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How well do cochlear implant intraoperative impedance measures predict postoperative electrode function?

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Abstract

Objective—Objectives were to: 1) evaluate the incidence of abnormal cochlear implant electrode impedance intraoperatively and at the initial activation, 2) identify the percentage of abnormalities that resolve by the initial activation, and 3) determine the incidence of normal intraoperative impedances that present as abnormal at the initial activation.

Study Design—Retrospective records review of intraoperative and postoperative cochlear implant electrode impedances.

Setting—Tertiary referral center.

Patients—Records were examined for 194 devices implanted in 165 pediatric and adult patients.

Results—Results indicate at least 1 open (OC) or short circuit (SC) in 12.4% (24/194) of devices intraoperatively, decreasing to 8.2% (16/194) postoperatively. OCs were more prevalent than SCs for intraoperative (92% vs. 8%) and postoperative (94% vs. 6%) intervals. Of the 3430 total electrodes, 78 had abnormal impedance intraoperatively. Sixty-four of those (82%) resolved by the postoperative interval (62 OC, 2 SC) while 14/78 (18%) remained abnormal postoperatively (12 OC, 2 SC). Six of 3430 (0.17%) electrodes had normal impedance intraoperatively but were abnormal postoperatively.

Conclusions—The incidence of SCs in the present study is likely underestimated due to poor sensitivity of monopolar coupling for detecting SCs. Intraoperative OCs have a high probability of resolving by the initial activation, particularly when contiguous electrodes are affected, and suggests limited need for the use of a backup device in these cases. Surgical technique and/or complications such as explant/reimplant or perilymphatic gushers may result in increased incidence of bubbles in the cochlea, and may play a role in abnormal intraoperative impedance results.

INTRODUCTION

Cochlear implantation is largely considered successful based on the device's ability to reliably send electrical signals to the auditory nerve fibers. Device and individual electrode function is often assessed at intraoperative and postoperative intervals as part of clinical

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Conflicts of Interest

No conflicts of interest are declared for any author.

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management of the patient. A common objective measure used to assess device and electrode function is impedance (a measure of the resistance to current flow). Impedance measures are affected by the electrode-tissue interface, resistivity in the fluid/tissue medium, and resistivity of the electrode contact and lead wires (1). It is not uncommon to encounter impedance abnormalities such as short (SC) or open circuits (OC) at the intraoperative or postoperative time periods. These abnormalities can negatively affect patient performance with the device and should be identified as soon as possible for proper clinical management.

Commercial cochlear implant (CI) software makes it relatively easy to identify OC and SC. The definition of OC and SC differs slightly across manufacturers; however, a SC is characterized by low impedance (~1 kilohm or less) and an OC is very high impedance (usually >20-30 kilohms). The prevalence of SC or OC among CI recipients is not well documented. While manufacturers monitor failure modes for explanted devices, individual electrode abnormalities are usually not cause for explant. Therefore, abnormalities are often managed clinically by disabling electrodes from speech-processor programs, making it difficult for device manufacturers to track and report this information.

Research has indicated that the incidence of devices having at least 1 OC or SC postoperatively ranges from approximately 9% to 19.7% (2-5). The literature regarding the incidence of abnormal impedances identified at the time of surgery appears more limited. Schulman (6) identified 8.8% (14/160) patients with Clarion devices having abnormally high intraoperative impedances that all resolved by the initial activation. It was assumed that the abnormalities were caused by air bubbles, which resolved during the time between surgery and activation. Garnham et al. (7) identified 10% (15/149) of Cochlear devices with abnormal impedance values at the time of surgery; however it was unclear from their report how many of those resolved postoperatively. Finally, Carlson et al. (2) noted that 57.9% of postoperative abnormalities were also present intraoperatively, but did not delineate the incidence of SC or OC at specific time intervals. Both of the latter studies reported that some abnormalities resolved from the time of surgery to initial activation, whereas others remained. Thus, it is not clear what percentage of intraoperative abnormal electrode impedances resolve by the time of the initial activation, which makes it difficult to make decisions about whether the back-up device should be used during the surgical procedure.

