition, and the pattern of neural survival. These factors collectively determine the quality of electrical stimulation delivered to the auditory nerve and, consequently, the auditory outcomes in CI recipients [1].

Currently, three major manufacturers dominate the global cochlear implant market and have received regulatory approval: Advanced Bionics (USA), Cochlear (Australia), and MED-EL (Austria). Despite differences in electrode design, signal processing strategies, and telemetry systems, all cochlear implant devices consist of two principal components: an internal implanted receiver-stimulator with an electrode array and an external speech processor that captures and encodes sound signals [2].

Objective intraoperative and postoperative assessments are integral to ensuring the proper functioning and long-term reliability of cochlear implants. Telemetry-based electrophysiological measures have become indispensable tools in CI programming and follow-up. These include electrode impedance measurements, electrically evoked compound action potentials (ECAP), electrically evoked auditory brainstem responses (EABR), and stapedius reflex testing. Such measures are non-invasive, reproducible, and particularly valuable in paediatric populations where behavioural audiometry may be unreliable [3,4].

Among these, electrode impedance measurement is one of the most fundamental and routinely used parameters. Impedance reflects the resistance encountered by electrical current as it passes through the electrode contacts, connecting wires, and surrounding biological tissues. It is expressed in ohms (Ω) and is calculated as the ratio of applied voltage to the resulting current flow within the system [5,6]. Clinically, impedance values provide critical information regarding electrode integrity, electrode-tissue interface, and possible pathological changes such as fibrosis or fluid alterations within the cochlea.

Previous studies have demonstrated variable trends in impedance changes following cochlear implantation. Sunwoo W et al. [7] reported a significant decrease in impedance values following the initial activation (“switch-on”), with stabilization occurring within the first postoperative month. In contrast, Wolf-Magele et al. [8] observed no significant differences in impedance values between intraoperative and early postoperative measurements, suggesting that early activation may be safely implemented without adverse effects on electrode function.

Despite these observations, comparative data evaluating impedance trends across different cochlear implant manufacturers, particularly in paediatric populations, remain limited. Differences in electrode design, surface characteristics, and insertion techniques may contribute to variability in impedance behaviour over time.

Objective of the Study

The present study aims to evaluate and compare the electrical impedance changes in paediatric cochlear implant recipients using devices from three different manufacturers over a defined postoperative period.

Impedance measurements were recorded at three key time points:

- Intraoperative period
- At initial activation (switch-on)
- Three months post implantation
- Six month post implantation

This study seeks to identify patterns of impedance variation over time and to determine whether significant differences exist among the three cochlear implant systems.

II. Materials And Methods

Study Design

This study was designed as a prospective observational, single-centre (mono-centric) study. All data collection and analysis were conducted in compliance with applicable Indian data protection and privacy regulations.

Study Population

The study cohort comprised 30 consecutive patients who underwent cochlear implantation between 2022 and 2024 at the Department of Otorhinolaryngology, Sir Sunderlal Hospital, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India.

Participants were equally distributed among three cochlear implant manufacturers, designated as:

- Company A
- Company B
- Company C

Each group included 10 patients, ensuring balanced representation.

Demographic and Clinical Characteristics(Age range 2 to 8 yrs)

- Mean age: 2 ± 7.6 years
- Age range: 2 to 8 years
- Median age: 5.1 years
- Gender distribution: 18 males and 12 females

All patients were diagnosed with bilateral profound sensory neural hearing loss and were selected for cochlear implantation based on standard clinical criteria.

Surgical Procedure

All cochlear implantations were performed by the same experienced surgeon using a standardized surgical approach involving Varia technique with cochleostomy (with minor technical variations as required). Full insertion of the electrode array was achieved in all cases.

Straight electrode arrays were used uniformly across all three implant systems to minimize variability related to electrode design.

Postoperative Performance

All patients were consistent, full-time users of their cochlear implants and demonstrated optimal auditory performance, defined as pure-tone audiometric thresholds below 30 dB HL across tested frequencies (250–6000 Hz).

Impedance Measurement Protocol

Electrode impedance measurements were obtained for all patients at multiple time points:

❖Intra-operatively
❖At initial activation (switch-on)
❖At 3 months post-implantation
❖At 6 months post-implantation

Measurements were recorded for each electrode channel to assess temporal changes and inter-device variability.

