Impact of Two Visualization Methods for Electrocochleographic Potentials on Hearing and Vestibular Function During Cochlear Implantation

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Purpose: This study investigates the impact of two distinct visualization methods for electrocochleographic potentials during cochlear implant electrode insertion on residual hearing preservation and vestibular function. Previous research has demonstrated the benefits of visualizing electrocochleographic (ECochG) potentials in preserving residual hearing during cochlear implantation. In this project, ECochG potentials are represented either through a graph or as arrows that provide a pre-interpreted version of the graph. We aim to determine if these visualization methods influence postoperative residual hearing and vestibular structure integrity.
Methods: Residual hearing is audiometrically assessed, and vestibular function is evaluated using the video head impulse test and the dizziness handicap inventory before and after surgery. Furthermore, the subjective workload of surgeons using these methods is assessed via the NASA-Task Load Index questionnaire. The study included 31 patients receiving Flex26 and Flex28 electrodes (MED EL). The patients were randomly assigned to one of the visualization methods.
Results: The results of the study demonstrate that there were no significant differences between the two visualization methods, both in terms of residual hearing preservation and postoperative dizziness. Also the ECochG parameters, such as amplitude, do not differ significantly. Additionally, no significant difference was observed in the surgical workload for the operating surgeon.
Conclusion: The two visualization methods can therefore be used equivalently in terms of preservation of cochlear structures and mental workload for the surgeons. A simplified ECochG potential interpretation could enable younger surgeons to perform more atraumatic insertions with stable quality of outcome.
Key Words: Audiology—Cochlear implants—Electrocochleography—Residual hearing—Vestibular function.

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INTRODUCTION

The preservation of residual hearing during cochlear implantation is a significant challenge, especially as the indications for cochlear implants (CI) expand to include patients with substantial low-frequency hearing. Electrocochleography (ECochG), which monitors cochlear responses to sound in real-time during electrode insertion, has shown promise in mitigating insertional trauma and preserving residual hearing (1,2). Recent advancements in digital imaging in digital microscopes, such as Arriscope (Munich Surgical Imaging GmbH, Munich, Germany) or RoboticScope (BHS Technologies, Innsbruck, Austria), have enabled the continuous visualization of these potentials, providing surgeons with visual feedback during the insertion process (3,4). The real-time feedback during electrode insertion allows surgeons to adjust their technique in terms of changing the angle or stopping the electrode to minimize trauma to the cochlea (5). Because of the divided attention between electrode insertion and the visualized ECochG, insertion time is prolonged (1), which has been associated with reduced cochlear damage (6). The preservation of ECochG potentials has been correlated with better postoperative hearing outcomes, making ECochG a valuable tool in modern CI surgery (7). However, there is still ambiguity regarding the precise interpretation and implications of alterations observed in ECochG measurements. Some studies report that intraoperative loss of amplitude correlates with higher levels of cochlear trauma (8), yet this amplitude loss does not consistently impact postoperative hearing thresholds (9). Moreover, various amplitude parameters, such as insertion track patterns, the magnitude of ECochG amplitude changes, and the total number of ECochG amplitude drops, have been identified as critical factors influencing surgical outcomes (10). These parameters provide valuable real-time feedback during electrode insertion and may offer predictive insights into both hearing and structure preservation.

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In particular, two methods of visualizing ECochG potentials have been developed: a traditional graphical representation and a novel arrow-based display that interprets the graph in real-time, offering a more intuitive interpretation of potential cochlear trauma. Although these methods have been individually assessed for feasibility in a previous study (3), their comparative impact on surgical long-term outcomes remains unexplored.

An equally important aspect of cochlear implantation is the preservation of vestibular function, as the vestibular system can be inadvertently affected during electrode insertion (11). Recent studies suggest that cochlear implantation can impair both canal and otolith function, potentially leading to postoperative dizziness and balance issues (12,13). Thus, the choice of visualization method could also have implications for vestibular preservation, especially if it influences the precision and atraumatic nature of the electrode insertion.

The importance of cognitive load in surgical performance cannot be overstated. High cognitive demands can lead to increased fatigue, reduced precision, and a higher likelihood of errors (14) and therefore cochlear damage. The NASA-Task Load Index (NASA-TLX) questionnaire, a validated tool for assessing perceived workload, has been widely used to evaluate cognitive load in surgical environments (15).

