frontiers | Frontiers in Audiology and Otology

TYPE Original Research
PUBLISHED 05 February 2026
DOI 10.3389/fauot.2025.1708896

OPEN ACCESS

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RECEIVED 19 September 2025
REVISED 25 November 2025
ACCEPTED 12 December 2025
PUBLISHED 05 February 2026

CITATION
Gisbert Aguilar J, Platero Zamarreño A, De Paula Vernetta C, Guzmán Calvete A, Martín-Lagos Martínez J, Müller Locatelli N, Martínez Martínez M and Martínez de Estíbariz Cerdán U (2026) Positive intra-operative electrocochleography track patterns with the HiFocus SlimJ electrode array are associated with stable and improved hearing preservation rates. *Front. Audiol. Otol.* 3:1708896. doi: 10.3389/fauot.2025.1708896

Positive intra-operative electrocochleography track patterns with the HiFocus SlimJ electrode array are associated with stable and improved hearing preservation rates

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Introduction: Electrocochleography (ECochG) has emerged as a valuable intra-operative monitoring tool in cochlear implantation, particularly for preserving residual hearing. This study evaluates the correlation between intra-operative ECochG responses and post-operative hearing outcomes in cochlear implant recipients.
Materials and methods: A cohort of 23 adult subjects with residual acoustic hearing in the low frequencies undergoing cochlear implantation were included. All subjects received Advanced Bionics' HiRes Ultra 3D implants and HiFocus SlimJ electrode arrays, with ECochG monitored during surgery via the AIM system. Intra-operative ECochG responses were categorized into positive, negative, and flat track patterns. Post-operative hearing outcomes were assessed at 1, 3, 6, and 12 months, focusing on hearing preservation.
Results: In 70% of participants, recordable ECochG responses were obtained, with positive track patterns correlating with significantly lower mean hearing loss (17.1 dB) compared to negative (27.5 dB) and flat patterns (30.7 dB). At the 12-month post-operative mark, 83% of all participants retained complete or partial hearing preservation, with 100% complete or partial preservation in subjects exhibiting positive track patterns.
Discussion: This study highlights the association between intra-operative ECochG responses and post-operative acoustic hearing outcomes, indicating its potential as a monitoring tool during cochlear implantation. While ECochG provides real-time insights into cochlear function, this observational study did not evaluate whether acting on ECochG feedback improves outcomes. Therefore, these findings should be interpreted as correlational rather than interventional. Future research should include larger cohorts and investigate whether integrating ECochG-guided strategies into surgical protocols can enhance hearing preservation and long-term outcomes.

KEYWORDS

cochlear implants, electrocochleography, intra-operative monitoring, hearing preservation, track patterns

1 Introduction

Electrocochleography (ECochG) has emerged as a pivotal tool in the field of cochlear implantation, particularly in the context of hearing preservation and recent advancements in intra-operative tools have further solidified its role in this field (Ordóñez Ordóñez et al., 2025; Greisiger et al., 2024; Harris et al., 2024; Höing et al., 2024; Sijgers et al., 2023).

A systematic review by Cooper et al. (2025) evaluated the effectiveness of intra-operative ECochG in predicting and preserving residual hearing during cochlear implant surgeries. The review concluded that ECochG is a promising method for real-time cochlear monitoring, with the potential to reduce trauma, improve electrode placement, and enhance hearing preservation.

This electrophysiological technique involves the recording of electrical potentials generated in the cochlea and from the auditory nerve in response to acoustic stimuli. The primary waveforms recorded during ECochG include the cochlear microphonic, summating potential, and action potential, each reflecting different aspects of cochlear health and function (Sohmer et al., 1980; Pappa et al., 2019). Among these waveforms, the cochlear microphonic has emerged as the most widely used component in intra-operative ECochG monitoring (Radeloff et al., 2012). Its sensitivity to outer hair cell function makes it a reliable indicator of cochlear integrity during electrode insertion (Choudhury et al., 2011).

The application of ECochG in cochlear implantation has gained traction due to the increasing emphasis on hearing preservation in the field. This trend is expected to continue as the criteria for cochlear implant candidacy expand, allowing for the implantation of candidates with better residual hearing (Verschuur et al., 2016). Preserving hearing post-operatively has been associated with several advantages for cochlear implant recipients, including improved speech intelligibility in noise, enhanced localization, and better music appreciation (O'Connell et al., 2017; Crew et al., 2015).

However, reports indicate that the preservation of residual hearing post-implantation varies significantly, with studies showing that between 50 and 90% of subjects retain usable acoustic hearing (Lenarz et al., 2009; Brant and Ruckenstein, 2016). Several studies have reported that preserved ECochG responses during surgery correlate with better low-frequency hearing outcomes (Calloway et al., 2014; Dalbert et al., 2015; Harris et al., 2024), suggesting its potential as a predictive tool. However, other investigations have found inconsistent predictive value, particularly in cases with advanced cochlear pathology or variability in surgical technique (Adunka et al., 2006; Giardina et al., 2019). These mixed findings highlight that ECochG is promising but not yet definitive for guiding intra-operative decisions.