The goals of the current study were to: 1) evaluate the incidence of abnormal electrodes at the intraoperative and initial-activation postoperative periods, 2) to assess the likelihood that intraoperative electrode abnormalities will spontaneously resolve by the initial activation, and (3) to assess the incidence of normal intraoperative measures that present as abnormal by the initial activation. Clinicians may utilize this information to guide decisions regarding whether or not to explant and reimplant with the back-up device during the initial surgical procedure, or to leave the device *in situ* with the expectation that the abnormal impedance(s) have a high likelihood of spontaneously resolving. The outcome of this decision could impact financial costs to the institution and device manufacturers as well as possible surgical risks to the patient. This topic has received little attention in the literature, thus empirical evidence for making these types of clinical decisions is warranted.

MATERIALS AND METHODS

A retrospective analysis of impedance data from 303 CI surgeries occurring from 2004 to 2011 at Boys Town National Research Hospital (BTRNH) was conducted. Intraoperative and postoperative impedance values were available for 194 devices in 165 pediatric and adult patients. Data were collected using the BTRNH Cochlear Implant Database, electronic patient records from the manufacturers' clinical CI software, and/or the audiologist's intraoperative and postoperative reports. This study was determined as exempt by the

BTNRH Institutional Review Board (protocol 10-21-X). Data were obtained for: 25 Nucleus 24RE(CA) Freedom (Cochlear Ltd., Macquarie, NSW, Australia) devices, 1 Nucleus 24RE(ST), 31 Nucleus CI512, 122 Advanced Bionics (AB) 90K HiFocus 1J (AB, Sylmar, CA, USA), 11 AB 90K Helix, 3 Med-El SONATATI¹⁰⁰ Standard Array (SA; Med-El, Innsbruck, Austria), and 1 Med-El SONATATI¹⁰⁰ Compressed Array (CA). The mean age of patients was 19 years, 5 months (range: 10 months to 86 years, 5 months). Study demographic information is further detailed in Table 1. Etiology of deafness ranged from genetic (24%), congenital-unknown (21%), progressive-unknown (15%), meningitis (8.4%), syndromic (including Usher, Donnai-Barrow, Waardenburg, Pendred, and CHARGE syndromes; 9.8%), auditory neuropathy spectrum disorder (5.7%), ototoxicity (5.7%), cytomegalovirus (4%), enlarged vestibular aqueduct syndrome (3.2%), sudden sensorineural hearing loss (1.6%), meniere's disease (0.8%), and diabetes (0.8%).

CI surgeries were performed by 3 surgeons; 1 implanted all 3 manufacturers, while 2 implanted only AB devices. A variety of surgical techniques were used; more recent approaches included the use of a small post-auricular incision, anchoring the implant by suturing the periosteum to bone, and a cochleostomy positioned inferior and anterior to the round window. Facial nerve monitoring was performed for all surgeries and steps to minimize trauma to the cochlea were used as much as possible (e.g., minimal drilling and suctioning around the cochlea, slow atraumatic insertion, careful packing of soft tissue).

Intraoperative impedances were measured on all electrodes during closure of the incision and before electrically evoked compound action potential measurements. Impedances were measured using the manufacturers' default modes: common ground (CG) and all 3 monopolar modes (MP1, MP2, or MP1+2) for Cochlear devices, and monopolar for AB and MED-EL devices. Because monopolar was the only test mode common to all 3 manufacturers, it was the only mode examined in the present study (MP2 was used for Cochlear devices). Monopolar, CG, and bipolar modes can identify OCs with high accuracy; however, monopolar mode typically does not accurately identify SCs (3). For devices that only have the capability of measuring impedance in monopolar mode (Advanced Bionics and Med-El), additional tools such as electrical field imaging (EFI; Advanced Bionics) or voltage tables (MED-EL) are used "behind the scenes" in newer versions of the software to identify SCs. With these additional tools, a single intracochlear electrode is stimulated and the voltage is measured at all electrodes. If 2 intracochlear electrodes are shorted together, a lower voltage will be measured at both shorted electrodes. For AB devices, this feature was not available prior to SoundWave v.1.4.

