Detection of Extracochlear Electrodes Using Stimulation-Current-Induced Non-Stimulating Electrode Voltage Recordings With Different Electrode Designs

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Hypothesis: Stimulation-Current-Induced Non-Stimulating Electrode Voltage Recordings (SCINSEVs) can help detect extracochlear electrodes for a variety of Cochlear Implant (CI) devices.

Background: Extracochlear electrodes (EEs) occur in 9 to 13% of cochlear implantations and commonly go unnoticed without imaging. Electrodes on the electrode array located extracochlearly are associated with non-auditory stimulation and a decrease in speech outcomes. We have previously shown that SCINSEVs, with hardware and software from one manufacturer, could detect EEs. Here, we test the generalizability to other manufacturers.

Methods: Fresh-frozen human cadaveric heads were implanted with Cochlear Ltd.’s CI522 (CI-A) and MED-EL’s FLEX24 (CI-B) electrodes. Contact impedances and SCINSEVs were measured, with Cochlear Ltd. research Custom Sound software (Transimpedance Matrix) and MED-EL’s clinical MAESTRO (Impedance Field Telemetry), for full insertion and EEs in air, saline and soft tissue. An automated detection tool was optimized and tested for these implants.

Intra-operative SCINSEVs with EEs were collected for clinical purposes for six patients.

Results: The pattern of SCINSEVs changed in the transition zone from intracochlear to extracochlear electrodes, even with low contact impedances on EEs. Automated detection in the cadaveric specimens, with two or more EEs in saline or soft tissue, showed a mean 91% sensitivity and specificity for CI-A and 100% sensitivity and specificity for CI-B. Quantification of EEs showed significant correlations of $r = 0.69$ between estimated and actual EEs for CI-A and $r = 0.76$ for CI-B.

Conclusion: The applicability of SCINSEVs to detect extracochlear electrodes could be expanded to other cochlear implant companies despite differences in electrode array design and measurement software.

Key Words: Cochlear implants—Extracochlear electrodes—Impedance field telemetry—SCINSEVs—Transimpedance matrix.

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Cochlear Implants (CIs) can be life-transforming devices for many patients with severe to profound hearing loss, but a subset of patients perform poorly (1–4). One reason for poor performance is incomplete insertion of the electrode array or extrusion postimplantation (5–7). Postimplantation electrode migration can be a reason for CI revision surgery, as well as causing nonauditory stimulation such as pain and facial nerve stimulation (7,8). Extracochlear electrodes (EEs), defined as those electrodes on the electrode array that are located outside of the cochlea, are estimated to be present in 9.2 to 13.4% of CI patients (9,10). Detection of EEs commonly goes unnoticed without postoperative computed tomography (CT), which is not standard clinical care in all centers, and involves radiation (10). Holder et al. reported that approximately 40% of CI recipients with EEs were not identified by standard measures such as contact impedances, evoked compound action potentials (eCAPs) and auditory mapping (10).

We have recently shown that Stimulation-Current-Induced Non-Stimulating Electrode Voltage recordings (SCINSEVs) can be used to detect EEs, even when contact impedances remain similar to intracochlear values (11). SCINSEVs are referred to by different names by different CI companies and are variously called Electric Field Imaging (EFI), Transimpedance Matrix (TIM) or Impedance Field Telemetry (IFT) (12). SCINSEVs are measured in a similar way to contact impedances, but instead of measuring the voltage response for a given injected current at the stimulating electrode with respect to the ground, SCINSEVs measure the voltage response along the non-stimulating electrodes on the electrode array. These recording electrodes do not have current flow through them and therefore no polarization potentials are generated, in contrast to contact impedances, which are measured at the stimulating electrode. SCINSEVs are an indirect measure of longitudinal electrical spread along the electrode array and transverse electrical spread out of the cochlea, expressed in voltage per unit current (kΩ). Some of the electrodes on this array showed continuously high contact impedances after insertion in the seventh specimen, after which we stopped data collection.

