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Prevalence of extracochlear electrodes: CT scans, cochlear implant maps, and operative reports

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Abstract

Objective: To quantify and compare the number of cochlear implant (CI) electrodes found to be extracochlear on postoperative CT scans, the number of basal electrodes deactivated during standard CI mapping (without knowledge of the postoperative CT scan results), and the extent of electrode insertion noted by the surgeon.

Study Design: Retrospective

Setting: Academic Medical Center

Methods: 262 patients underwent standard cochlear implantation and postoperative temporal bone CT scanning. Scans were later analyzed to determine the number of extracochlear electrodes. Standard CI programming had been completed without knowledge of the number of extracochlear electrodes identified on the CT. These standard CI maps were reviewed to record the number of deactivated basal electrodes. Lastly, each operative report was reviewed to record the extent of reported electrode insertion.

Results: 13.4% (n=35) of the CIs were found to have at least one electrode outside of the cochlea on the CT scan. Review of CI mapping for these 35 patients indicated that audiologists had deactivated extracochlear electrodes in 60% (21) of these cases. Review of operative reports revealed that surgeons correctly indicated the number of extracochlear electrodes in 6% (2) of these cases.

Conclusions: Extracochlear electrodes were correctly identified audiologically in 60% of cases and in surgical reports in 6% of cases; however, it is possible that at least a portion of these cases involved postoperative electrode migration. Given these findings, postoperative CT scans can provide information regarding basal electrode location, which could help improve programming accuracy, associated frequency allocation, and audibility with appropriate deactivation of extracochlear electrodes.

Introduction

Cochlear implants (CI) are implanted devices that are used to restore audibility and speech understanding to individuals with sensorineural hearing loss (SNHL) who do not receive benefit from acoustic amplification. Although CI technology has improved in recent years,

re-establishment of normal auditory fidelity remains elusive. Personalized CI programming is one such means to optimize performance^{1–5}. More personalized programming is especially important as candidacy criteria continue to expand, allowing people with greater residual hearing and higher preoperative word recognition scores to receive a CI^{6–8}.

One method used to individualize CI programming includes deactivating electrodes resulting in poor loudness growth, poor sound quality, and/or non-auditory stimulation. Electrodes that require a disproportionally high stimulation level relative to the other electrodes or electrodes that do not evoke a hearing percept, are typically turned off. For basal electrodes, it is possible that this is caused by extracochlear electrodes or regions containing poor neural survival^{9–13}. For patients who are unable to accurately report loudness or sound quality, electrical evoked compound action potentials (ECAPs) measures can be used as a way to objectively assess electrode neural interface. While ECAPs are not always directly correlated with behavioral response, they do provide confirmation that the auditory nerve fibers are responding to electrical stimulation, and therefore, the stimulation should be audible when ECAPs are present¹⁴.

Previous studies investigating selective deactivation of electrodes report improved speech recognition and sound quality when poorly performing electrodes are turned off^{1,3,15,16}. Additionally, at least one group¹⁷ has shown that stimulation of the basal part of the cochlea is integral for optimal speech recognition. Thus, it would appear that detecting and deactivating electrodes that can easily be identified as extracochlear, while maintaining basal stimulation is a worthwhile pursuit to maximize individual outcomes.

There are generally two explanations for extracochlear electrodes: 1) The surgeon was unable to insert all of the electrodes due to resistance (i.e. ossification, variation in cochlear length, surgical technique, and/or electrode type), which should be documented in the operative note or 2) the electrode extruded from the cochlea after placement. Multiple studies tracking large numbers of CI surgeries found the prevalence of electrode extrusion or migration to range from 0.3–2%^{18–23}. One study in the literature reported a much higher rate of migration (29%); however, their study was confounded by a much smaller sample size and single electrode type²⁴. Lesser known is the incidence of extrusion during surgical closing (i.e. coiling of the electrode array and packing) or during the days immediately following surgery. Shpizner et al.²⁵ and Coombs et al.²⁶ reported that 9.2% of implants were found to have incomplete insertion on plain film X-rays.