Several cochlear implant manufacturers have developed integrated ECochG recording platforms to facilitate intra-operative monitoring. These systems leverage direct contact with the implant's most apical electrode, enabling real-time feedback without the need for external research equipment. Compared to extra-cochlear recording methods, which often require additional hardware and complex setups, manufacturer-integrated solutions offer practical advantages such as streamlined workflow, reduced noise interference, and improved signal quality (Dalbert et al., 2015; Giardina et al., 2019; Harris et al., 2024). While research systems remain valuable for experimental flexibility and advanced signal analysis, clinical platforms are increasingly adopted for their ease of use and compatibility with surgical environments.

Despite this growing body of work, there remains limited evidence on how specific intra-operative ECochG track patterns relate to long-term hearing preservation beyond early post-operative stages. Most studies focus on short-term outcomes or single-point correlations rather than longitudinal trends. The present study addresses this gap by evaluating the relationship between ECochG responses and hearing preservation at 12 months post-implantation in adult recipients with residual acoustic hearing. By analyzing ECochG track patterns during surgery, this research aims to clarify their association with long-term auditory outcomes and contribute incremental evidence to the ongoing discussion of ECochG's role in cochlear implantation.

2 Materials and methods

This longitudinal study investigated the role of ECochG in monitoring cochlear function during cochlear implantation, with a specific focus on long term hearing preservation outcomes.

2.1 Participants

Three sites within mainland Spain took part in the study and recruited from their cochlear implant candidacy cohort: Hospital Universitari de La Ribera in Alzira, Hospital Universitari i Politècnic La Fe in Valencia, and Hospital Universitario Clínico San Cecilio in Granada.

Participants were required to be adults aged 18 years or older at the time of cochlear implantation. They must have demonstrated unaided pre-operative hearing thresholds of 80 dB or better at 500 Hz. Additionally, all participants were required to have a normal cochlea as confirmed by radiological imaging and to be implanted with the Advanced Bionics HiRes Ultra 3D implant and HiFocus SlimJ straight electrode array.

Individuals were excluded from the study if they had a history of chronic otitis media, cochlear malformations, auditory neuropathy spectrum disorder, the presence of trans-tympanic tubes, or prior middle ear surgery or trauma, including ossicular disjunction.

All study procedures were conducted according to the principles of Good Clinical Practices and the World Medical Association Declaration of Helsinki. Informed written consent from all subjects was obtained and, where required, all participating sites obtained appropriate institutional approval from their respective ethics committees.

2.2 ECochG procedure

A standard ear preparation protocol was followed to ensure that the ear canal was free of debris or fluid prior to the insertion of the earphone.

Intra-operative ECochG recordings were captured using the Advanced Bionics AIM system from the apical electrode of the cochlear implant array as it was inserted into the cochlea. A 50-ms tone burst at 115 dB HL was delivered with alternating starting phases and a 2-ms rise/fall or a single cycle (Hanning window) at a frequency of 500 Hz. Measurements were collected at a rate of eight alternating polarity repetitions per second. The acoustic stimuli produced by the AIM tablet were delivered into the external auditory canal through ER3C earphones (Etymotic Research, Inc.), which were connected to a sterile insert (CI-6120; Advanced Bionics LLC). The audible ECochG feedback tone was accessible to the surgeon.

No pre-agreed intervention in response to the ECochG monitoring feedback was deployed. Nevertheless, surgeons were allowed to modify the insertion speed, vector, and to advance or retract the electrode during the insertion based on the feedback received, their interpretation and experience. In all instances, the electrode array was required to be inserted to the full-depth marker.

2.3 Data acquisition

CM amplitude over time was collected during the surgical procedure. The recorded waveforms were classified by type according to Harris et al. (2024) (see Figure 1), resulting in one of four track pattern types: A, identified by a rise in amplitude from the onset of insertion until the insertion is fully completed, with no signal drop exceeding 6 dB; C, marked by a peak amplitude occurring during the mid-insertion phase, showing a drop of 6 dB or more with no recovery afterwards; CC, showing one or more drops of 6dB with significant growth/recovery afterwards; D, characterized by a lack of response above the noise floor, with a signal to noise ratio lesser than 3:1 across the recording.

2.4 Post-operative assessment

Hearing outcomes were evaluated at 1, 3, 6, and 12 months post-operatively, via unaided air conduction audiometric thresholds averaging the three main low frequencies (LFPTA): 125, 250, and 500 Hz. The residual hearing was evaluated in absolute terms (hearing loss in dB) and relative terms (preservation in percentage) adapting the formula described by Skarzynski et al. (2013) based on the main three low frequencies used in this study. See formula in equation 1 below.

$$S\,(\%) = \left(1 - \left(\frac{\mathbf{PTApost} - \mathbf{PTApre}}{\mathbf{PTAmax} - \mathbf{PTApre}}\right)\right) {}^{*}100 \qquad (1)$$

Correlations with intra-operative ECochG findings were analyzed. Additionally, all cases were classed in preservation groups as proposed by Skarzynski et al. (2013): complete (100–76%), partial (75–26%), minimal (25–1%), and loss of hearing (0%).

2.5 Statistical analysis

Statistical analyses were conducted using Microsoft Excel, with a significance level set at $p < 0.05$. Descriptive statistics were calculated for demographic and clinical variables, and inferential statistics were employed to determine the relationship between intra-operative ECochG responses and post-operative hearing outcomes.

3 Results

3.1 Demographics

A total of twenty-three subjects were recruited for the study in three sites. Hospital Universitari de La Ribera recruited nine subjects (38%), Hospital Universitari i Politècnic La Fe recruited seven subjects (31%), and Hospital Universitario Clínico San Cecilio recruited seven subjects (31%).