Three cadaveric heads were implanted with the same MEDEL (MED-EL Medical Electronics, Innsbruck, Austria) CONCERTO FLEX24 electrode (lateral-wall design), hereafter referred to as Cochlear Implant B (CI-B). The CI-B has 12 electrode contacts (numbered 1–12 from apex to base), of which the basal seven electrodes have double electrode contacts. The CI-B was driven by the MAX coil, connected to the MAX programming interface and a computer. Contact impedances and Impedance Field Telemetry (IFT, CI-brand specific name for SCINSEVs) were measured using MAESTRO clinical software (v7.0.3). This measures SCINSEVs by presenting a cathodic-first biphasic charge-balanced pulse (amplitude: 94 μA, phase duration: 24.2 μs, interphase gap: 2.1 μs), and expresses the contact impedance in voltage per unit current (kΩ) and SCINSEV results in voltage (V). Some of the electrodes on this array showed continuously high contact impedances after insertion in the third specimen, after which we stopped data collection.

When referring to the previously published SCINSEV recordings in de Rijk et al., which were obtained with the Advanced Bionics (Advanced Bionics LLC, Valencia, CA) HiRes90K and HiFocus 1J lateral-wall electrode, Clarion Platinum sound processor, CPI-2 programming interface and Volta 1.1.1 Software, this device is referred to as Cochlear Implant C (CI-C) (11).

**Experimental Design**

The experimental design is similar to that used in our previous work (11). SCINSEVs and contact impedances were measured at full insertion, and with 2, 4, 6, 8, and 10 EEs for the smaller-spaced (0.85–0.95 mm contact spacing) CI-A electrode array. For the wider-spaced (1.9 mm contact spacing) CI-B electrode array, measurements were taken at full insertion, and with 1 to 5 EEs. The actual number of electrodes located extra-cochlearly was determined by inspection through a surgical microscope. Measurements were made in three conditions: air, 1.0% saline and soft tissue (temporalis muscle) around the EEs. These conditions were chosen to mimic fluid in the middle ear (saline condition, i.e., during and early post-surgery by irrigation or blood, or later because of middle

**MATERIALS AND METHODS**

**Cochlear Implantation and SCINSEV Recordings in Human Cadaveric Heads**

Fresh-frozen human cadaveric heads were procured from the Anatomy Gifts Registry (USA) within a surgical training facility in our institution. This study was approved by the Human Biology Research Ethics Committee (Project no. HBREC.2018.25) at our institution.

Cochlear implantation was performed as in de Rijk et al., via a mastoidectomy, posterior tympanotomy, round window approach and flushing of the cochlea with 1.0% saline through a 1 mm opening in the lateral semi-circular canal (LSCC) prior to implantation (11).

Seven cadaveric heads were implanted with the same Cochlear Ltd. (Cochlear Ltd., Sydney, Australia) CI522 (lateral-wall design), hereafter referred to as Cochlear Implant A (CI-A). The CI-A has 22 electrode contacts (numbered 22-1 from apex to base). The CI-A was driven by the Nucleus® CP910 Sound Processor, connected to the Nucleus® Freedom Speech processor, programming pod and a computer. Contact impedances and Transimpedance Matrices (TIMs, CI-brand specific name for SCINSEVs) were measured using Custom Sound EP 5.1 (v2017) software with the TIMs add-on. This measures SCINSEVs by presenting a cathodic-first biphasic charge-balanced pulse (amplitude: 94 μA, phase duration: 24.2 μs, interphase gap: 8 μs), and expresses the results in voltage per unit current (kΩ). Some of the electrodes on this array showed continuously high contact impedances after insertion in the seventh specimen, after which we stopped data collection.