This study aims to compare the effects of these two visualization methods on both residual hearing preservation and vestibular function, as well as to assess the cognitive load imposed on surgeons and to determine whether these methods can be considered equivalent. Audiometric assessments was conducted pre- and postoperatively to evaluate residual hearing, whereas vestibular function was monitored using the video head impulse test (vHIT), which seems to be a useful tool to easily assess vestibular function in CI patients (16). Additionally, the NASA-TLX questionnaire was used to quantify the subjective workload of surgeons using each visualization method. The findings could lead to a broader adoption of these tools, particularly among less experienced surgeons, facilitating more consistent hearing and structure preservation across varied surgical expertise.

MATERIALS AND METHODS

ECochG signals were continuously recorded during electrode insertion. Two different visualizations of the ECochG potentials were displayed using the Picture-in-Picture (PiP) mode of the digital surgical microscope RoboticScope. The first visualization method used the traditional graphical display format, requiring the surgeon to manually interpret the raw ECochG waveforms. The graph visualization is shown in the upper left corner in Figure 1. The second method displayed the ECochG potentials as arrows, providing a pre-interpreted version of the graphical data. The arrows indicated both the direction and magnitude of changes in the ECochG signals, which perhaps simplify the interpretation of the signals during electrode insertion. This automatic interpretation was based on the standard deviation of the last 10 measured ECochG data points. Potentials significantly exceeding the standard deviation were classified as increasing and represented by an upward green arrow. Potentials fluctuating within the range of the standard deviation were considered stable and depicted by a blue line. When potentials fell below the standard deviation, they were classified as decreasing, and a downward red arrow was displayed. An exemplary visualization of the arrows is displayed in the upper right corner of Figure 1. During surgery, only one of the arrows appears. Cochlear implantations were performed by two experienced surgeons. Testing this new approach with experienced surgeons only, because of their advanced skills and extensive procedural knowledge, reduce variability and enhance the reliability of outcomes. This approach minimizes potential errors related to the learning curve, ensuring a more accurate evaluation of the techniques efficacy and safety. The intraoperative setup used in this study corresponds to that described in our recent publication (3). Patients were randomly assigned to one of two groups based on the visualization method used for intraoperative ECochG. The study included 31 patients, with 11 receiving Flex26 electrodes and 20 receiving Flex28 electrodes (MED-EL). The graph group comprised 16 patients (mean age, 59.2 ± 18.8 yr) with a mean preoperative pure-tone average for low frequencies (PTAlow; mean of hearing level at 125, 250, and 500 Hz) of 61.8 dB HL. The arrows group included 15 patients (mean age, 67.3 ± 8.8 yr) with a mean preoperative PTAlow of 62 dB HL. All participants provided informed consent before the procedure, and the study was approved by the institutional ethics committee of the University Essen-Duisburg (20-9695_1-BO).

All patients underwent a measure of audiometric thresholds preoperatively and postoperatively at 6 weeks, 4 months, and 7 months using standard pure-tone audiometry. The hearing thresholds were determined to assess residual hearing, with specific focus on low-frequency thresholds (125–500 Hz). Vestibular function was evaluated using the vHIT for all three semicircular canals (lateral, anterior, posterior), performed both preoperatively and 4 months postoperatively. The vHIT is performed by having the patient fixate on a visual target, whereas the examiner delivers rapid, small-amplitude, unpredictable head movements in the plane of the semicircular canals. High-speed video goggles track the eyes' movements to assess the vestibulo-ocular reflex (VOR) by detecting compensatory eye movements and identifying saccades indicative of vestibular dysfunction. This assessment was used to determine the structural integrity of the vestibular organ following cochlear implantation. Additionally, the Dizziness Handicap Inventory (DHI) questionnaire was administered pre- and postoperatively to assess the patients' subjective perception of their vestibular function.

Directly after surgery, the surgeons were asked to complete the NASA-TLX questionnaire, which evaluates subjective workload across six dimensions: mental demand, physical demand, temporal demand, effort, performance, and frustration. The NASA-TLX was administered to