Thirteen (56.5%) had their right ear implanted and 15 (65.2%) were female. All subjects underwent full insertions and a round window (RW) except one case where an extended round window (ERW) surgical approach was required. For this reason, no sub-analysis of RW vs. ERW was performed. No cochleostomy approaches occurred within the study cohort. The mean age at implantation was 52.1 years old (SD: 15.8). A summary of all subjects' data can be found in Table 1.

3.2 ECochG recording and track patterns

During insertion, ECochG responses typically change in amplitude as the electrode approaches or moves away from viable cochlear regions, and these amplitude trends form the basis of the track pattern classifications. Track patterns A and CC are characterized by a rise in response amplitude toward the end of insertion, indicating preserved cochlear responsiveness, whereas type C patterns show a gradual decrease and type D patterns show little to no change (flat). Because the study included a limited number of cases, and because both A and CC patterns

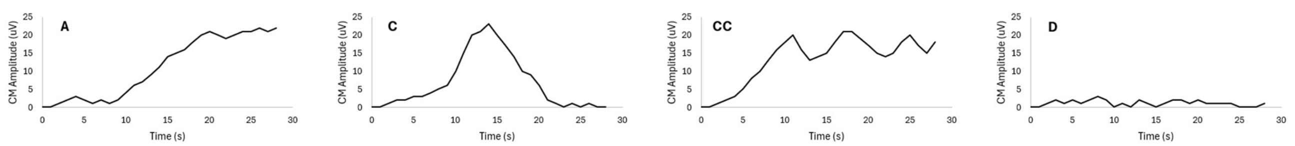

FIGURE 1
Visual representation of the ECochG track patterns (adapted from classification proposed by Harris et al., 2024), showing time of insertion vs. EcochG amplitude. From left to right: types **A**, **C**, **CC** and **D**.

TABLE 1 Summary of all subjects' data.

Item	Data
Sex	
Male	8
Female	15
Ear implanted	
Left	10
Right	13
Site	
Hospital Universitari La Ribera	9
Hospital Universitari i Politècnic La Fe	7
Hospital Universitario Clínico San Cecilio	7
Surgical approach	
Round window	22
Extended round window	1
Age at implant (years)	52.1 ± 15.8 ($n = 23$)
LFPTA (dB HL)	
Pre-op	54.9 ± 12.0 ($n = 23$)
1-month postop	69.5 ± 11.8 ($n = 20$)
3-months postop	73.0 ± 13.1 ($n = 21$)
6-months postop	76.4 ± 14.4 ($n = 21$)
12-months postop	79.7 ± 14.1 ($n = 23$)
Change in LFPTA from pre-op (dB)	
1-month postop	15.5 ± 10.4 ($n = 20$)
3-months postop	18.3 ± 11.1 ($n = 21$)
6-months postop	20.3 ± 10.7 ($n = 21$)
12-months postop	24.9 ± 11.0 ($n = 23$)

reflect a similar positive amplitude-increase behavior, these were grouped together as "positive" patterns. This grouping is supported by Harris et al. (2024), who found no significant physiological differences between these two types. For consistency, type C patterns are referred to as "negative," and type D patterns as "flat."

Sixteen cases (70%) had recordable responses above the noise floor, and seven cases had flat responses below noise floor. This is in line with the literature, with this measurement accrual ranging from 52 to 100% (Cooper et al., 2025). Eight subjects (35%) showed positive type track patterns, eight subjects (35%) presented negative type track patterns, and seven subjects (30%) had flat responses. See ECochG traces and track pattern classifications for all subjects in Figure 2.

3.3 Hearing thresholds

Figure 3 shows the mean unaided air conduction audiometric thresholds from 125 to 8000 Hz at the pre-operative stage with a mean of 31.2 days before surgery (SD: 35.9 days; range: 0–103 days) and four post-operative stages (1 month, 3 months, 6 months, and 12 months).

3.4 Hearing preservation

From the 23 subjects recruited, hearing preservation data were collected for all 23 subjects at the 12-months post-operative stage, data for 21 subjects were collected at the 6 and 3-months post-operative stages, and data for 20 subjects was collected at the 1-month post-operative stage.

For completeness, the seven missing datasets were interpolated by taking the next chronological dataset for each subject. In this way, the estimation of thresholds at the interpolated stages is conservative as we expect a progression in hearing loss post-operatively.

At the 1-month post-operative assessment, the mean hearing loss was 15.5 dB (SD = 10.4 dB HL). The mean relative hearing preservation during this period was 67.6% (SD = 20.2%). Among the hearing preservation categories, 22 cases (96%) demonstrated either complete or partial preservation, whereas one case (4%) exhibited minimal preservation.

By the 3-month post-operative mark, the average hearing loss increased to 18.3 dB (SD = 11.1 dB). The mean relative hearing preservation at this time was 60.5% (SD = 21.7%). In terms of preservation groups, 20 cases (87%) maintained complete or partial hearing, while three cases (13%) showed minimal preservation.

At the 6-month post-operative evaluation, the mean hearing loss was 20.3 dB (SD = 10.7 dB). The mean relative hearing preservation decreased to 53.3% (SD = 22.3%). In this assessment, 20 cases (87%) exhibited complete or partial preservation, while three cases (13%) had minimal preservation.