Three cadaveric heads were implanted with the same Cochlear Ltd. (Cochlear Ltd., Sydney, Australia) CI522 (lateral-wall design), hereafter referred to as Cochlear Implant A (CI-A). The CI-A has 22 electrode contacts (numbered 22-1 from apex to base). The CI-A was driven by the Nucleus® CP910 Sound Processor, connected to the Nucleus® Freedom Speech processor, programming pod and a computer. Contact impedances and Transimpedance Matrices (TIMs, CI-brand specific name for SCINSEVs) were measured using Custom Sound EP 5.1 (v2017) software with the TIMs add-on. This measures SCINSEVs by presenting a cathodic-first biphasic charge-balanced pulse (amplitude: 94 μA, phase duration: 24.2 μs, interphase gap: 8 μs), and expresses the contact impedance in voltage per unit current (kΩ) and SCINSEV results in voltage (V). Some of the electrodes on this array showed continuously high contact impedances after insertion in the third specimen, after which we stopped data collection.

**DETECTING EXTRACOCHLEAR ELECTRODES WITH ELECTRODE VOLTAGE MEASUREMENTS**

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ear infection), or fibrotic tissue located on the EEs (the temporalis muscle condition, i.e., early postsurgery with packing, or with long-term postoperative fibrosis). Measurements were repeated thrice and the mean and standard deviation was calculated. The sum of the mean of recorded SCINSEVs was calculated, showing the voltage or voltage per unit current as one value per recording electrode, to allow for easier comparison between specimens and conditions.

The automated detection and quantification algorithm for EEs in saline or soft tissue as introduced in de Rijk et al., was adapted to the number of electrodes on the CI-A and CI-B arrays (11). This previously published algorithm, using MATLAB’s fliplr function, so that the recording electrodes are numbered in the apical-to-basal direction. It then applies MATLAB’s findchangepts function, which finds the three changepoints within this transposed sum in which the mean and the slope changes most significantly. The four segments of the SCINSEV sum, separated by these three changepoints, are then fitted using MATLAB’s polyval and polyfit functions, and the ratio of the slope of the second most basal to the most basal segment is calculated. The SCINSEVs with only one EE were excluded from this analysis, as the polynomial fit cannot be calculated for one datapoint. A range of 200 cut-off values for the slope ratio from 0 to 4 (step size of 0.02) was tested using the exhaustive leave p-out cross-validation method (LpOCV) for $p = 3$ out of 7 for CIA (meaning 4 datasets in each training set and 3 in each test set for 34 repeats of unique combinations) and $p = 1$ out of 3 for CI-B (meaning 2 datasets in each training set and 1 in each test set for 3 repeats of unique combinations). The optimal cut-off for each repeat was determined by the largest value in combined sensitivity and specificity. When multiple cut-offs gave identical sensitivity and specificity values, the mean of the cut-off was taken as a representative for that repeat. The mean cut-off was then used to calculate the sensitivity and specificity on the remaining datasets in the test set for each repeat. The mean ± standard deviation (SD) was calculated across all sensitivities and specificities of the test sets. The number of EEs was determined as the most basal changepoint of the SCINSEV sum rounded down, as introduced in de Rijk et al. (11). Correlations between estimated and actual quantification were calculated using the correlation coefficient $r$ and the coefficient of determination $R^2$.

SCINSEV Recordings with Extracochlear Electrodes in Human Cadaveric Heads

As part of regular clinical care at our facility, SCINSEVs were recorded intra-operatively for five patients during slow insertion or when the final insertion point was a partial insertion. The slow insertion is routinely done in order to preserve residual hearing. At our clinical facility, SCINSEVs are also measured intra-operatively for clinical validation of full insertion, and as a baseline for any future changes in SCINSEVs, which might indicate electrode malfunction or changes due to intracochlear conditions. An additional SCINSEV (patient #3) was included as part of a research study (ethical approval via HRA and Health and Care Research Wales (HCRW) through University Hospitals NHS Foundations Trust and the University of Cambridge (IRASID:285894).