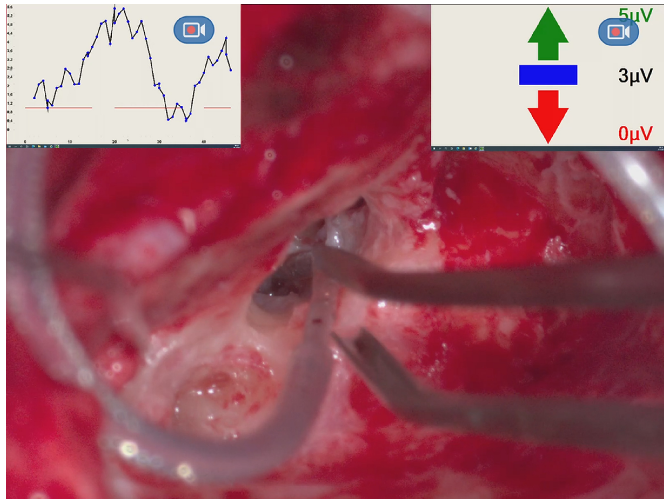

FIG. 1. Example of the two visualization methods. Upper left corner: Graph. Upper right corner: Arrows. Only one of them is displayed during insertion of the electrode.

compare the cognitive workload associated with interpreting the two different ECochG visualization methods.

RESULTS

ECochG Parameters

No significant differences were observed between the two visualization methods in terms of ECochG amplitude ($F(1,34) = 1.117$, $p = 0.29$, $\eta^2 = 0.03$). The mean ECochG amplitude at the end of the insertion (last 10 datapoints) for the graph group (N = 16) was 39.1 ± 25.7 µV, whereas the arrow group (N = 15) had a mean amplitude of 52.3 ± 46.8 µV. Additionally, there were no significant differences in insertion time between the two groups ($F(1,33) = 1.5$, $p = 0.23$, $\eta^2 = 0.04$). The mean insertion time for the graph group was 112.42 seconds, and for the arrow group, it was 130.31 seconds. However, a strong positive correlation was observed between insertion time and ECochG amplitude, as indicated by Pearson's correlation analysis ($r = 0.463$, $p < 0.01$). The correlation analysis included all patients, without dividing them into groups based on visualization method.

Audiometric Thresholds

A repeated-measures ANOVA revealed no significant differences between the two visualization methods at any time point (preoperative, 6 wk, 4 mo, and 7 mo postoperative) across all frequencies ($F(1,19) = 0.05$, $p = 0.82$, partial $\eta^2 = 0.003$). As shown in Figure 2, preoperative hearing thresholds were significantly different from all postoperative thresholds across all measured frequencies ($F(1.4,27.5) = 29.3$, $p < 0.001$, partial $\eta^2 = 0.6$). Additionally, a Kaplan–Meier survival analysis, including a log-rank test, showed no significant difference between the two groups in terms of time to complete hearing loss after cochlear implantation ($\chi^2(1) = 2{,}46$, $p = 0.117$). This suggests that the time until total hearing loss post-implantation did not significantly vary between the graph and arrow groups.

Vestibular Function

No significant differences were found between the two visualization methods in vestibular function for any of the semicircular canals, as measured by the vHIT. Additionally, there were no statistical significant differences between preoperative and postoperative vHIT results as shown in Figure 3. However, a positive correlation was found between the difference pre- and postoperative vHIT gain for each semicircular canal and the insertion time as indicated by Pearson's correlation analysis (lateral: $r = 0.348$, $p = 0.04$; anterior: $r = 0.434$, $p = 0.013$; posterior: $r = 0.538$, $p = 0.002$). No significant correlation was observed between the gain difference and the ECochG amplitude (lateral: $r = 0.178$, $p = 0.187$; anterior: $r = 0.17$, $p = 0.198$; posterior: $r = 0.058$, $p = 0.387$). The correlation analysis included all patients, without dividing them into groups based on visualization method. Despite the observed correlation between insertion time and the gain in vHIT, the subjective perception of dizziness, as assessed by the DHI questionnaire, did not change significantly between preoperative and postoperative time points ($F(1,7) = 0.22$, $p = 0.886$). In addition, the scores of the DHI questionnaire showed no significant differences between the two visualization groups ($F(1,7) = 0.75$, $p = 0.415$), suggesting that the perception of dizziness was unaffected by the choice of visualization method and remained stable throughout the study.

