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Results of post-operative, CT-based, electrode deactivation on hearing in pre-lingually deafened adult cochlear implant (CI) recipients

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INTRODUCTION

Despite extensive study, the only strong predictor of cochlear implant (CI) performance is length of auditory deprivation with shorter deprivation portending better performance [1–4]. The extreme of auditory deprivation is prelingual deafness in which an individual has never heard sound, and in such cases the literature supports implantation before a crucial neural imprinting period – thought to be before the age of 1.5 to 2 years – to optimize CI performance [5]. While extensive efforts are aimed at achieving this goal, some patients miss this window and present as prelingually-deafened adults for consideration of CI. This population represents a minority of CI candidates primarily due to universal newborn hearing screening (NBHS) which is likely to continue to improve our rates of early identification of sensorineural hearing loss. Despite the prevalence of NBHS and associated early identification and intervention, there will be patients with severe-to-profound hearing loss that do not pursue CI until adulthood. Underlying reasons for this delay may range from cultural, religious, and/or parental opposition.

Counseling of pre-lingually deafened patients regarding outcomes can be extremely difficult. Audiological results for pre-lingually deafened adults who receive CIs are highly variable with the only strong predictors of auditory-only performance being length of auditory deprivation. The impact of auditory deprivation may be dampened by use of oral communication when compared to total communication or sign communication [6,7]. Preoperative estimates of speech intelligibility [8] are thought to be related to mode of communication with oral communication portending better outcomes. Multiple studies conclude that pre-lingually deafened patients who present in their teenage years or older for CI will achieve minimal speech understanding without visual cues although high variability is observed [6–16]. This does not mean that CIs in this population are not useful. Dramatic

improvements in audibility and quality of life (QOL) can be demonstrated for this population [6,7,15]. However, most CI centers counsel realistic expectations consisting of primarily environmental sound awareness with meaningful auditory-only speech understanding being unlikely, though possible.

When treating a group in which wide variability in outcomes is expected, it is difficult to ascertain the point at which maximal benefit has been achieved. For pre-lingually deafened patients who present for CI after childhood, much effort is spent trying to optimize performance. Various methods have been employed, most of which rely upon “trial and error” iteration with subjective feedback guiding future iterations. Recently, the use of imaging has been proposed as a means of providing customized maps based on the geometric relationship between the final post-operative location of the CI electrode and the neural endings contained within the modiolus [17,18]. An initial implementation of image-guided CI programming (IGCIP) includes deactivation of sub-optimally placed electrodes in an effort to provide a clearer signal. This is based on the concept of reducing channel interaction which occurs when more than one electrode stimulates the same neural region resulting in a “smearing” of the signal and poorer speech understanding especially in noisy environments [19,20,21]. Early results with IGCIP have led to statistically significant improvement in audiological performance in post-lingually deafened adult CI recipients [17,18]. Thus we hypothesized that this technique may also improve speech understanding and sound quality for pre-lingually deafened adult CI recipients who communicate with listening and spoken language.

METHODS

As described previously [17], clinically-applicable post-operative computerized tomography (CT) scans of CI recipients are subject to image processing techniques to determine the position of CI electrodes relative to the modiolus. Processing consists of first using a cochlear atlas constructed from μ CTs of 10 cochlear specimens to predict the location of intracochlear anatomy not visible in clinical CT scans including the basilar membrane and the modiolus. To accomplish this first step of processing, the cadaveric atlas is rigidly and non-rigidly linked to the clinical CT scan using either the inner cochlear wall (i.e. the bone-fluid interface between the promontory and cochlear scalae) [22,23,24] or the inner semicircular canal walls as the constant anatomic feature visible in both the atlas and CT scan [25,26]. Next, electrode location is determined using automatic and semi-automatic procedures we have previously developed for Cochlear Contour Advance electrodes [27] and for all other electrodes [28]. The output of this processing is geometric knowledge of the distance from each electrode in the array to the tonotopically mapped modiolus, which can be presented graphically as shown in Figure 1.

To date, use of this information to make programming changes for CI recipients has focused on deactivating sub-optimally positioned electrodes [17,18]. More specifically, our hypothesis is that interference occurs when neighboring electrodes stimulate overlapping regions of the modiolus causing a blurred rather than a clear signal [19,20,21]. Thus, our strategy is to deactivate electrodes whose adjacent electrodes are closer to the modiolus thereby providing more effective coverage of the intended stimulation region. A minimum

of 8 electrodes were kept active as research has shown that a minimum of 4–8 electrodes are necessary for effective coverage of the frequency spectrum for speech understanding with adult listeners [29,30]. In the example shown in Figure 1, our algorithms recommend turning off electrodes 6, 8, 10, 11, 13, and 15. These changes are made by an audiologist using standard CI programming software. After deactivation, the software remaps the sound spectrum to the remaining active electrodes with stimulation speed adjusted to account for the deactivated electrodes (i.e. overall stimulation speed remains constant). Manufacturer specific alterations with programming are noted in the footnote below.¹ We have used this technique, which we call image-guided cochlear implant programming (IGCIP), on over 100 patients and have reported long-term results in 68 post-lingually deafened adult CI recipients of whom 78% of the 68 recipients (72 ears) favored and kept the IGCIP for routine use [18]. This remarkable response prompted the current study of pre-lingually deafened adult CI recipients.