Finally, at the 12-month post-operative stage, the mean hearing loss was noted at 24.9 dB (SD = 11.0 dB). The mean relative hearing preservation further declined to 44.9% (SD = 21.8%). In terms of hearing preservation categories, 19 cases (83%) showed complete or partial preservation, while four cases (17%) indicated minimal preservation.

Throughout the 12 months of post-operative follow-up, no cases of total hearing loss were observed in the study cohort.

Figures 4, 5 show hearing loss and relative hearing preservation throughout post-operative stages, and Figure 6 shows the proportion of cases with complete or partial hearing preservation across all study stages.

3.5 Hearing preservation and ECochG track patterns

An assessment of the impact of ECochG track patterns on post-operative hearing loss and preservation at the 12-month mark indicates that positive ECochG track patterns are associated with reduced hearing loss and higher rates of hearing preservation compared to negative and flat patterns.

Specifically, positive ECochG track patterns result in a mean hearing loss of 17.1 dB (SD = 7.1 dB) at 12 months post-operation. In contrast, negative ECochG track patterns show a mean hearing

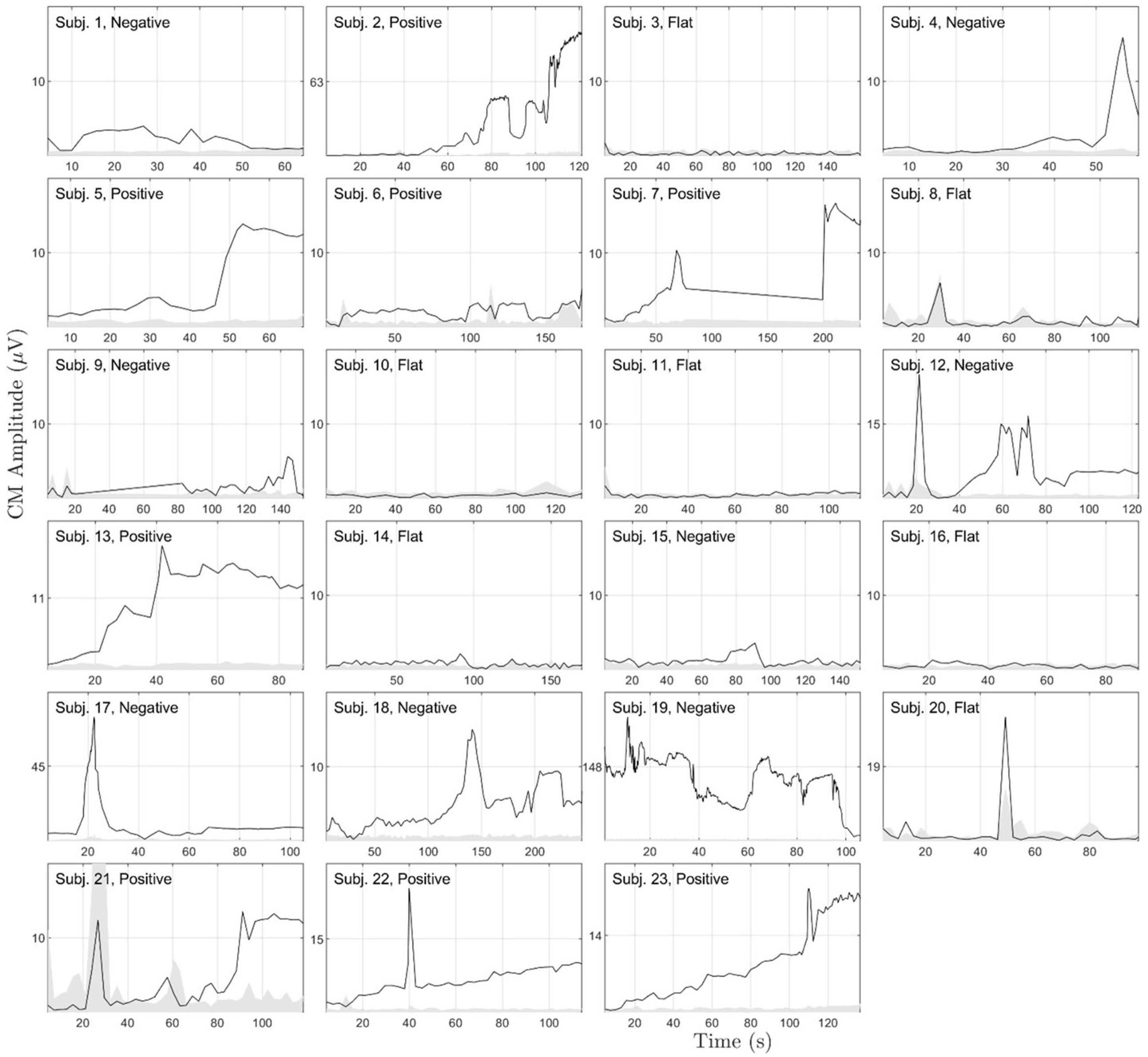

FIGURE 2
ECochG traces and track pattern classification for all subjects (noise floor in gray) showing time of insertion vs. EcochG amplitude.

loss of 27.5 dB (SD = 7.9 dB), while flat patterns exhibit a mean hearing loss of 30.7 dB (SD = 12.7 dB).