Measurements for patient #1 were made during insertion rests, and after full insertion took place. A full insertion for patients #2, #3, #4, and #5 was not possible and measurements were made at the final insertion point. The SCINSEVs for patient #6 were made on the day of revision surgery, occurring 2 months after initial implantation. One SCINSEV was recorded prior to reinsertion and one after full insertion for this patient. Patients #1, #4, and #5 received an electrode array with perimodiolar design (same brand as CI-A with a different electrode array design) and patients #2, #3, and #6 received an electrode array with lateral-wall design similar to the CI-A electrode array. SCINSEVs were measured using the CI-brand specific software as listed for CI-A, but with a different amplitude for the input pulse (128–1,114 $\mu$A range).

RESULTS

Contact Impedances with the CI-A and CI-B in Human Cadaveric Heads

Full insertion of the CI-A in flushed cochleae (1.0% saline) resulted in a mean contact impedance of 5.2 k$\Omega$ (range: 1.4–10.9 k$\Omega$). For full insertion of the CI-B in flushed cochleae, a mean contact impedance of 4.9 k$\Omega$ (range: 2.3–12.0 k$\Omega$) was recorded.

Contact impedances for the three different conditions with EEs are shown for devices CI-A and CI-B in parts A and B of Figure 1, respectively. For EEs in air, the contact impedances were generally higher overall than for the intracochlear electrodes (Fig. 1A and B). In this condition, the mean contact impedances for the intracochlear electrodes was 5.3 k$\Omega$ for the CI-A and 4.8 k$\Omega$ for the CI-B, while the mean contact impedances of the EEs in air were 23.0 and 15.7 k$\Omega$ for the CI-A and CI-B, respectively. When the EEs were in saline or soft tissue, the contact impedances on the EEs remained low, and in a similar range to the intracochlear electrodes for both implants (middle and bottom rows of Fig. 1A and B). The mean contact impedances for the CI-A on the EEs in saline and soft tissue was 2.83 and 3.45 k$\Omega$, respectively, while the mean contact impedances for the CI-B on the EEs in saline and soft tissue was 2.0 and 2.4 k$\Omega$, respectively. These values are within the range of contact impedances for a full insertion stated previously.

Live-Patient Intra-Operative SCINSEV Recordings

SCINSEVs with Extracochlear Electrodes in Human Cadaveric Heads

Figure 2 shows an example of SCINSEVs and contact impedances with EEs for the previously published CI-C (11), and the CI-A and CI-B arrays. SCINSEVs with EEs in saline or soft tissue show a transition in voltage (per unit current) on the EEs compared to the intracochlear electrodes, while the contact impedances stay similar to the intracochlear electrodes. Figure 3 shows the sum of SCINSEVs as a function of recording electrode for all specimens with extracochlear conditions in saline and soft tissue. A line is drawn for the predicted transition zone from intracochlear to EEs, based on visual inspection through surgical microscope.

The automated detection algorithm for EEs as introduced in de Rijk et al. (11), was optimized to the data collected with CI-A and CI-B by testing a range of 200 cut-off points from 0 to 4 using LpOCV. Receiver operating characteristic (ROC) analysis was applied to find the optimal cut-off which would allow for inclusion of those SCINSEVs with EEs as identified by visual inspection and exclusion of those that were marked as full
FIG. 1. A, Contact impedances for the CI-A for different conditions and number of extracochlear electrodes (EEs). Contact impedances are shown for each specimen (A1-A7), as well as the mean across the seven specimens. “EE” refers to the number of extracochlear electrodes, for example, 4EE = 4 extracochlear electrodes. Each row represents a different condition extra-cochlearly, while the intracochlear position and condition remains similar across the three conditions. Colored patches show the intracochlear section and the extracochlear section of the electrode array. Recording electrode 22 refers to the most apical electrode, while 1 refers to the most basal electrode.