Post-operative impedances were measured at the beginning of the initial-activation appointment, before any electrophysiological or behavioral measures were obtained. On average, the initial activation occurred 14 days (range: 2 to 46 days) after the surgical procedure. In the event that multiple impedance measures were collected for a single patient at the intraoperative or postoperative intervals, the first measurement from each interval was used for analysis in order to maintain consistency across recipients and to control for effects of repeated electrode stimulation, which results in lower impedance (8-9). Intraoperative measures were made with a clinic speech processor, whereas the post-operative measures were made with the patient's processor.

RESULTS

Table 1 displays the incidence of abnormal monopolar impedance values per device for intraoperative and postoperative intervals. The total incidence of devices with at least 1 electrode with abnormal impedance (OC/SC) across all 3 manufacturers at the intraoperative period was 12.4% (24/194 devices); 92% (22/24) of abnormalities were OCs while 8%

(2/24) were SCs. Postoperatively, 8.2% (16/194) of devices presented with at least 1 abnormal impedance value, 94% (15/16) were OCs and 6% (1/16) were SCs.

The single Med-El ^{SONATATI}100 CA had 1 OC intraoperatively; therefore, given the small sample size, the incidence of intra-operative OCs for this device was 100%. This OC resolved by the initial postoperative visit. If the Med-El CA is excluded, the AB 90K 1J had the highest incidence of intra-operative OCs per device type with 13.1% (16/122), followed by the AB 90K Helix with 9% (1/11). At the postoperative interval, 8.2% (10/122) of 90K 1J devices had remaining OCs while 9% (1/11) of 90K Helix devices had OCs. The 90K Helix had the highest incidence of intra-operative (18.2%) and postoperative (9%) SCs. SCs were not found for any of the other devices tested. For the Nucleus 24RE(CA) and CI512 devices, 8% (2/25) and 6.5% (2/31) of devices had at least 1 OC at the intraoperative period, with the same incidence remaining postoperatively for both devices. The single Nucleus 24RE(ST) did not have any OCs or SCs for intraoperative or postoperative intervals, nor did the 3 MED-EL ^{SONATATI}100 SA devices.

Figure 1 shows the incidence of abnormal values across devices according to electrode number for the intraoperative (top) and postoperative (bottom) periods. Intraoperative data for AB devices (N = 133 devices, 2128 electrodes) showed that basal electrodes 12, 13, and 14 had the highest incidence of intraoperative OCs, with each electrode having a total of 7 OCs. AB electrodes 11, 12, 14, and 15 each had 1 occurrence of an intraoperative SC (recipients H2 and H6). Postoperatively, basal electrode 15 had the highest number of abnormalities with 3 OCs and 1 SC. Only electrodes 14 and 15 remained shorted together postoperatively in a single AB subject. In sum, 3.4% (72/2128) of all AB electrodes had abnormal impedance intraoperatively, and 0.7% of electrodes (15/2128) were abnormal postoperatively. For Cochlear devices (N = 57 devices, 1254 electrodes), electrode 14 (mid-apical region) had a total of 2 OCs for both intraoperative and postoperative time intervals. Basal electrode 1 and apical electrodes 17 and 20 had only 1 intraoperative and postoperative OC. In sum, 0.4% (5/1254) of all Cochlear electrodes had abnormal impedance both intraoperatively and postoperatively. For Med-El (N = 4 devices, 48 electrodes), only basal electrode 12 contained an OC for the intraoperative interval (representing 2.1% of all electrodes); none of the Med-El devices contained postoperative electrode abnormalities.