In the analysis of mean low-frequency hearing loss, positive track patterns exhibited significantly greater hearing loss compared to negative track patterns ($t(14) = -2.60$, $p = 0.02$, two-tailed, mean difference = 10.4 dB). Positive track patterns also showed significantly greater hearing loss compared to flat track patterns ($t(9) = -2.34$, $p = 0.04$, two-tailed, mean difference = 13.6 dB). In contrast, negative track patterns did not differ significantly from flat track patterns ($t(10) = -0.54$, $p = 0.60$, two-tailed, mean difference = 3.2 dB). Given the exploratory nature of these three pairwise comparisons, these —values should be interpreted with caution as no correction for multiple comparisons was applied. See Figure 7 for a visual representation of hearing loss across the three track patterns at 12 months post-operatively.

In terms of relative hearing preservation, in subjects with positive ECochG track patterns, mean relative hearing preservation was 64.1% (SD = 14.2%) at the 12-month post-operative stage. Conversely, negative ECochG track patterns yield a mean preservation of 35.6% (SD = 21.3%), while flat patterns show a mean of 33.7% (SD = 13.1%).

In the analysis of mean low-frequency hearing preservation, positive track patterns exhibit a significant difference when compared to negative traces, with results indicating $t(12) = 2.95$, $p = 0.01$ (two-tailed) and a mean difference of 28.6%. Additionally, positive track patterns also show a significant distinction from flat traces, yielding $t(13) = 4.02$, $p = 0.001$ (two-tailed) and a mean difference of 30.4%. In contrast, negative track patterns do not demonstrate a significant difference when compared to flat responses, as evidenced by $t(12) = 0.19$, $p = 0.85$ (two-tailed) and a

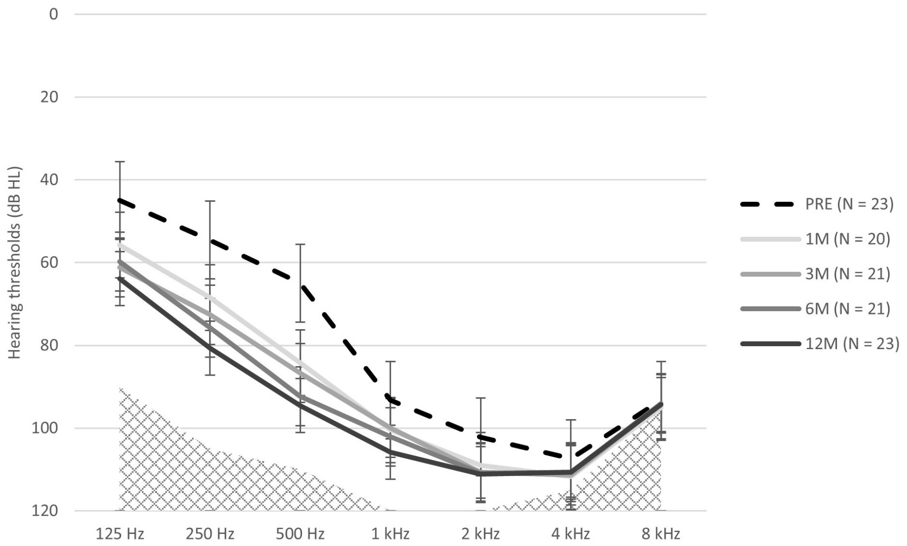

FIGURE 3
Mean unaided audiometric thresholds with standard error bars (max values of audiometer shown in diamond grid pattern).

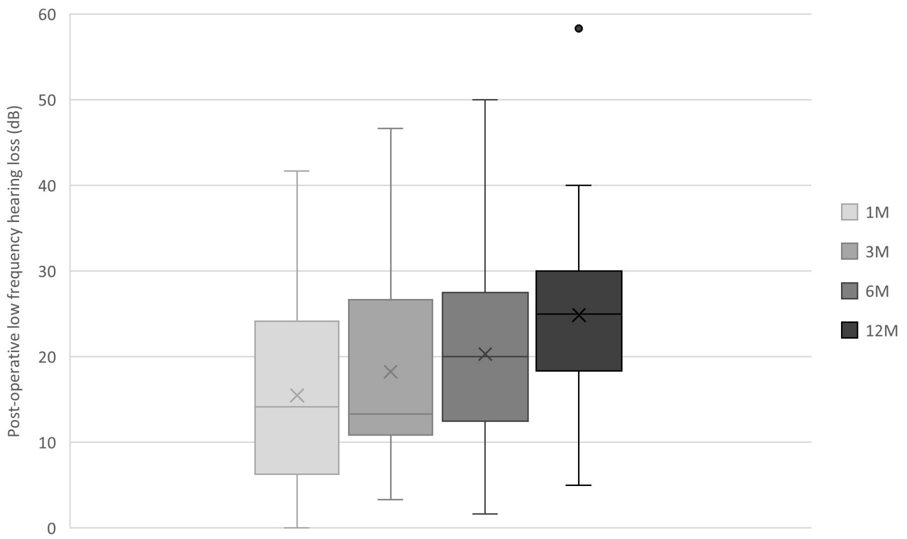

FIGURE 4
Low frequency hearing loss for all study participants at all post-operative stages with standard error bars: from left to right: 1 month, 3 months, 6 months and 12 months.

mean difference of 1.8%. See Figure 8 for a visual representation of hearing preservation across the three track patterns at 12 months post-operatively.