B, Contact impedances for the CI-B for different conditions and number of extracochlear electrodes (EEs). Contact impedances are shown for each specimen (B1-B3), as well as the mean across the three specimens. “EE” refers to the number of extracochlear electrodes, for example, 4EE = 4 extracochlear electrodes. Each row represents a different condition extra-cochlearly, while the intracochlear position and condition remains similar across the three conditions. Colored patches show the intracochlear section and the extracochlear section of the electrode array. Recording electrode 1 refers to the most apical electrode, while 12 refers to the most basal electrode.
FIG. 2. Contact impedances and SCINSEVs for each CI brand tested for all three conditions (air, 1.0% saline, soft tissue). Data is shown as the mean of three repeats, with error bars representing the standard deviation for the contact impedance measurements. The data shown from CI-C was previously published in de Rijk et al. (11). For the CI-A, recording electrode 22 refers to the most apical electrode, while 1 refers to the most basal electrode. For the CI-B, recording electrode 1 refers to the most apical electrode, while 12 refers to the most basal electrode. For the CI-C, recording electrode 1 refers to the most apical electrode, while 16 refers to the most basal electrode. The CI-A conditions with extracochlear electrodes are for 4 EEs, while for CI-B and CI-C 3 EEs are shown.

FIG. 3. Sum of SCINSEVs plotted for all number of extracochlear electrodes (EEs) in saline and soft tissue. The sum is taken from the mean of the three repeats per condition and specimen. A vertical red line is plotted as a reference line for the predicted transition zone from intracochlear to extracochlear electrodes, based on the number of EEs present during inspection through a surgical microscope. This reference line theoretically corresponds to the round window opening. For the CI-A, recording electrode 22 refers to the most apical electrode, while 1 refers to the most basal electrode. For the CI-B, recording electrode 1 refers to the most apical electrode, while recording electrode 12 refers to the most basal electrode. The outlier seen for “CI-B - 1EE,” for both saline and soft tissue, is most likely due to high contact impedances on electrode 2 in this specimen (23 kV vs. an average of 7.4 kV for the other intracochlear electrodes in that specimen in the 1EE condition).
insertion by visual inspection (Fig. 4). The mean optimized cut-off across training sets for CI-A was 0.81 ± 0.099 (1SD), with a mean sensitivity of 91% ± 4.3% (1SD) and specificity of 91% ± 9.9% (1SD) for the remaining test sets. The mean optimized cut-off across training sets for CI-B was 2.02 ± 0.242 (1SD), with a mean sensitivity of 100% ± 0% (1SD) and specificity of 100% ± 0% (1SD) for the remaining test sets. Quantification of the EEs was performed for all datasets (Fig. 4), with a correlation of $r = 0.69$ ($p < 0.001$) between estimated and actual number of EEs for CI-A and $r = 0.76$ ($p < 0.001$) for CI-B. The mean signed difference (Fig. 4) shows a possible trend of overestimation at low EEs and underestimation at higher EEs with an inflection point at 4 EEs.

**Live Patient Intra-Operative SCINSEV Recordings**

As part of intra-operative testing, SCINSEVs were recorded and are shown in Figure 5 for six patients. While patient #1, #3, #4, #5, and #6 had relatively low contact impedances on all electrodes, suggesting the EEs were likely to be within fluid (e.g., saline or blood) or tissue, patient #2 reached the maximum contact impedance (30 kΩ) on the most basal electrode, suggesting this electrode was in air. Applying the automated detection algorithm showed that the ratio of slopes between the second most basal and most basal segment was 3.38 for patient #1 with a partial insertion, 0.44 after full insertion, 0.02 for patient #2, 0.30 for patient #3, 1.06 for patient #4, 3.38 for patient #5, 0.23 for patient #6 before revision, and 0.6 after revision. For patient #1, this is above the criterion of 0.81 for the identification of EEs with the CIA for partial insertion and below the criterion for full insertion. For patient #4 and #5 the ratio of the two segments is also above the criterion of 0.81 at their final partial insertion point. However, it is below the cut-off for patient #2, #3, and #6 with a partial insertion. The SCINSEV sum of patient #2 on the most basal electrode is dominated by the high contact impedance. When removing the most basal electrode from the SCINSEV, the automated detection algorithm shows a value of 5.03, which is above the cut-off value needed to identify this SCINSEV as containing EEs. The automated detection tool was not able to detect the EEs for patient #3 and #6.