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics software. The following analytical methods were applied:

❖Paired Samples t-test: Used to compare mean impedance values across different time points within each manufacturer group.
❖Computed parameters included:
➢Mean difference
➢Standard deviation
➢Standard error
➢t-statistic
➢p-values (one-tailed and two-tailed)

III. Results And Analysis:

Inter-Company Comparison of Impedance Values

Company Name	N	Mean (Ω)	SD	F-value	p-value
A	10	9.49	3.48		
B	10	5.09	1.58	2.704	0.094
C	10	8.02	4.28		

Table 1: Intraoperative Impedance Comparison

At the intraoperative stage, the mean impedance values differed across the three cochlear implant systems. The Nucleus Cochlear Implant group demonstrated the highest mean impedance (9.49 ± 3.48 Ω), followed by the Advanced Cochlear Implant (8.02 ± 4.28 Ω), while the MED-EL Cochlear Implant group exhibited the lowest mean value (5.09 ± 1.58 Ω).

One-way ANOVA analysis revealed that these differences were not statistically significant (F = 2.704, p = 0.094). Although baseline variability in impedance values was observed, it did not reach statistical significance, suggesting that intraoperative impedance differences among implant systems may reflect variations in electrode design, surface characteristics, or insertion depth rather than true functional disparity.

Company Name	N	Mean (Ω)	SD	F-value	p-value
A	10	10.24	2.68		
B	10	7.66	1.40	1.195	0.326
C	10	9.85	4.36		

Table 2: Impedance at Initial Activation (Switch-On)

At the time of initial activation, impedance values showed a similar distribution pattern. The Company A system again demonstrated the highest mean impedance (10.24 ± 2.68 Ω), followed by Company C(9.85 ± 4.36 Ω), and company B (7.66 ± 1.40 Ω).

However, inter-group comparison using ANOVA indicated no statistically significant difference (F = 1.195, p = 0.326). This suggests that despite observable numerical differences, impedance values at switch-on are comparable across manufacturers, indicating similar early postoperative electrode-tissue interactions.

Company Name	N	Mean (Ω)	SD	F-value	p-value
A	10	10.56	1.29		
B	10	7.51	1.74	2.807	0.087
C	10	8.33	3.42		

Table 3: Impedance at 3 Months Post-Implantation

At 3 months, impedance values demonstrated a trend toward divergence among the groups. The company A maintained the highest mean impedance (10.56 ± 1.29 Ω), followed by Company C (8.33 ± 3.42 Ω) and Company B (7.51 ± 1.74 Ω).

The ANOVA test approached statistical significance (F = 2.807, p = 0.087), indicating a borderline trend toward inter-device variability. This finding suggests evolving electrode-tissue interface dynamics, potentially influenced by fibrotic encapsulation, tissue healing, or differences in electrode array design.

Company Name	N	Mean (Ω)	SD	t-value	p-value
A	10	10.64	1.66		
B	10	7.39	1.75	11.770	0.006

Table 4: Impedance at 6 Months Post-Implantation

At 6 months, a statistically significant difference in impedance values was observed between implant systems. The company A implant demonstrated significantly higher mean impedance (10.64 ± 1.66 Ω) compared to Company B (7.39 ± 1.75 Ω).

Statistical analysis showed a significant difference (t = 11.770, p = 0.006), indicating that long-term impedance profiles vary significantly across implant types. This finding underscores the potential role of device-specific factors such as electrode material, geometry, and intracochlear positioning in influencing long-term electrical characteristics.

Intra-Company (Within-Group) Comparison

Implant-A

Paired sample t-test analysis for the company A implant system demonstrated no statistically significant changes in impedance values across all time intervals:

Comparison Pair	Time Point 1	Mean (Ω)	SD	Time Point 2	Mean (Ω)	SD	t-value	p-value
Pair 1	Intraop	9.49	3.48	Switch-on	10.24	2.68	-0.949	0.379
Pair 2	Intraop	9.49	3.48	3 Months	10.56	1.29	-0.954	0.377
Pair 3	Intraop	9.49	3.48	6 Months	10.64	1.66	-1.021	0.347
Pair 4	Switch-on	10.24	2.68	3 Months	10.56	1.29	-0.383	0.715
Pair 5	Switch-on	10.24	2.68	6 Months	10.64	1.66	-0.540	0.608
Pair 6	3 Months	10.56	1.29	6 Months	10.64	1.66	-0.274	0.793