The progression of hearing loss varies according to the track pattern observed. As illustrated in Figure 9, the incidence of complete or partial hearing preservation for each track pattern reveals that positive track patterns maintain 100% hearing preservation throughout the 12 months post-operation. In contrast, negative track patterns demonstrate a decline in preservation rates starting from the 3-month mark, while flat track patterns begin at a lower level and continue to decrease by the 12-month stage.

4 Discussion

The present study highlights the effect of ECochG in monitoring cochlear function during cochlear implantation, particularly in the context of hearing preservation. Our findings demonstrate that intra-operative ECochG responses correlate with post-operative hearing outcomes, reinforcing the utility of this technique as a predictive tool for hearing preservation.

The results indicate that 70% of participants exhibited recordable ECochG responses above the noise floor, consistent with previous literature that reports a similar range of 50–90%

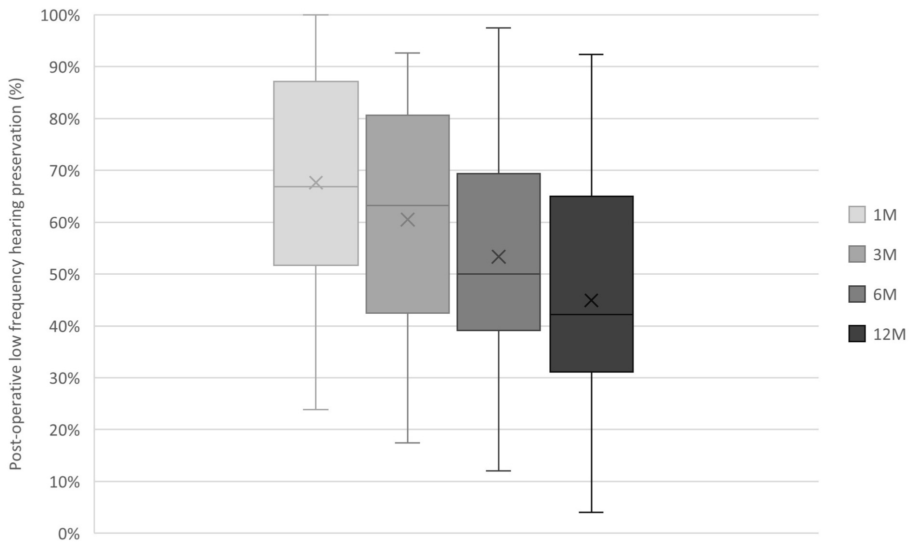

FIGURE 5
Low frequency hearing preservation for all study participants at all postoperative stages with standard error bars. From left to right: 1 month, 3 months, 6 months and 12 months.

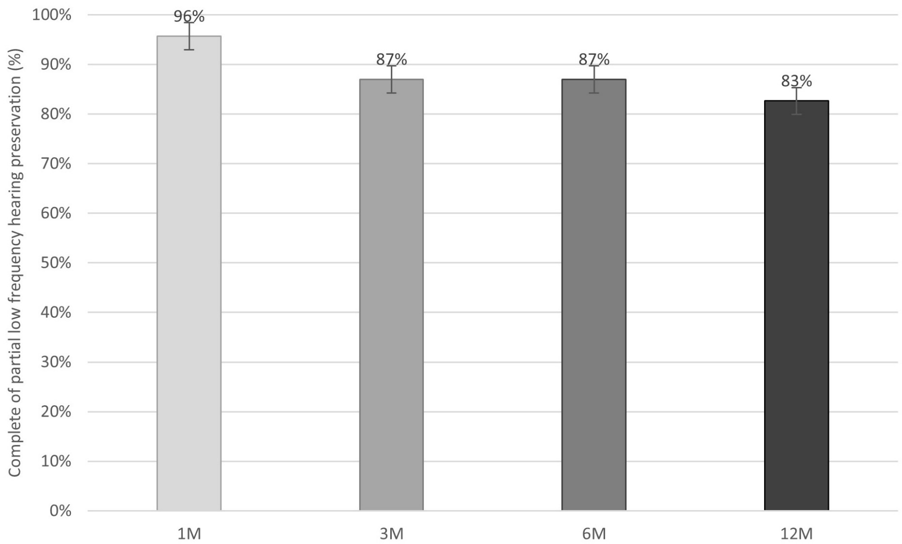

FIGURE 6
Proportion of complete or partial low frequency hearing preservation cases at all post-operative stages with one standard. From left to right: 1 month, 3 months, 6 months and 12 months.

(Harris et al., 2024; Buechner et al., 2022; Schuerch et al., 2022; Lenarz et al., 2009). The 24.9 dB of average hearing loss at the 12-month post-operative stage for all study participants aligns with previous work using the HiFocus SlimJ electrode array with post-operative hearing losses ranging from 16 dB to 27 dB (Lenarz et al., 2020, 2022; Schwam et al., 2021; Jensen et al., 2022; Harris et al., 2022, 2024; Buechner et al., 2022; Eitutis et al., 2023; Schleich et al., 2025; Skarżyński et al., 2025). Notably in this study, the presence of positive ECochG track patterns was associated with reduced hearing loss and higher rates of hearing preservation at the 12-month post-operative mark, with subjects with positive track patterns experiencing a mean hearing loss of only 17.1 dB.