Extracochlear electrodes, or electrodes positioned outside the round window, do not provide optimal stimulation to the high-frequency regions of the cochlea and therefore warrant CI mapping changes or, in extreme cases, reinsertion²⁷. Before CI mapping changes can be made, the audiologist must first become aware that electrodes are extracochlear potentially through the use of postoperative imaging. Several studies have investigated and support the use of postoperative imaging to evaluate electrode insertion depth and position in the cochlea^{24,26,28–36}, and it has the added benefit of giving feedback regarding tip-foldover³⁷.

Currently, however, postoperative computerized tomography (CT) scans are not standard of care, and most CI centers rely on intraoperative measurements including impedance and

ECAP combined with surgeon's operative reports and/or plain film radiography to assess final electrode array position. Intraoperative impedance measurements have been shown to be an unreliable measurement in detecting extracochlear electrodes because extracochlear electrodes are often surrounded by muscle or other packing materials, thus yielding normal impedance values²⁶. Research on the agreement between surgeon report, plain film radiography, and electrode function testing has been mixed. Several studies have shown a large amount of variability between plain films and surgeon's reports^{28,36,38}. In contrast, Bettman et al.³⁹, in a small study of 16 patients, found no significant differences between three methods (intraoperative electrode counting by the surgeon, plain film radiography using Stenvers view, and postoperative electrode function testing) used to determine electrode insertion depth. Coombs et al.²⁶ further suggested that plain film X-rays are not detailed enough to capture electrode location precise enough for clinical decision-making.

Given the conflicting literature regarding the prevalence of extracochlear electrodes and disagreement between the various identification methods, the aim of the current study was to quantify and compare the number of extracochlear CI electrodes via postoperative CT scans, the number of basal electrodes deactivated during standard CI mapping (without knowledge of the postoperative CT scan results), and the extent of electrode insertion noted by the surgeon in the operative report. We hypothesized that surgical report would not accurately report the number of extracochlear electrodes because of movement during packing and/or failure to include information regarding insertion depth in the operative report (given the retrospective nature of our study). Second, we hypothesized that audiologists would not accurately identify extracochlear electrodes due to spread of excitation occurring during upper stimulation level measurements and ECAP recordings. Third, we hypothesized that CT imaging would reveal a significantly higher number of extracochlear electrodes than could be identified by the surgeon or audiologist.

Methods

Two hundred and sixty-two (262) adults (average age = 61.7 years) underwent standard cochlear implantation. Patients selected the CI manufacturer of their choosing (See Table 1) with input regarding electrode array based on surgeon and audiologist recommendations with 68 patients prospectively intended for hearing preservation (Advanced Bionics, AB = 51, Cochlear Americas = 147, MED-EL = 64; lateral wall arrays = 113, precurved arrays = 149). All patients underwent postoperative CT scanning, which occurred at least one month after surgery. Temporal bone CT scans were analyzed using methods previously described by Noble et al.¹ to determine which electrodes, if any, were extracochlear. This process involved first relying on algorithms developed to automatically localize the cochlea and its substructures in the patient's preoperative CT⁴⁰ (or in postoperative CT^{41,42} if preoperative CT was not available) using a statistical atlas of inner ear anatomy constructed from a set of high resolution μ CTs of a set of cadaveric specimens. Next, the CI electrodes were automatically localized in postoperative CT using one of a suite of algorithms developed for the various electrode array models^{43–45}. Finally, once the position of the electrode array is known, determining which electrodes are extracochlear is straightforward (Figure 1).

Standard clinical CI programming was completed by a CI audiologist without knowledge of the CT results. After activation, each patient was scheduled to return for CI mapping adjustments at two weeks, one month, three months, six months, and twelve months. Standard CI maps occurring at the 3–6-month post-activation time-point were reviewed to record the number of deactivated basal electrodes. By the 3-month postoperative time-point, the clinical protocol dictates that upper stimulation levels are measured for each electrode using loudness scaling. During standard CI mapping, clinical audiologists had access to intraoperative ECAPs and impedance measures to guide clinical programming.

Lastly, each operative report was retrospectively reviewed to record the extent of reported electrode insertion. It should be noted that the surgeons were not aware of this retrospective review, and at no time were they specifically asked to report the number of extracochlear electrodes in their operative reports.