Vanderbilt Institutional Review Board protocols were in place to screen and offer IGCIP to CI recipients. Patients were recruited from both the large cohort of CI recipients at our Institution, from collaborating Institutions, and from individuals who contacted our Institution requesting IGCIP. All patients were consented at Vanderbilt. Pre-lingually deafened patients (defined for this study as being > 6 years of age at time of CI) who were between 18 and 80 years of age at the time of testing were invited to participate in the study. Patients were reimbursed for their travel and time of participation at standard rates. At the time of potential enrollment, CI recipients had used a traditional map for at least 6 months after activation and had been considered by an expert audiologist to have achieved the best hearing performance possible with traditional CI programming. For CI recipients expressing interest in IGCIP, the study requirements were described in detail and informed consent obtained. Following baseline testing, the participant's CI was reprogrammed with IGCIP. So that performance with a new program could be measured in a semi-chronic condition, each subject returned for retesting 3–6 weeks following IGCIP reprogramming. During this 3- to 6-week period, each subject was asked to listen as they normally would; however, they were only provided with the new map so as to require compliance with full time use of IGCIP. While datalogging was not widely-available during the course of this study, all participants reported full time usage of their CI during waking hours.

¹For participants with Advanced Bionics (AB) implants, prior to deactivating the selected electrodes in the clinical software, we removed Fidelity120 processing (i.e. current steering) to allow selective deactivation of electrodes without deleting a viable electrode in the 'pair'. For individuals making use of ClearVoice prior to study enrollment, removal of Fidelity120 required deactivation of ClearVoice as well. We were careful to ensure that the resultant channel stimulation rate was within 400 pulses per second (pps) of the participant's beginning rate with Fidelity120. Stimulation rates for all AB recipients remained above 1,500 pps even after removing Fidelity120. For participants with MED-EL implants, we kept the participant's strategy consistent (high definition CIS or fine structure processing) and fixed the stimulation rate manually to that which was used in the patient's own map. All participants with Cochlear Corporation implants used an advanced combination encoder programming strategy. For these participants, after deactivating the selected electrodes, if the participant had 12 or fewer active electrodes in their map, we set the number of maxima equivalent to the number of active electrodes, thereby converting to a CIS program. For participants with more than 12 active electrodes in their experimental map, we kept the maxima consistent with what was used in the patient's own map which ranged from 8 to 12 maxima. Channel stimulation rate and pulse width were unaltered. For all implant recipients, regardless of implant manufacturer, manipulation of M/C or T levels of individual electrodes was not performed. For patients reporting significantly 'softer' or less frequently 'louder' programs following selective electrode deactivation, we would globally increase or decrease M/C levels to the participant's desired overall volume.

At baseline and after using IGCIP for 3–6 weeks, participants underwent audiological assessment with the adult Minimum Speech Test Battery (MSTB) [31], SMD testing, and QOL testing. Estimates of spectral resolution were obtained using the quick spectral modulation detection (SMD) task [32]. SMD is a non-speech-based hearing performance metric that provides a psychoacoustic estimate of spectral resolution, i.e. the ability of the auditory system to decompose a complex spectral stimulus into its individual frequency components [33–37]. To measure performance qualitatively, participants completed the Abbreviated Profile of Hearing Aid Benefit (APHAB) [38] as well as the Speech, Spatial and Qualities of Hearing Scale (SSQ) [39]. All auditory stimuli were presented at a calibrated presentation level of 60 dBA using a single loudspeaker presented at 0° azimuth at a distance of 1 m. After follow-up testing, patients were allowed to select either their original map of IGCIP as their preferred everyday map. Study data were collected and managed using the REDCap (Research Electronic Data Capture) secure data management tools hosted at Vanderbilt [40]. Patients' pre and post data was compared using paired t-tests. Additionally, data were plotted and deemed significant if the change for an individual fell outside the 95th percentile confidence intervals.