Table 2 details the abnormal electrodes identified by subject number for the intraoperative and postoperative intervals. Across all 3 manufacturers, results indicate a total of 78/3430 (2.3%) electrodes with abnormal intraoperative impedances. Of these, 74/78 (95%) had OCs and 4/78 (5%) had SCs. Postoperatively, 20/3430 (0.5%) electrodes were abnormal, with 18/20 (90%) OCs and 2/20 (10%) SCs. Of the 78 electrodes with abnormal intraoperative impedance, 64 (82%) resolved from the intraoperative to postoperative interval (62 OC, 2 SC), whereas 14/78 (18%) of the abnormalities remained abnormal postoperatively (12 OC, 2 SC). Six (0.17%) electrodes with normal intraoperative impedance presented as abnormal postoperatively (all OC). Subject J89 (AB 90K 1J) had the highest incidence of intraoperative abnormalities with 11 total OCs (electrodes 5-15), which all resolved postoperatively. Similarly, recipients J22, J82, J87, and J106 had 8-9 intraoperative OCs on several nearly-consecutive electrodes which all resolved postoperatively except for an OC on electrode 15 for J22.

The categorization (normal versus abnormal) for intraoperative and postoperative impedances for the 3430 electrodes is shown in Table 3. The majority of electrodes (3346/3430 or 97.5%) had normal impedance both intraoperatively and postoperatively. Only 6 electrodes (0.17%) had normal impedance intraoperatively and abnormal measures postoperatively. In contrast, 1.9% (64/3430) of electrodes had abnormal intraoperative

impedance and normal measures postoperatively. Finally, the incidence of an electrode having an abnormal value for both the intraoperative and postoperative periods was 0.41% (14/3430).

DISCUSSION

In the present study, the total incidence of devices with at least 1 abnormal electrode impedance value was 12.4% and 8.2% at the intraoperative and postoperative intervals, respectively. These results are slightly higher than those reported by Neault et al. (5), who found intraoperative electrode abnormalities in approximately 10% of devices, decreasing to 5.5% postoperatively when measured across the initial-activation to 12-month intervals. In the present study, OCs were more prevalent than SCs for both intraoperative (95% vs. 5%, respectively) and postoperative (90% vs. 10%) intervals across all device manufacturers. For postoperative intervals, Carlson et al. (2) also reported a higher incidence of OCs (63.2%) compared to SCs and alternating (partial) SCs (37%); Neault et al. (5) reported that OCs were more prevalent (55%) in their cohort of patients, followed by short circuits (43%). However, it is possible that the incidence of SCs in the present study was underestimated because of the limited capability of older devices and software to detect a SC in monopolar mode (i.e., for AB devices, prior to implementation of SoundWave v.1.4 in 2006). Recall that SCs are typically not accurately identified with monopolar stimulation (3). For the Cochlear devices in the present study, CG impedances were examined (which more reliably identifies SCs), and none of those devices presented with SCs. Because we cannot know the exact reason for open or short circuits without explanting a device for analysis, we can only speculate regarding why differences existed for the intraoperative and postoperative intervals. Clearly, this is a limitation of the present study.

The AB 90K 1J device had the highest percentage of intraoperative and postoperative abnormalities compared to the other devices analyzed (excluding the Med-El CA due to the small sample size; Table 1). The 90K 1J device was more susceptible to transient high impedance values. Given that most resolved postoperatively (Table 2, 82%), these high impedances were presumed to be caused by air bubbles introduced during the electrode insertion. One possible contributing factor may have been a “delayed insertion” technique used for some of the earlier AB procedures, in which the cochleostomy was drilled at the beginning of the procedure, followed by suturing the implant prior to the actual insertion of the array. This sequence may have resulted in loss of cochlear perilymph, and thus a greater number of electrode abnormalities due to the introduction of air bubbles. From the present records review, limited information was available to determine which patients this technique was explicitly used for; therefore, this technique alone cannot be linked to the occurrence of multiple OCs on an individual basis. Another possible explanation may be attributed to the design of the HiFocus electrode array, in which the electrode contacts are recessed relative to the silicone carrier. This slight recession may increase the incidence of air bubbles upon insertion.