Results

Of the 262 patients implanted, 35 (13.4%) were found to have at least one extracochlear electrode as identified by the CT scan. Review of CI mapping indicated that the clinical audiologist had appropriately deactivated the basal, extracochlear electrode(s) in 21 (60.0%) of these 35 cases. Surgical operative reports revealed that surgeons indicated an incomplete insertion in 9 (25.7%) of these 35 cases and accurately reported the correct number of extracochlear electrodes in 2 (6.0%) of these 35 cases. ECAP measurements were considered consistent with an extracochlear electrode if there was no response. ECAP measurements correctly alerted the audiologist of an extracochlear electrode in 9 (25.7%) of the 35 cases showing an extracochlear electrode on the CT scan. Impedance measurements were normal for all 35 patients with extracochlear electrodes; thus, they were not indicative of incomplete insertions. A comparison of these methods used to identify extracochlear electrodes for each subject is displayed in Table 2.

Given that the dataset did not meet the assumptions of normality, a Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks was completed with method of extracochlear electrode identification (CT, operative report, audiology mapping, or ECAP) as the independent variable and number of extracochlear electrodes as the dependent variable. Statistical analysis revealed a significant effect of identification method [$H_3 = 41.3$, $p < 0.001$]. Post hoc testing using all pairwise multiple comparison (Tukey) revealed that there was no statistically significant difference between the number of extracochlear electrodes identified via CT and audiology programming ($q = 1.7$, $p > 0.05$) nor between the operative report and ECAP ($q = 1.8$, $p > 0.05$); however there was a statistically significant difference between the number of extracochlear electrodes identified via CT and operative report ($q = 7.7$, $p < 0.05$), between the CT and ECAP (5.9 , $p < 0.05$), between the operative report and audiologist programming ($q = 5.8$, $p < 0.05$), and between the audiologist programming and ECAP ($q = 4.1$, $p < 0.05$).

Discussion

To our knowledge, this is the first study that reports prevalence of extracochlear electrodes identified by postoperative CT scan for an aggregate population of CI patients, with all three implant manufacturers, and inclusion of both lateral wall and pre-curved arrays. Two hundred and sixty-two (262) postoperative CT scans were analyzed for electrode placement and subsequently compared with other clinical ways of identifying extracochlear electrodes—operative reports, audiology mapping, impedances, and ECAP measurements. Postoperative CT scanning identified 35 (13.4%) with extracochlear electrodes; of these with extracochlear electrodes, 60% were correctly identified during audiology mapping and 6% were correctly identified by surgeons in their operative report. For discussion purposes, we have included impedance measurements and ECAP measurements under the umbrella of audiology mapping since these tools were available to audiologists during CI mapping appointments.

As presented in the introduction, there are two primary reasons for extracochlear electrodes—extrusion and incomplete insertion. Given numerous previous reports of extrusion rates of ~1%, the authors speculate that the current data are suggestive of incomplete insertion or migration occurring during surgical closing and/or in the perioperative period. We suspect, as others have also speculated, that subtle movement of electrode arrays occurs during closure when the transmitting wires may be manipulated. Our data suggests that this is more common in lateral wall electrodes (27.4%) versus pre-curved electrodes (2.6%) because the pre-curved electrodes' coiling tethers them intracochlear.

Our findings indicate that operative reports are a poor indicator of extracochlear electrodes, identifying them in only 6% of occurrences. This may be partially explained by how “complete insertion” is interpreted by surgeons and partially by ambiguity in manufactures' designation of “complete insertion”. Some surgeons might report a complete insertion when the electrode is inserted until the point of resistance, which assumes some variation in cochlear length, while others would only report a complete insertion if all active electrodes were within the round window. Manufacturers have variation in what complete insertion is, which can vary over millimeters (e.g. the Cochlear 522 has two white lines approximately 8mm apart indicating a minimum and maximum insertion but all insertion between the two white lines are considered “complete”). For clarity, moving ahead, we recommend that in operative notes surgeons explicitly state how many electrodes are inserted (e.g. electrode 16 at the RW) as opposed to the generic “complete insertion achieved”.