Subjective Workload

No significant differences were found in the unweighted overall mean workload between the two visualization methods, as assessed using the NASA-TLX questionnaire ($T(42.31) = -1.16$, $p = 0.241$, with a medium effect size according to Cohen's $d = 0.35$). Similarly, no significant differences were observed in any of the individual workload categories (mental demand, physical demand, temporal demand, performance, effort, frustration). The distribution of workload is shown in Figure 4. It was demonstrated that the

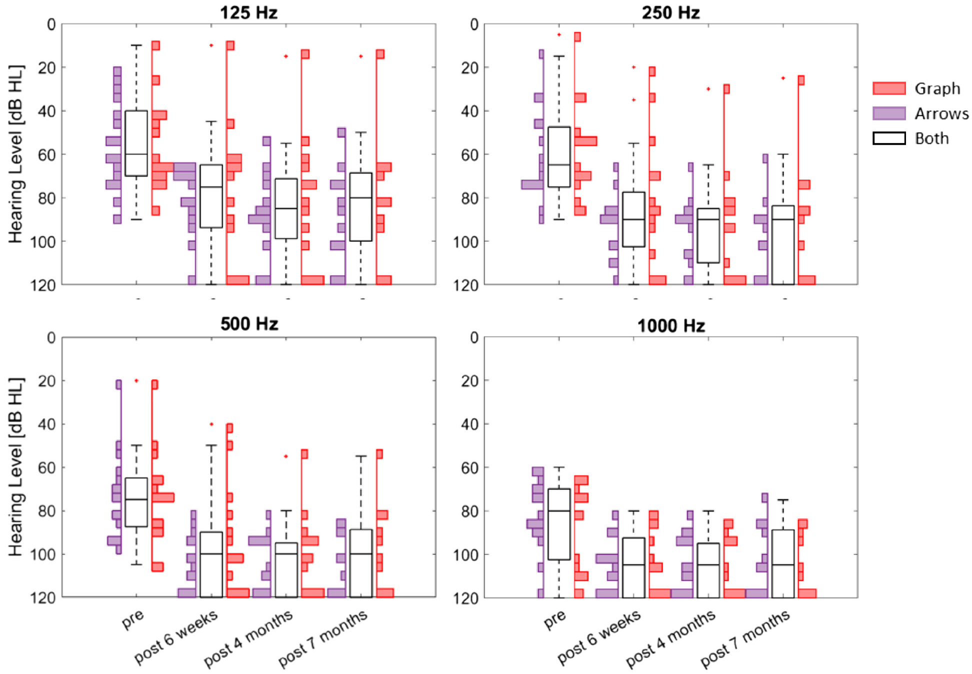

FIG. 2. Audiometric thresholds (dB HL) at 125, 250, 500, and 1000 Hz for the graph and arrow groups. Hearing thresholds are compared at four time points: Preoperative, 6 weeks postoperative, 4 months postoperative, and 7 months postoperative. The graph group (red) and arrows group (purple) are represented separately as histograms next to the combined boxplot (black) showing overall distributions.