Table 5: Within-Group Comparison – Implant A

- Intraoperative vs Switch-on: p = 0.379
- Intraoperative vs 3 Months: p = 0.377
- Intraoperative vs 6 Months: p = 0.347
- Switch-on vs 3 Months: p = 0.715
- Switch-on vs 6 Months: p = 0.608
- 3 Months vs 6 Months: p = 0.793

Although a gradual increase in mean impedance values was observed over time, these changes were not statistically significant. This suggests that the Nucleus system demonstrates stable impedance characteristics over the early postoperative period, reflecting a relatively steady electrode-tissue interface.

Implant-B

The Company B implant system exhibited statistically significant changes in impedance between intraoperative and early postoperative periods:

Comparison Pair	Time Point 1	Mean (Ω)	SD	Time Point 2	Mean (Ω)	SD	t-value	p-value
Pair 1	Intraop	5.09	1.58	Switch-on	7.66	1.40	-3.377	0.020
Pair 2	Intraop	5.09	1.58	3 Months	7.51	1.74	-2.764	0.040
Pair 3	Intraop	5.09	1.58	6 Months	7.39	1.75	-2.558	0.051
Pair 4	Switch-on	7.66	1.40	3 Months	7.51	1.74	0.242	0.818
Pair 5	Switch-on	7.66	1.40	6 Months	7.39	1.75	0.444	0.675
Pair 6	3 Months	7.51	1.74	6 Months	7.39	1.75	1.153	0.301

Table 6: Within-Group Comparison – B Implant

- Intraoperative vs Switch-on: Mean difference = -2.575, p = 0.020
- Intraoperative vs 3 Months: Mean difference = -2.422, p = 0.040
- Intraoperative vs 6 Months: Mean difference = -2.303, p = 0.051

No significant differences were observed in later comparisons:
- Switch-on vs 3 Months: p = 0.818
- Switch-on vs 6 Months: p = 0.675
- 3 Months vs 6 Months: p = 0.301

These findings indicate a significant early postoperative increase in impedance, followed by stabilization over time. This pattern may reflect initial biological responses such as protein adsorption and tissue healing around the electrode array.

Implant-C

Comparison Pair	Time Point 1	Mean (Ω)	SD	Time Point 2	Mean (Ω)	SD	t-value	p-value
Pair 1	Intraop	8.02	4.28	Switch-on	9.85	4.36	-10.347	0.000
Pair 2	Intraop	8.02	4.28	3 Months	8.33	3.42	-0.345	0.741
Pair 3	Switch-on	9.85	4.36	3 Months	8.33	3.42	1.614	0.151

Table 7: Within-Group Comparison

The company C implant system demonstrated the most pronounced early change:
- Intraoperative vs Switch-on: Mean difference = -1.835, p < 0.001 (highly significant)

However, subsequent comparisons were not statistically significant:
- Intraoperative vs 3 Months: p = 0.741
- Switch-on vs 3 Months: p = 0.151

This indicates that the company c system undergoes a significant immediate postoperative impedance shift, followed by a plateau phase with minimal further variation. The early change likely reflects acute electrode-tissue interface adaptation after implantation.

IV. Discussion

The present study evaluated the temporal changes in electrical impedance among paediatric cochlear implant recipients using three different implant systems— Company A,B and Cover a follow-up period of six months. The findings provide important insights into both inter-device variability and intra-device impedance evolution.

Inter-Company Comparison

In the present study, inter-group comparisons revealed that although mean impedance values differed numerically among the three implant systems at all time points, these differences were not statistically significant during the early postoperative period (intraoperative and switch-on stages). This observation is consistent with previous reports suggesting that immediate postoperative impedance values are largely influenced by surgical factors such as electrode insertion technique, intracochlear fluid environment, and initial electrode-tissue contact rather than intrinsic device characteristics [9,10].

However, a progressive divergence in impedance values was observed at 3 months, reaching statistical significance at 6 months. Specifically, the Company A system demonstrated consistently higher impedance values compared to the Company B system. This finding suggests that long-term impedance behaviour may be influenced by device-specific factors, including electrode design, surface coating, and material properties [11].