At the 12-month follow-up, the majority of our participants (83%) achieved complete or partial hearing preservation, and markedly positive track patterns leading to a 100% rate of complete or partial preservation at this stage. Without factoring track patterns, the literature reports a range of 79–100% rate of complete or partial hearing preservation at stages ranging from 1 month to 12 months post-operatively (Wang et al., 2025; Schwam et al., 2021; Skarżyński et al., 2025). The observed gradual increase in hearing loss highlights the necessity for continuous monitoring and intervention strategies to enhance long-term outcomes.

The study's limitations include the relatively small sample size and the variability in surgical techniques, which may influence

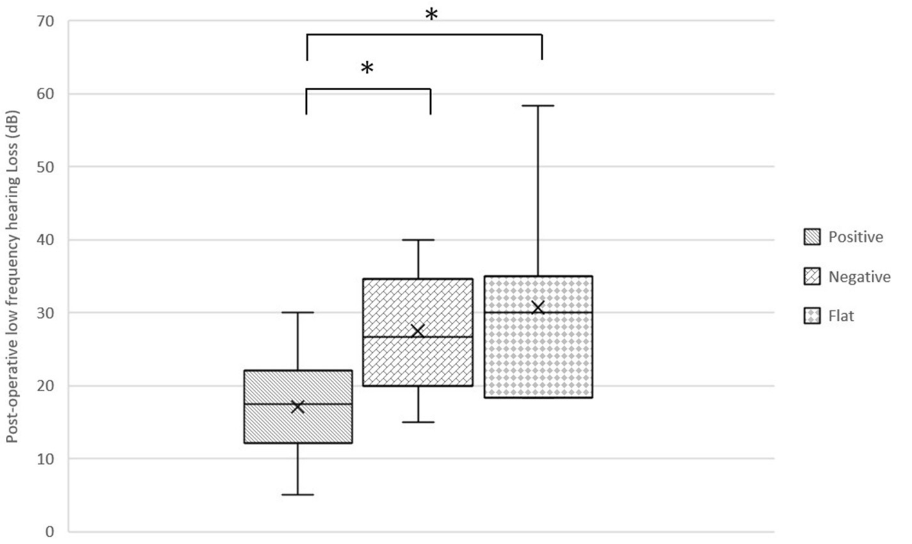

FIGURE 7
Low frequency hearing loss by track pattern at 12 months post-operatively. From left to right: positive, negative and flat track patterns.

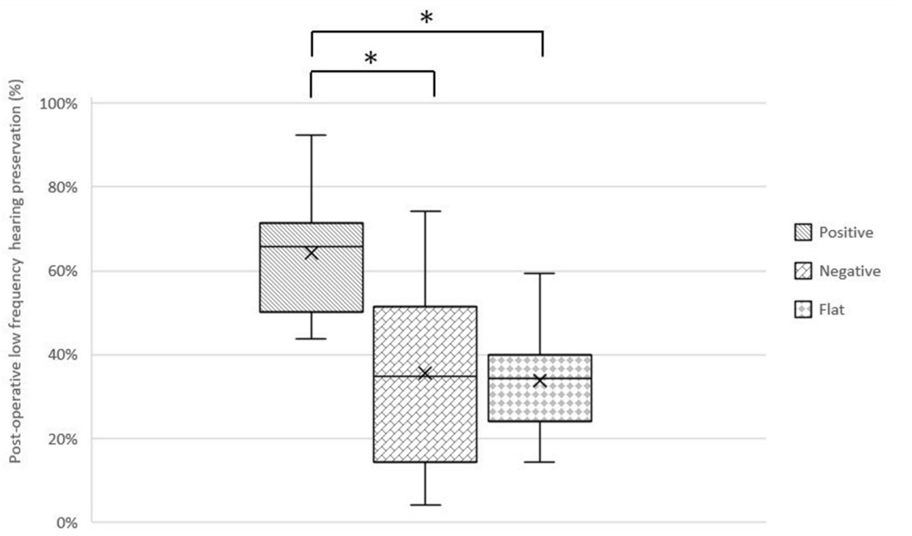

FIGURE 8
Hearing preservation by track pattern at 12 months post-operatively. From left to right: positive, negative and flat track patterns.

outcomes. The absence of a pre-agreed intervention may represent a potential confounding factor, as the specific interventions implemented and their timing remain uncertain. More detailed guidance on the required intervention in response to ECochG feedback has been studied and some promising evidence on the key steps to maximize the options of recording positive responses and improved hearing preservation have already been proposed for cochlear implant electrodes arrays. For straight electrodes, it appears the stop and retract technique may be of benefit to ensure potentially traumatic contact can be minimized (Bester et al., 2022). For pre-curved arrays, the pull-back technique at the end of the insertion has shown some benefit in terms of hearing preservation (Walia et al., 2025).