The current results demonstrated that audiologists were able to correctly identify extracochlear electrodes in 60% of cases. The remaining 40% of patients had active electrodes stimulating and delivering high-frequency information to an area outside of the round window in the middle ear space. We speculate that audiologist's inability to detect these extracochlear electrodes is due to spread of excitation and patients' poor ability to report on loudness and sound quality at high frequency regions. When an electrode is stimulated at a sufficient level and there is no auditory percept, it is an easy decision for the audiologist to deactivate that electrode. In some cases, however, it is possible that the stimulation from an extracochlear electrode spreads to nearby neural tissue resulting in

suboptimal auditory percept and/or ECAP response²⁶. Additionally, high-frequency, basal electrodes, even ones that are intracochlear, are often the most difficult for patients to qualify. Previous studies have shown that basal electrodes require higher upper stimulation levels (i.e. M-levels, C-Levels, MCLs)⁴⁶ and have higher ECAP thresholds¹³, both of which are thought to be attributed to poorer spiral ganglion cell survival and density in the basal cochlea⁴⁷. Conversely, absent ECAP responses are not always indicative of electrode misplacement; previous studies have shown absent ECAP responses from intracochlear, functional electrodes^{48,49}.

Given these inconsistencies, it is difficult to confirm extracochlear electrode positioning without imaging – a topic which has been previously studied albeit with plain film radiography. Coombs et al.²⁶ conducted a study comparable to the current study in which they reviewed electrode location using postoperative plain X-rays. Although they found 9.2% of arrays to have at least one extracochlear electrode, they ultimately concluded that X-rays were not reliable enough to implement routinely. Previous reports are in agreement that X-rays have falsely suggested correct electrode placement due to suboptimal capture angles and limited detail^{50–52}. We speculate that the current dataset showed a slightly higher, more precise percentage of extracochlear electrodes due to greater detail available in CT scans than plain X-rays. This increased detail, however, comes at a price – both the financial cost of the machine and the increased radiation exposure. Regarding financial cost, portable CT scanners range from approximately \$300K (Xoran XCAT, Ann Arbor, MI) to over \$1 million dollars (Medtronic O-arm; Minneapolis, MN). However, their integration into operating suites is becoming more widespread at major academic centers especially to facilitate intraoperative image-guidance utilized by neurosurgeons and rhinologists. Regarding radiation risk, the exposure of a traditional, stationary multi-slice CT scan is approximately 15 times that of a single lateral skull x-ray (0.1 mSv⁵³), but low dose CT protocols are rapidly becoming the norm reducing radiation exposure from over 1.4mSv to approximately 0.35mSv⁵⁴. As with any intervention in medicine, the decision is made based on minimizing risk-benefit ratio with, in this case, the risk of radiation exposure being offset by the benefit of improved CI function.

The present data clearly indicate that extracochlear electrodes are not an uncommon finding among CI users with 13.4% of recipients having at least one extracochlear electrode. To make such findings more aware to programming audiologists in the hopes of improving outcomes, we recommend the following:

- Surgical documentation as to the final location of the electrode in reference to an identifiable maker on the electrode array (e.g. the 2nd indicator line was located 1mm outside the round window).
- Audiologists to be aware of the incidence of extracochlear electrodes and limitations in identifying them using currently available programming techniques.
- Where available, post-operative CT scanning should be performed especially in patients where there is a high suspicion given operative findings, programming difficulties, and/or poor-patient outcomes.

- And, finally, recognition within the field that, given wide inter-subject variability of the cochlear duct (25–35mm⁵⁵), that extracochlear electrodes should not be seen in a negative light given that “under” insertion may have prevented lateral displacement of electrode array in the basal turn and and/or translocation^{56,57}. Only the inability to correctly identify and deactivate extracochlear electrodes should be viewed in a negative light.

Limitations

There are a few limitations to the current study. Firstly, we are unable to rule out extrusion as a cause of the extracochlear electrodes reported herein. Van der marel²⁴ suggested that the most likely time for the array to move is in the first weeks after implantation because it is not yet covered by a fibrous sheath. In order to appropriately evaluate this phenomenon, two CT scans would be required— intraoperative CT scan (immediately following implantation) and postoperative CT scan (at least 3 weeks later). Another limitation to the current study is the retrospective design. In the future, we hope to be able to record a more precise operative report regarding insertion completeness. Third, the postoperative CT scans that our patients underwent did not all occur at the same time-point relative to their implantation date. Despite these limitations, we feel that our current clinical tools used to detect extracochlear electrodes are not sufficient for individualized CI programming, and further investigation into the use of routine intra or post-operative CT scanning is warranted. And, finally, the clinical significance of leaving an extracochlear electrode active or deactivating basal electrodes for all patients could not be studied in this retrospective review. Prior literature does support that optimal outcomes are obtained when only intracochlear electrodes are active and that complete basal coverage (high frequency) is maintained¹⁷.