The higher impedance values observed in the Nucleus system could be attributed to increased fibrotic tissue formation or tighter electrode-tissue interface; whereas the relatively lower impedance in Company Bimplants may reflect differences in electrode surface area or intracochlear positioning that allow more efficient current flow [12]. Such variations have been previously linked to differences in electrode geometry and current spread characteristics [13].

Intra-Company (Temporal) Impedance Changes
Implant-A

The Company A implant system demonstrated remarkable stability in impedance values across all time points, with no statistically significant differences observed between intraoperative, switch-on, and follow-up measurements.

Although a slight upward trend in mean impedance was noted over time, this change was not statistically significant. This stability suggests a consistent electrode-tissue interface and minimal biological reactivity over the study period. Clinically, such stability is advantageous as it ensures predictable device performance and simplifies programming during follow-up sessions [14,15].

Implant-B

In contrast, the Company B implant system exhibited significant changes in impedance during the early postoperative period. A statistically significant increase in impedance was observed between intraoperative and switch-on measurements, as well as between intraoperative and 3-month values.

This early rise in impedance may be explained by acute biological responses following implantation, including protein adsorption, inflammatory reactions, and initial fibrotic encapsulation around the electrode array [16,17]. Notably, impedance values stabilized thereafter, with no significant differences between later time points.

These findings are in agreement with previous studies that reported significant impedance changes in the early postoperative phase, followed by stabilization as the electrode-tissue interface matures [18].

Implant-C

The Company C cochlear implant system demonstrated the most pronounced early impedance change, with a highly significant increase between intraoperative and switch-on measurements. However, subsequent changes were not statistically significant, indicating a plateau in impedance values after the initial postoperative phase.

This pattern suggests a rapid initial electrode-tissue interface adjustment, possibly due to electrode surface properties or insertion dynamics, followed by stabilization [19,20]. Such early changes may necessitate careful programming adjustments during the initial activation phase.

Comparison with Previous Studies

The findings of the present study are in partial agreement with earlier reports. For instance, Henkin et al. demonstrated a significant decrease in impedance values following initial stimulation, with stabilization occurring within the first postoperative month [21]. However, in the present study, an increase in impedance from intraoperative to switch-on was observed in certain groups.

This discrepancy may be attributed to differences in:

- Study population (pediatric vs mixed populations)
- Electrode design and implantation techniques
- Timing of impedance measurements
- Postoperative healing responses

Similarly, Meghanadhet al. reported no significant differences between intraoperative and early postoperative impedance values, suggesting that early activation is feasible without affecting electrode function [22]. In contrast, the present study observed early significant changes in some implant systems, indicating that impedance evolution may vary depending on device characteristics and biological factors.

The observed differences in impedance behaviour have several important clinical implications:

- Device Programming**:** Variations in impedance influence current delivery and may require individualized programming strategies [23].
- Monitoring**:** Systems showing early impedance changes may require closer follow-up during theinitial postoperative period [24].
- Long-term Outcomes**:** Significant inter-device differences at 6 months highlight the importance of device-specific considerations in long-term evaluation [25].
- Pediatric Relevance**:** In children, where behavioral responses are limited, impedance telemetry serves as a reliable and objective monitoring tool [26,27].

V. Strengths And Limitations

Strengths

- Comparative evaluation of three major cochlear implant systems
- Uniform surgical technique and single-surgeon consistency
- Prospective design with serial impedance measurements

Limitations

- Small sample size (n = 30)
- Short follow-up duration (6 months)
- Lack of correlation with auditory and speech outcomes
- Potential variability in biological response among patients

VI. Conclusion

The present study demonstrates that while early postoperative impedance values are comparable across cochlear implant systems, significant differences emerge over time, particularly at 6 months. Each implant system exhibits a distinct impedance evolution pattern, reflecting differences in electrode design and biological interaction.

These findings emphasize the importance of device-specific monitoring and individualized programming strategies, especially in paediatric cochlear implant recipients.

Conflict of Interest: The authors declare no conflict of interest related to this study. There are no financial, personal, or professional relationships that could be construed to have influenced the design, data collection, analysis, interpretation, or reporting of the findings in this research.

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