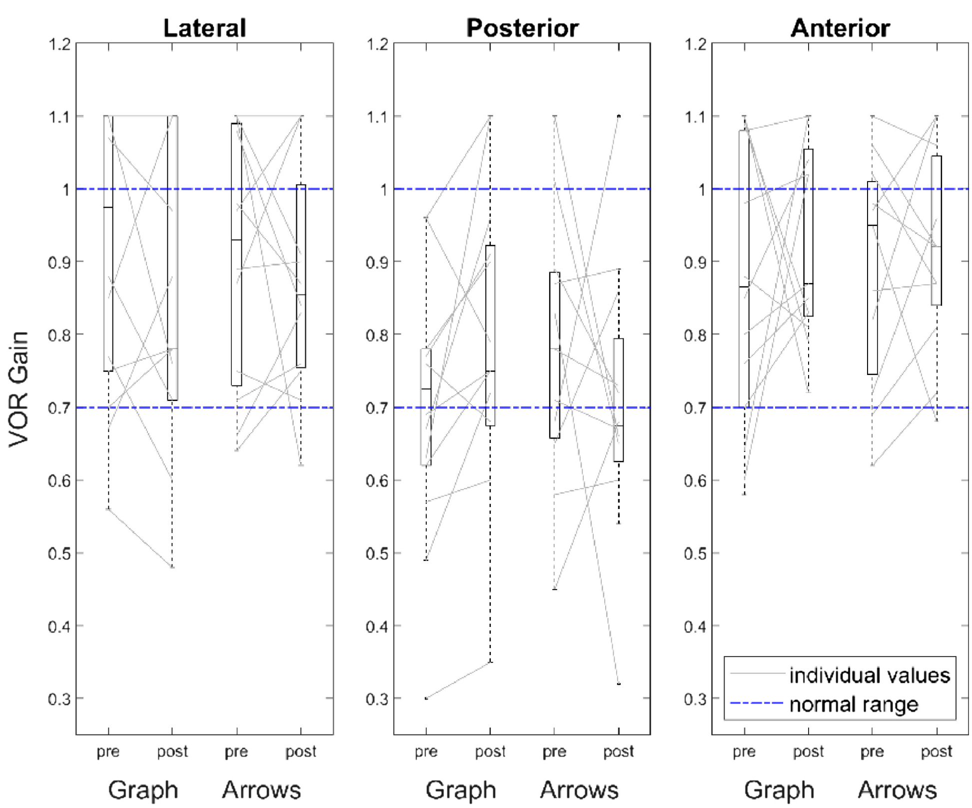

FIG. 3. Vestibulo-ocular reflex (VOR) gain values for the lateral, posterior, and anterior semicircular canals, measured preoperatively and postoperatively, across both visualization methods. The area between the two dashed blue lines represent the normal VOR gain range. Individual patient data are shown with connected lines in light gray, and the box plots indicate the distribution of values in each group.

overall workload is relatively low, with scores ranging between 0 and 30 out of 100, but shows greater variability when using the graph visualization.

DISCUSSION

This study compared two methods of visualizing intraoperative ECochG potentials—graph and arrows—during cochlear implantation, with the goal of determining their impact on residual hearing preservation, vestibular function, and surgical workload. The findings show that both visualization methods are equivalent in their effects on postoperative outcomes.

Residual Hearing Preservation

No significant difference was observed in audiometric outcomes between the graph and arrow groups. Both groups experienced a comparable degree of hearing loss postoperatively, which is consistent with the results of the preliminary feasibility study. Demonstrating that intraoperative ECochG, regardless of the visualization format used, is beneficial for hearing preservation is complicated, due to a lack of a control group. The overall preservation of hearing across both groups highlights that ECochG, when properly used, might help mitigate cochlear trauma, a result that aligns with previous studies that stress the importance of performing (17,18) and visualizing (1,4) real-time monitoring during electrode insertion to reduce insertion trauma. Furthermore, the correlation observed between insertion time and ECochG amplitude at the end of the insertion suggests that prolonged insertion, facilitated by ECochG monitoring, may help reduce cochlear trauma and preserve hearing. A further analysis of the raw ECochG data, particularly focusing on the amplitude drops and magnitude of amplitude changes, as suggested by Harris et al. (10), should be conducted in the future to better elucidate the potential of ECochG. This reinforces the importance of ECochG as an intraoperative tool and warrants further exploration of ways to enhance its effectiveness through improved visualization technologies. Although the positive effects of ECochG visualization on hearing preservation are evident (2,19), the lack of a significant difference between the two methods suggests that both can be equally effective for this purpose for experienced surgeons. An evaluation with less experienced surgeons is ongoing but not included in this study.

Vestibular Function

The impact of cochlear implantation on vestibular function remains a concern due to the proximity of the cochlea to vestibular structures (20). The results of this study show no significant difference between the two visualization groups regarding postoperative vestibular function, as measured by the vHIT. Additionally, subjective dizziness perception, evaluated by the DHI, showed no difference between the two groups. Even though existing literature indicates that cochlear implantation can affect vestibular function (11,21), the specific visualization method of ECochG does not seem to play a major role in reducing or exacerbating this risk. In the cohort examined here, no significant loss of vestibular function was observed after cochlear implantation. This is contradictory to the literature, which reports a deterioration in vestibular function in 30% of patients after surgery (22). However, further research with