Unfortunately, there is no information available for the number of EEs present by visual inspection through the surgical microscope at the time of the intra-operative SCINSEV recordings for three patients, #1, #2, and #6, as only a general note of partial insertion was made. The automatic quantification of EEs shows 5 EEs for patient #1 during an insertion rest and 5 EEs for patient #2 at final positioning. A postoperative x-ray of patient #2, 2 weeks after implantation, showed 9 EEs. Patient #4 had 5 EEs intra-operatively, while patient #5 had 7 EEs intraoperatively. The automatic quantification for both patients’ SCINSEVs was identified at 5 EEs, indicating a correct quantification for patient #4 and an underestimation for patient #5. Both patients showed 7 EEs on their postoperative x-ray a few weeks later, suggesting further extrusion postoperative for patient #4 and/or underreporting by the surgeon intra-operatively.

**DISCUSSION**

This study demonstrates that the previously shown potential for SCINSEVs to detect extracochlear electrodes (11) also applies to other CI-specific electrode designs, software and measurement details. When EEs were located in air, contact impedances were higher than for intracochlear electrodes, and therefore SCINSEVs did not show additional diagnostic benefit. In contrast for EEs located in saline or soft tissue, contact impedances remained in a range similar to that for the intracochlear electrodes and would therefore not alert the clinician to the fact that the implant was not fully intracochlear. SCINSEVs showed a clear transition from intracochlear to extracochlear electrodes in saline and soft tissue conditions, which is consistent with our previous findings with the CI-C (11). Since it has been hypothesized that electrode migration can arise from minor movement of the implant intra-operatively during skin closure, measuring SCINSEVs intra-operatively at the time of closure, could prevent revision surgery (17). In addition, SCINSEVs could act as an objective measure of post-surgery electrode migration, as previously reported by our group (18), and this could allow one to identify EEs in patients incapable of reporting behavioural thresholds, and without the expense or radiation exposure associated with postoperative CT scans.

Although implantation in fresh-frozen human cadaveric allows us to systematically test multiple conditions without variation in anatomy, limitations of the experimental set-up do exist, most of which are noted in de Rijk et al. (11). Most importantly, we are unaware of what happens to the cadaveric cochlea during the freezing and defrosting process. We are also unaware of the intra-cochlear conditions during these experiments and are only guided by the intracochlear contact impedances. Despite these limitations of cadaver experiments, the intra-operative SCINSEVs in Figure 5 show that SCINSEVs of the CI-A specific brand have potential to be used as a clinical tool. The automated detection tool identified 4 out of 6 intra-operative SCINSEVs correctly as having EEs, when contact impedances were low, and identified 2 out of 2 correctly as a full insertion. Automated quantification intra-operatively seems to be in line with our cadaver model, where quantification above 4 EEs is either correct (patient #4) or underestimated (patient #5 and likely patient #2 where further extrusion postoperatively was likely present).