Conclusion

Extracochlear electrodes occur in 13.4% of CI recipients, but current methods (surgeon report, audiology mapping, impedance measurements, and ECAPs) detect only 65.7% of these occurrences. To improve upon this rate, further investigation into the use, feasibility, and safety of routine intraoperative or immediate postoperative CT scanning to evaluate electrode position is warranted.

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Figure 1.

Shown in (a) is an axial slice of an example postop CT. In (b) and (c) are axial and oblique (plane of the basal turn) zoomed in views of the cochlea and implanted electrode array. (d) and (e) show the same views with contours around the cochlea shown in orange. (f) shows a 3D reconstruction of the cochlea and the implanted electrode array. In this example, three electrodes (labeled P10, P11, and P12) are extracochlear.

Table 1.

Number of patients receiving each brand and electrode type are shown.

	Total	Extracochlear	AB	Cochlear	MED-EL
Precurved	149	4	28	121	N.A.
Lateral Wall	113	31	23	26	64
Conventional	45	14	23	3	19
Hearing Preservation	68	17	0	22	46
Total	262	35	51	147	64

Table 2.

Cochlear implant information and number of extracochlear electrodes detected by each method are shown. “-” indicates that no data was available for this particular measurement.

					Number of Extracochlear Electrodes			
	Electrode Type	Manufacturer	Electrode	CT	Operative Report	CI Mapping	ECAP	Detected without CT?
1	Lateral	AB	IJ	6	2	3	Normal	No
2	Lateral	AB	IJ	4	0	0	-	No
3	Lateral	AB	IJ	2	0	0	-	No
4	Lateral	AB	IJ	1	0	0	-	No
5	Precurved	AB	Helix	1	0	0	-	No
6	Lateral	AB	IJ	1	0	1	Normal	Yes
7	Lateral	Cochlear	CI422	4	0	2	2	No
8	Lateral	Cochlear	CI422	3	0	1	3	Yes
9	Lateral	Cochlear	CI422	3	0	5	3	Yes
10	Lateral	Cochlear	CI422	2	0	2	3	Yes
11	Precurved	Cochlear	CI24RE-CA	2	0	3	1	Yes
12	Lateral	Cochlear	CI422	2	0	2	3	Yes
13	Lateral	Cochlear	CI24RE-ST	2	0	5	-	Yes
14	Precurved	Cochlear	CI24RE-CA	1	0	0	1	Yes
15	Precurved	Cochlear	CI24RE-CA	1	0	2	-	Yes
16	Lateral	Cochlear	CI422	1	0	1	Normal	Yes
17	Lateral	Cochlear	CI24RE-ST	5	5	5	5	Yes
18	Lateral	Cochlear	CI422	1	0	2	Normal	Yes
19	Lateral	MED-EL	Standard	5	2	5	4	Yes
20	Lateral	MED-EL	Standard	5	2	3	3	No
21	Lateral	MED-EL	Flex 28	4	0	0	Normal	No
22	Lateral	MED-EL	Flex 28	3	1	3	3	Yes
23	Lateral	MED-EL	Standard	3	1	3	-	Yes
24	Lateral	MED-EL	Standard	3	0	0	-	No
25	Lateral	MED-EL	Standard	3	0	2	Normal	No
26	Lateral	MED-EL	Flex 24	3	2	4	-	Yes
27	Lateral	MED-EL	Flex 28	2	1	3	-	Yes
28	Lateral	MED-EL	Standard	2	0	3	-	Yes
29	Lateral	MED-EL	Flex 28	2	0	1	Normal	No
30	Lateral	MED-EL	Flex 28	2	2	2	2	Yes
31	Lateral	MED-EL	Flex 28	1	0	1	Normal	Yes
32	Lateral	MED-EL	Flex 28	1	0	3	Normal	Yes
33	Lateral	MED-EL	Flex 24	1	0	1	1	Yes
34	Lateral	MED-EL	Standard	1	0	0	-	No
35	Lateral	MED-EL	Flex 28	1	0	1	-	Yes
Total # of electrodes				35	2	21	9	23