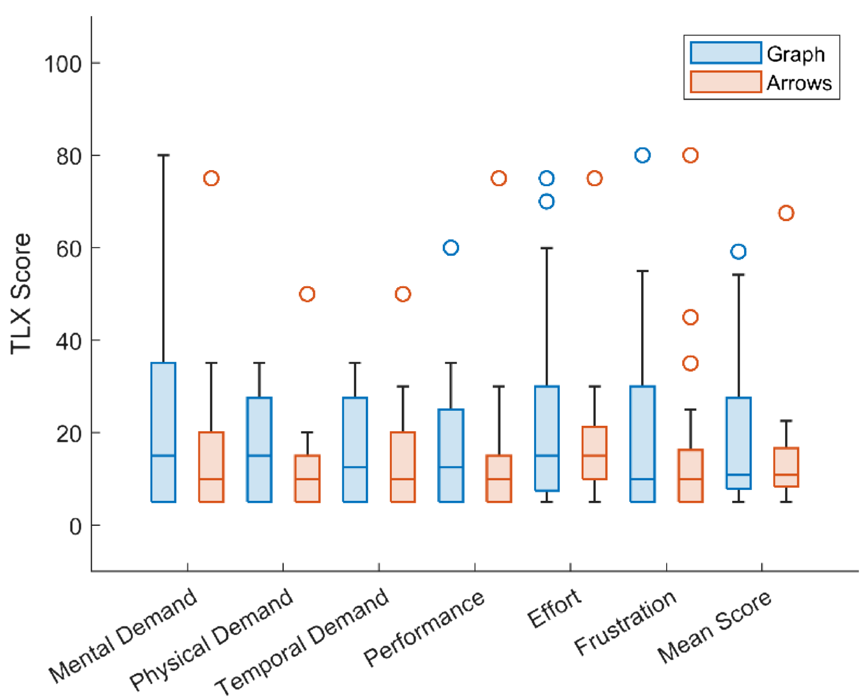

FIG. 4. NASA-TLX workload scores for the graph (in blue) and arrows (in orange) groups across the six workload dimensions and the overall mean score. The dimensions assessed include mental demand, physical demand, temporal demand, performance, effort, and frustration.

a larger cohort is needed to investigate the influence of ECochG monitoring on vestibular function.

Cognitive Workload

A crucial aspect of this study was the comparison of the cognitive load experienced by surgeons using the two different visualization methods, assessed through the NASA-TLX questionnaire (15). The findings revealed no significant differences in the overall cognitive load or its subcomponents (mental demand, effort, frustration, etc.) between the two groups. This suggests that the arrow-based visualization, designed to provide a more intuitive and simplified interpretation of ECochG signals, does not significantly reduce cognitive load compared with the traditional graph display for an experienced surgeon. Although the arrow method theoretically offers a more straightforward interpretation, the results imply that both methods require a similar level of focus and cognitive effort from the surgeons. These findings emphasize that despite advances in visualization technology, surgical expertise and the complexity of the procedure itself continue to impose a substantial cognitive burden (14). However, the NASA TLX, being based on subjective self-assessment, tends to exhibit significant variability in its results due to individual differences in perception (23). The participating surgeons expressed a clear preference for one of the visualization methods: one preferred the graph, one the arrows. Both had previous experience exclusively with the graphical visualization approach. The large spread in the data could affect the reliability of the workload assessment. Therefore, it may be advantageous to complement or replace subjective methods with more objective measures of workload, such as physiological monitoring (e.g., eye-tracking) (24), to obtain a more accurate and consistent evaluation of cognitive and physical demands during surgical procedures.

The equivalence of the two visualization methods in terms of hearing preservation, vestibular function, and cognitive load suggests that either can be effectively used in clinical practice, allowing for flexibility in surgeon preference. However, given the potential for the arrow-based method to be easier for less experienced surgeons to interpret, it could serve as a valuable training tool for younger or less experienced surgeons, thereby promoting more consistent surgical outcomes across varied levels of expertise. Further, it is essential to establish standardized procedures for the interpretation and measurement of ECochG signals (25,26). The arrow visualization, due to its equivalence to the graph representation, may offer the potential for such standardization. A common standard may also improve the usage of robot-assisted operations. Current systems for robot-assisted insertion enable tremor-free, consistent insertions (27–29). However, with the elimination of manual handling the electrode, additional haptic feedback of, e.g., resistance is also lost. To address this, the objective tool of ECochG to report any incidents back to the surgeon can be used. The arrow visualization could serve as a tool to provide feedback to both, surgeon and robot. As described by Weder et al. (30) and O'Leary et al. (2,17), amplitude drops correlate with the loss of residual hearing. By pre-interpreting the data, the robot could, in the future, autonomously stop the insertion in response to such a drop in potentials, without reacting to minimal fluctuations, which could potentially lead to prolonged improvements in terms of residual hearing and structure preservation.

Conclusion

In conclusion, this study demonstrates that both the graph and arrow visualization methods for intraoperative ECochG provide similar outcomes in terms of hearing preservation, vestibular function, and cognitive load in a larger patient cohort. Although these methods may not differ significantly in their clinical impact, the potential ease of use of the arrow method may offer advantages in training environments. Future research should explore the long-term outcomes of these visualization methods and investigate additional strategies for optimizing cochlear implantation to minimize trauma and preserve both auditory and vestibular functions. In the next phase, less experienced surgeons will be included to perform operations using both visualization methods to assess the effectiveness of simplifying ECochG tracking, which may lead to a lower cognitive burden.

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