The differences in the optimal cut-off values for the different electrode array designs, 0.81 for the CI-A, 2.02 for the CI-B, and 1.53 for the CI-C (11), could potentially be explained by the difference in electrode contact spacing. The CI-B has the widest contact spacing of 1.9 mm, the CI-C has a contact spacing of 1.1 mm, while the CI-A has contact spacing of 0.85 to 0.95 mm. Smaller contact spacing is expected to produce a less
FIG. 4. Detection and quantification of extracochlear electrodes (EEs). Receiver Operating Characteristics (ROC) are shown in the top row for the leave p-out crossvalidation (LpOCV) for both the CI-A (p = 3) and CI-B (p = 1), showing the true positive and false positive rate for 200 equally spaced cut-off points from 0 to 4. The mean ± 1 standard deviation of the 34 repeats for CI-A and 3 repeats for CI-B is shown, as well as all repeats. Quantification plots are shown in the middle row for all 7 datasets for the CI-A and all 3 datasets for the CI-B, for both saline and soft tissue. The size of the plotted triangle corresponds to the amount of SCINSEVs corresponding to that combination of actual and estimated number of EEs. The dotted line shows the correct number of EEs, as determined by visual inspection. The correlation between estimated and actual number of EEs is $r = 0.69$ ($p < 0.001$) for CI-A and $r = 0.76$ ($p < 0.001$) for CI-B. The mean signed difference ± 1 standard deviation is shown in the bottom row for the error in quantification per actual number of EEs, for both CI-A and CI-B.
FIG. 5. Intra-operative contact impedances and SCINSEVs for six patients. Patient #1, #4, and #5 received a perimodiolar electrode array, while patient #2, #3, and #6 received a lateral-wall electrode with a similar design to CI-A. The top graphs (5A, 5C, 5E, 5G, 5I, 5K, 5M, and 5O) show the contact impedances, while the bottom graphs (5B, 5D, 5F, 5H, 5J, 5L, 5N, and 5P) show the SCINSEVs.
abrupt change in electrical spread measured with SCINSEVs compared to large contact spacing, and therefore the ratio between the slope of the polynomial fit of the SCINSEV sum of the most basal intracochlear segment and the extracochlear electrode segment should be smaller for electrodes with smaller contact spacing. It should be noted that the CI-B dataset is relatively small, due to limited availability of this implant for experimental use at the time, and so this should be taken into account when interpreting the detection and quantification results. An additional general limitation of this automated detection and quantification tool is that it cannot be applied to SCINSEVs with only 1EE, as one extracochlear datapoint cannot be fitted with a polynomial function.

The experiments performed in cadavers are a better model for the intra-operative condition than the clinical long-term postoperative condition, since intra-operatively there is no implantation-induced fibrosis formed around the electrodes, which can develop postoperatively, that is thought to lead to an increase in contact impedances (19,20). The soft tissue experiments in this study are a step toward showing potential changes when the EEs are located in a fibrous sheath, but cannot be directly compared to a compact fibrous sheath and do not include intracochlear fibrosis. The use of the automated detection and quantification tool needs to be optimized to account for contact impedance changes, and subsequently expected SCINSEV changes, in long-term postoperative patients. The high contact impedance and SCINSEV recordings on the most basal electrode in patient #2 (Fig. 5E) shows the need to perhaps integrate a way to exclude high impedance recordings in the automated method, when these high contact impedances do not already alert the clinician of potential EEs in air. This will need to be optimized on a large dataset of patient SCINSEVs in the future.

While in this report we use an objective automated method to detect and quantify the number of EEs, with increasing experience with SCINSEV interpretation, we have subjectively found it relatively easy to detect and estimate the number of EEs based on the SCINSEV patterns visualized (e.g., Fig. 5J showing a transition in measured values when stimulating intracochlear electrodes and measuring on extracochlear electrodes). The SCINSEV of patient #6 before full insertion (Fig. 5N) is an example of the effect of fibrotic tissue formation around the electrodes on the SCINSEV pattern, where the automated detection tool was unable to mark this SCINSEV as having EEs but the visual pattern may stand out to a clinician. Many audiologists and surgeons may find this a more rapid method as experienced is gained, while the automated tool is not yet clinically implemented by any company’s software.

In summary, this study expands the application of SCINSEVs and shows its ability to detect extracochlear electrodes in a variety of electrode designs and brand-specific software. The automated detection and quantification tool could be of use for clinicians not familiar with SCINSEV interpretation and, in future, may be further optimized for long-term postoperative conditions.

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