In the present study, approximately half of the total recipients (15/29) with impedance abnormalities had a complicating factor that likely increased the incidence or risk of electrode abnormalities. For example, 13/19 (68%) of the AB recipients had intraoperative complicating factors such as: explant/re-implant (J22, J93, J82, J112, H6), perilymphatic gusher (J37), delayed insertion as described above (J36, J89), reloading of the array (J14, J15, J67), or ossified cochlea (J87). The surgery for recipient H6, who had intraoperative and postoperative SCs on electrodes 14 and 15, was a revision in which a positioner was left in place and a full insertion of the new device was reported. No surgical complications were reported for recipient H10, who had intra-operative SCs on electrodes 11 and 12 that resolved postoperatively.

Cochlear Corp. devices had a lower incidence of abnormal impedance values for intraoperative and postoperative periods compared to AB; however, all Cochlear abnormalities that were identified during the intraoperative interval remained abnormal postoperatively. For the 4 recipients with abnormalities, 2 had no surgical complications (F7, F10), 1 underwent an explant/re-implant (N2), and 1 had Mondini dysplasia with a perilymphatic gusher (N36). The presence of air bubbles affecting several intraoperative electrodes was essentially not an issue with the Cochlear devices. For the single MED-EL recipient with the OC (on basal electrode 12), the 3 most basal electrodes were reported as positioned outside of the cochlea (due to ossification secondary to meningitis); upon initial-activation the impedance for this electrode (as well as the other 2) was normal.

Electrode abnormalities were more common along the basal end of the array in AB and MED-EL devices; while abnormalities in Cochlear devices were more common along the middle to apical portion of the array. According to a study by Mason (10), high impedances on a few basal electrodes in Cochlear devices was likely the result of a dry electrode or air bubble, which did not raise significant concerns or warrant the use of a back-up device. The present study identified only 1 OC at the basal end of the array across all Cochlear devices (recipient N2). This was an explant/re-implant case and a full insertion was obtained. The OC remained for the intraoperative and postoperative periods.

The present study also identified 6 incidences (0.17%) of electrode abnormalities at the postoperative evaluation that presented as normal during the intraoperative measure (recipients J5, J7, J21, J39, and 2 electrodes for J42; AB 90K 1J devices only). Further analysis of these recipients revealed that all OCs resolved after repeated impedance or conditioning runs at the initial-activation appointment (J7, J21, J39, J42) or on the second day of initial activation (J5). Device activation occurred 8-10 days after surgery for all recipients except for J42, which was 37 days postoperatively. Recall that the first intraoperative and postoperative impedance measure was used for analysis to maintain a standard across all recipients. Oftentimes, repeating impedance measures or using electrode conditioning may help to reduce high impedance measures, which are typically classified as an OC. This is a technique that clinicians should utilize in the presence of intraoperative or postoperative electrode abnormalities, particularly OCs. Analysis of these cases did not reveal any complications that would have increased the likelihood of observing an OC at the initial-activation. Given that this finding is not common (0.17%), we speculate that the OCs at initial-activation may have been caused by air bubbles located within the cochlea, but not at the electrode-tissue interface (e.g., between electrode contacts). It is possible that the air bubbles subsequently shifted to the surface of the electrode contact after the intraoperative testing was completed, resulting in postoperative OCs. Once electrical stimulation was introduced at the initial stimulation, the air bubble(s) resolved.

Study results reveal that the presence of OCs and SCs remains fairly low for the intraoperative interval and even lower for the initial-activation postoperative interval. Additionally, there was high reliability for intraoperative impedance measures given that 98% (3360/3430) of electrodes maintained the same categorization (normal vs. abnormal) from the intraoperative to initial-activation interval. Only 2% (70/3430) of electrodes had a different categorization from the intraoperative to postoperative interval. The majority of these were likely due to air bubbles introduced during the surgical procedure, resulting in 64/78 (82%) abnormalities that resolved from the intraoperative to postoperative interval.