RESULTS

Twenty-six prelingually deafened adults who underwent IGCIP were identified within our IGCIP database. Of these 26, 3 had bilateral CIs and elected to have IGCIP performed on each side sequentially with each ear being considered a separate and distinct data point resulting in 29 subjects. Average length of deafness, i.e. birth to date of CI, was 35.85 ± 16.20 years (median 38.61, range 7.93 – 69.31). The study population consisted of 15 Cochlear, 10 Advanced Bionics (AB), and 4 MED-EL recipients. Prior to IGCIP, 13 patients had electrodes deactivated for reasons including sound quality, open circuit, and non-auditory stimulation with 1, 2, or 3 electrodes typically deactivated although one recipient had the 9 most distal electrodes of a Cochlear device deactivated due to vibrotactile stimulation. IGCIP deactivated on average $33.9\% \pm 0.1\%$ electrodes (median 36.4%, mode 50%, range 4.5 – 55.5%). For the 10 AB recipients, the following number of electrodes was deactivated: 2, 2, 4, 5, 6, 6, 7, 7, 8, and 8 (average $\pm$ standard deviation, 5.5 ± 2.2). For the 15 Cochlear recipients, the following number of electrodes was deactivated: 1, 4, 6, 7, 7, 7, 8, 8, 9, 9, 11, 11, 12, 12, and 12 (average $\pm$ standard deviation, 8.3 ± 3.2). For the 4 MED-EL recipients, the following number of electrodes was deactivated: 2, 2, 2, and 3 (average $\pm$ standard deviation, 2.3 ± 0.5). Figure 2 shows histograms of frequency of deactivation of individual electrodes for each implant type. No pattern could be identified regarding electrode location and likelihood of deactivation.

Grouped data are summarized in Table I – audiological performance both before and after IGCIP – and Table II – QOL measure before and after IGCIP. The only statistically significant difference noted was that for SMD at 0.5 cycles/octave. A trend towards significance ($0.05 < p < 0.10$) was noted for SMD at 1.0 cycles/octave and APHAB Ease of Communication. Individual audiological data are shown in Figure 3 with 95% confidence intervals shown as the thin curves. In these figures, data points representing no change from baseline to IGCIP would lie on the diagonal, improvement would lie above the diagonal, and decline would lie below the diagonal. (The opposite relationship holds for the BKB-SIN

curve where decreases, values below the diagonal, represent an improvement.) Thus, statistically significant individual improvement for Consonant-Noun-consonant (CNC) words was noted for 4 subjects (noting that each side implanted is considered a “subject”), statistically significant decline noted in 3, and the remaining 22 were equivocal. For Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN), 2 subjects showed statistically significant improvement, 7 statistically significant decline, and 20 were equivocal. For AzBio sentence tests in Quiet, 6 subjects showed statistically significant improvement, 5 statistically significant decline, and 18 were equivocal. For AzBio +10 decibels (dB) signal-to-noise ratio (SNR), only 17 patients could perform the test at baseline. Of those 17, 3 demonstrated statistically significant improvement, 4 statistically significant decline, and 10 were equivocal. Figure 4 shows individual data from SMD testing for the 25 recipients who completed this test. For 1 cycle/octave, 15 subjects showed statistically significant improvement, 6 statistically significant decline, and 4 were equivocal. For 0.5 cycle/octave, 15 subjects showed statistically significant improvement, 4 statistically significant decline, and 4 were equivocal.

If patients made comments either directly after IGCIP or after the month long testing period, they were recorded and classified as positive (e.g. “That’s a lot clearer now.”), negative (e.g. “I don’t like it. Your voice sounds different.”), or equivocal (e.g. “It’s hard to tell if there is a difference.”). Acutely, 21 comments were recorded with 10 positive, 4 negative and 7 equivocal. At the end of the month long testing, 23 comments were recorded with 14 positive, 4 negative and 5 equivocal. Twenty-one of the 29 (72.4%) elected to keep the IGCIP map.

DISCUSSION

Pre-lingually deafened adults who receive CIs can be difficult to program as they have limited-to-no memory of auditory stimuli and have a difficult time conveying whether a CI map is better or worse in terms of audibility, sound quality, and/or speech understanding. Because of such difficulties, programming this population can be time consuming without much objective or subjective benefit noted for the effort. Strategies to help these and other patients help themselves program have resulted in self-guided map adjustments [41,42], although no published data have demonstrated significant improvements in audibility, speech understanding, sound quality, or any other subjective ratings using these in prelingually deafened CI populations.

Presented herein is the use of an objective, non-audiological measure – namely location of the CI electrode array in reference to the modiolus via post-operative CT scanning – to facilitate CI programming. Prior work has shown significant improvement in post-lingually deafened adults who underwent IGCIP [17,18]. Perhaps the largest difference between results found in the prior study was that improvement was noted across all test batteries – MSTB, SMD, and QOL – for post-lingually deafened adults. In the current study with pre-lingually deafened individuals, while some individuals had dramatic audiological improvement, e.g. a 28-percentage point improvement in CNC words and a 35-percentage point improvement in AzBio sentences, the only consistent improvement shown to be statistically significant at the group level was SMD, an estimate of spectral resolution.