An inherent limitation of ECochG measurements is the dependence on pre-operative acoustic hearing thresholds. Reported pre-operative threshold criteria in the literature typically range from ≤70 to ≤90 dB HL (Lenarz et al., 2020, 2022; Bester et al., 2022; Harris et al., 2022, 2024; Buechner et al., 2022; Schleich et al., 2025). In this study, a threshold of 80 dB HL or better was chosen as a compromise between cochlear implant candidacy and the likelihood of successful ECochG recordings. Selecting stricter criteria (better pre-operative hearing) would

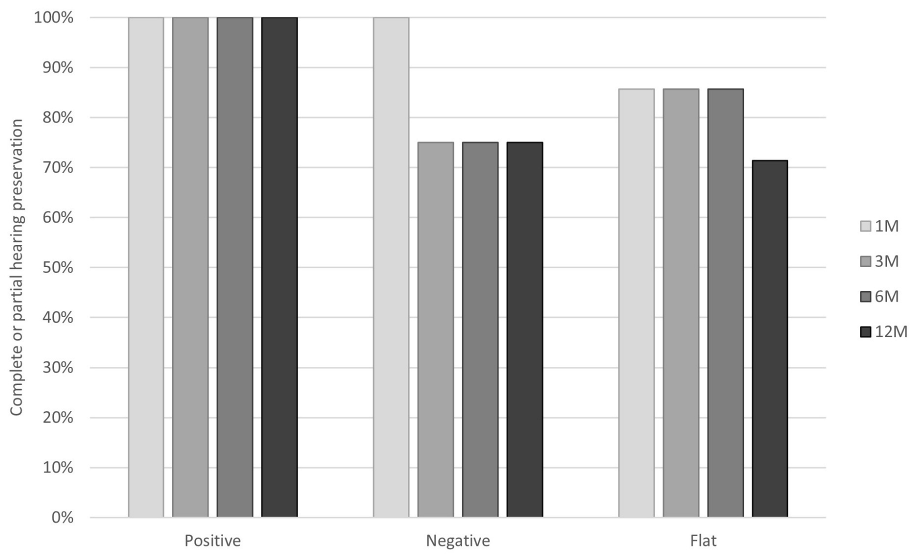

FIGURE 9
Proportion of cases showing complete or partial hearing preservation at 12 months post-operative depending on EcochG track. From left to right: positive, negative and flat track patterns at the four stages: 1 month, 3 months, 6 months and 12 months.

reduce the pool of implant candidates but increase the probability of obtaining recordings, as more residual acoustic hearing is present. Conversely, relaxing the threshold (worse pre-operative hearing) would expand candidacy but likely decrease recording success, given the anticipated postoperative decline in hearing (Harris et al., 2022, 2024; Buechner et al., 2022).

Post-operative thresholds of 90 dB HL or poorer generally preclude effective electroacoustic stimulation (Battmer et al., 2019). In the study cohort, 95%, 90.4%, 80.9%, and 78.2% of subjects demonstrated residual hearing better than 90 dB HL at 1, 3, 6, and 12 months post-operatively, respectively. Although the study did not report whether participants were ultimately fitted with electric-only or electroacoustic stimulation, the preservation rates indicate that a substantial proportion of recipients retain potentially aidable low-frequency hearing during the first postoperative year, thereby maintaining candidacy for electroacoustic stimulation where clinical criteria are met.

The interpolation of missing datasets is also a limitation of the current work, as it assumes a monotonic decline in hearing and may result in an underestimation of variability.

The combination of ECochG and robotics in assisting in the insertion of cochlear implant arrays is also growing, with publications showing that ECochG measurements are feasible using a robot (Gawecki et al., 2022) and placement optimisation within the scala tympani (Kashani et al., 2024).

Future research should aim to include larger cohorts and explore the impact of different electrode designs and surgical approaches, including robotic insertions, on ECochG responses and hearing preservation.

In conclusion, our study reinforces the importance of ECochG as a valuable intra-operative monitoring tool in cochlear implantation. This research demonstrates that ECochG provides real-time insights into cochlear function during surgery and that these responses correlate with hearing outcomes. While these findings are promising, the study does not establish whether acting on ECochG feedback improves results. Notably, positive ECochG track patterns were significantly associated with reduced post-operative hearing loss and higher rates of hearing preservation at 12 months, underscoring the correlation between intra-operative monitoring and favorable hearing outcomes.

The clinical implications of our findings suggest that ECochG may serve as a useful intra-operative monitoring tool, given its association with post-operative hearing outcomes. However, this study was observational and did not evaluate whether ECochG-guided interventions improve outcomes. Future research should investigate whether incorporating ECochG feedback into surgical decision-making can enhance hearing preservation.

Data availability statement

The original contributions presented in the study are included in the article and further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by Hospital Universitari de La Ribera, Hospital Universitari i Politècnic La Fe, and Hospital Universitario Clínico San Cecilio. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JG: Writing – original draft, Writing – review & editing, Investigation, Project administration, Methodology, Supervision, Conceptualization. AP: Writing – review &

editing, Investigation. CD: Writing – review & editing, Investigation. AG: Writing – review & editing, Investigation. JM-L: Investigation, Writing – review & editing. NM: Investigation, Writing – review & editing. MM: Investigation, Writing – review & editing. UM: Formal analysis, Conceptualization, Methodology, Data curation, Supervision, Writing – original draft, Project administration, Writing – review & editing, Visualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was supported by Advanced Bionics GmbH, Hannover, Germany.

Acknowledgments

We would like to thank the study participants for their commitment to the study and the clinical teams from Hospital Universitari de La Ribera, Hospital Universitari i Politècnic La Fe, and Hospital Universitario Clínico San Cecilio, for the audiological support provided throughout the study. Additionally, we would like to thank the clinical specialists from Advanced Bionics Spain for their support during intra-operative measurements.

Conflict of interest

UM was employed by the manufacturer (Advanced Bionics GmbH) of the devices under investigation.

The remaining authors declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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