During the 7-year time span investigated for this study, the back-up device was used only 1 time due to device-related concerns. This occurred in the case of a pediatric patient implanted with a CI512 device. An OC was identified on the extracochlear MP2 ground electrode that could not be resolved during the surgical procedure. Cochlear Ltd. reported

that <0.3% of CI512 devices implanted as of June 2011 had an OC on MP2 (11). Although the presence of an OC on MP2 should not alter the hearing performance of a recipient, it could hinder NRT recordings. The Cochlear Update recommends the surgeon use his/her own judgment regarding whether to use the back-up device in this situation (11). It was the decision at this center to use the back-up device given the young age of the patient, expected limitations in obtaining accurate behavioral feedback for processor programming, and subsequent increased need for objective measures to guide programming. Following the completion of this study in 2012, we experienced a second case in which an open circuit was identified on MP2 during the surgical procedure without resolution (this time in a Freedom device). This was a pediatric patient undergoing a revision due to a failed device; therefore, given the young age of the patient and prior failed device, the back-up device was used.

Results from this study show that it is rare for a high number of intraoperative OCs to remain at the postoperative interval. Across all devices, no more than 2 OCs or SCs remained at the postoperative appointment (Table 2). This finding is consistent with that of Neault et al. (5) who reported only 3 devices with more than 2 OCs, and no more than 2 pairs of SCs in any particular device at the postoperative period in their analysis of 508 pediatric cases. Taken together, these findings have important clinical implications for use of the backup device intraoperatively. Garnham et al. (7) reported using the backup device when as few as 1-2 electrodes presented as abnormal, and that in slightly less than half of those cases, the explant report from the manufacturer showed no abnormalities in the device. Findings from the present study suggest that use of the backup device on the basis of a few abnormal impedance measures may not be warranted. In the event that a clinician experiences a large number of OCs during the intraoperative assessment of the device, he or she can be fairly confident that these values will resolve by the time of the initial-activation appointment (6). The exception would be if OCs are obtained for all intracochlear electrodes; this would likely indicate an OC on the monopolar ground electrode. Intraoperative impedance results that may prompt using the back-up device would include the presence of multiple SCs (given the low incidence of SCs identified in this study and in the previous literature), or an OC on a monopolar ground electrode. Finally, surgical technique and/or complications may increase the likelihood of intraoperative impedance abnormalities.

Despite the overall low incidence of abnormal impedance intraoperatively and the high incidence of resolution postoperatively, we believe that intraoperative impedance testing still has significant clinical value. Intraoperative device testing can provide peace of mind for families and clinicians to know immediately that the device is functioning appropriately. It also provides clinicians with advance notice of potential issues that may need to be managed postoperatively. Finally, intraoperative testing provides a baseline for device function over time. Given the multi-faceted nature of performance among CI recipients, it is therefore important to monitor electrode impedance during the intraoperative procedure and at regular postoperative appointments.

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Figure 1.

The incidence of open and short circuits across AB (left column), Cochlear (middle), and MED-EL (right) devices according to electrode number for the intraoperative (top) and initial-activation postoperative (bottom) intervals. Data are arranged by electrode number from apex to base along the x-axis. Data reflect results for monopolar testing (re: MP2 for Cochlear devices).

Table 1

Study demographics and incidence of abnormal monopolar impedance values per device for intraoperative and postoperative evaluations (MP2 is reported for Cochlear).

Device Type	Total Number	Avg age at CI y,m (range)	Intraoperative		Postoperative	
			# Devices with OC	# Devices with SC	# Devices with OC	# Devices with SC
AB 90K HiFocus IJ	122	15,7 (0,10 - 86,5)	16 (13,1%)	0 (0%)	10 (8,2%)	0 (0%)
AB 90K Helix	11	5,0 (1,2 - 21,3)	1 (9,0%)	2 (18,2%)	1 (9,0%)	1 (9,0%)
Cochlear 24RE (CA)	25	24,7 (0,11 - 83,8)	2 (8,0%)	0 (0%)	2 (8,0%)	0 (0%)
Cochlear 24RE (ST)	1	0,11 (N/A)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Cochlear CI512	31	11,5 (0,11 - 84,9)	2 (6,5%)	0 (0%)	2 (6,5%)	0 (0%)
MED-EL SONATA T1 ¹⁰⁰ SA	3	48,6 (0,11 - 74,4)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
MED-EL SONATA T1 ¹⁰⁰ CA	1	0,11 (N/A)	1 (100%)	0 (0%)	0 (0%)	0 (0%)
Total	194	19,5 (0,10 - 86,5)	22 (11,3%)	2 (1,0%)	15 (7,7%)	1 (0,5%)

OC = open circuit; SC = short circuit; y, m = years, months; AB = Advanced Bionics; SA = standard array; CA = Compressed Array

Table 2

Summary of recipients with abnormal electrode impedances in monopolar mode (re: MP2 for Cochlear devices).

Intraoperative		Postoperative	
Recipient	Abnormal electrodes	Recipient	Abnormal electrodes
J5		J5	2 ^o
J7		J7	15 ^o
J8	1 ^o	J8	1 ^o
J12	16 ^o	J12	
J14	13 ^o , 14 ^o , 15 ^o	J14	
J15	13 ^o	J15	13 ^o
J21		J21	4 ^o
J22	1 ^o , 2 ^o , 3 ^o , 4 ^o , 5 ^o , 9 ^o , 10 ^o , 12 ^o , 15 ^o	J22	15 ^o
J36	15 ^o , 16 ^o	J36	16 ^o
J37	7 ^o , 10 ^o , 11 ^o , 12 ^o	J37	
J39		J39	1 ^o
J42		J42	2 ^o , 15 ^o
J66	7 ^o	J66	7 ^o
J67	11 ^o , 12 ^o , 13 ^o , 14 ^o	J67	
J82	3 ^o , 4 ^o , 7 ^o , 8 ^o , 12 ^o , 13 ^o , 14 ^o , 15 ^o , 16 ^o	J82	
J87	8 ^o , 10 ^o , 11 ^o , 12 ^o , 13 ^o , 14 ^o , 15 ^o , 16 ^o	J87	
J89	5 ^o , 6 ^o , 7 ^o , 8 ^o , 9 ^o , 10 ^o , 11 ^o , 12 ^o , 13 ^o , 14 ^o , 15 ^o	J89	
J93	6 ^o	J93	
J106	5 ^o , 6 ^o , 7 ^o , 8 ^o , 9 ^o , 10 ^o , 11 ^o , 12 ^o , 13 ^o	J106	
J110	16 ^o	J110	
J112	14 ^o	J112	
H2	7 ^o , 14 ^o	H2	7 ^o , 14 ^o
H6	14 ^s , 15 ^s	H6	14 ^s , 15 ^s
H10	11 ^s , 12 ^s	H10	
F7	14 ^o	F7	14 ^o
F10	17 ^o , 20 ^o	F10	17 ^o , 20 ^o
N2	1 ^o	N2	1 ^o

Intraoperative		Postoperative	
Recipient	Abnormal electrodes	Recipient	Abnormal electrodes
N36	14 ^{<i>o</i>}	N36	14 ^{<i>o</i>}
MC1	12 ^{<i>o</i>}	MC1	
Total = 29	74^{<i>o</i>}, 4^{<i>s</i>}		18^{<i>o</i>}, 2^{<i>s</i>}

J = AB 90k 1J; H = AB 90K Helix, F = Cochlear 24RE(CA) Freedom, N = Cochlear CI512; MC = Med-El Sonata Ti¹⁰⁰ Compressed Array

^{*o*} open circuit

^{*s*} short circuit

Table 3

Incidence of normal or abnormal impedance measures for intraoperative and postoperative test intervals using monopolar stimulation.

Total: 3430 electrodes	Postoperative	
Intraoperative	Normal	Abnormal
Normal	97.6% (N=3346)	0.17% (N=6)
Abnormal	1.9% (N=64)	0.41% (N=14)