Interestingly, similar percentages of both the prelingually deafened (72.4%) and postlingually deafened (78%) groups kept the IGCIP map for long-term use. It is this finding that is most intriguing given the different cortical processing that accompanies prelingual deafness in which neural decoupling within the auditory pathway is hypothesized to occur in the absence of an auditory signal [43]. This decoupling appears to not occur if the auditory pathway is stimulated via CI by before a critical age, thought to be 2 years of age [5, 44]. If early CI does not occur, as in our prelingually deafened cohort, it is hypothesized that cortical areas originally dedicated to auditory input acquire new functionality via cross-modal cortical reorganization [45–48].

What happens then when an auditory signal via CI is introduced after cortical reorganization as in pre-lingually deafened individuals who undergo CI as adults? First, it is likely that the level of neural decoupling and cortical reorganization is highly variable depending upon individual level of auditory deprivation, length of auditory deprivation, use of oral communication, and intelligence level. Second, it is likely that in pre-lingually deafened individuals who present as adults that the complex auditory pathways have been pruned to their bare minimum so that neural tissue can be utilized for other input. We hypothesize that the pared-down auditory signal offered by IGCIP presents a clearer signal with less interference between neighboring electrodes. This hypothesis is supported by the fact that the vast majority of the prelingually deafened patients showed improvement in the SMD – a test of the ability of the auditory system to decompose a complex spectral stimulus into its individual frequency components – but did not show similar improvement on auditory comprehension.

It is entirely possible, even likely, that the improvements in spectral resolution noted with the IGCIP mapping may take longer than 3 to 6 weeks for the prelingually deafened CI recipient in order to take full advantage of the improved spectral resolution and for those improvements to translate to better speech understanding. Implementation of IGCIP at initial activation may be optimal in presenting a clearer signal to a deprived auditory neural complex [49]. Another possibility is that SMD may not be related to speech understanding for pre-lingually deafened adults—at least not to the degree that has been shown for post-lingually deafened adults [32,37,50,51]. Both possibilities warrant further investigation.

Limitations of the current study include (i) lack of randomization (ii) lack of blinding of the programming audiologist and patient, and (iii) lack of a formal control group (e.g. randomly deactivated electrodes). Regarding (i) and (ii), we are embarking upon a blinded, randomized-controlled trial in post-lingually deafened adult CI recipients to address these concerns and plan to follow that with a similar study in pre-lingually deafened adult CI recipients. Additionally, while we acknowledge the potential bias which the audiologist and/or CI recipient may have being introduced to a new map which holds out the prospect of benefit, prior studies clearly demonstrate that there is strong bias towards not changing from a long-standing CI map [52]. The bias towards existing maps makes us interpret the 72.4% conversion rate to IGCIP as clinically significant. Regarding (iii), the concept of an appropriate control group is difficult to define in this setting as the image analysis specifies the number of electrodes to be deactivated. Without the *a priori* knowledge provided by the image analysis of how many electrodes are to be deactivated, what is considered random?

Randomly deactivating each electrode ensuring that 8 electrodes remain active? In our postlingually deafened adult cohort we have experimented acutely with “random” deactivation using successful IGCIP plans from other patients with similar electrode array types and have seen no benefit and high non-compliance with use of the map longer than a few days (unpublished data).

From a pragmatic standpoint, for the challenging prelingually deafened adult CI population, IGCIP offers a favorable risk-benefit ratio with the risks of IGCIP being the additional radiation dose from the post-operative CT scan and the benefit being better objective and/or subjective hearing. Regarding radiation exposure, we predominantly utilize a flat-panel volumetric computerized tomography machine which delivers a fraction of the radiation dose of traditional multi-slice CT scanners. Regarding benefit, if patients do not benefit either objectively or subjectively they can return to their prior map without sequelae. While IGCIP is not a panacea, it offers – for the first time – a logistically feasible way to utilize the geometric relationship between an individual’s CI electrode array and the neural interface to impact upon their CI map.

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References

1. Blamey P, Artieres F, Ba kent D, et al. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: an update with 2251 patients. *Audiol Neurol*. 2013; 18:36–47.
2. Friedland DR, Venick HS, Niparko JK. Choice of ear for cochlear implantation: the effect of history and residual hearing on predicted postoperative performance. *Otol Neurotol*. 2003; 24(4):582–9. [PubMed: 12851549]
3. Roditi RF, Poissant SF, Bero EM, Lee DJ. A predictive model of cochlear implant performance in postlingually deafened adults. *Otol Neurotol*. 2009; 30(4):449–54. [PubMed: 19415041]
4. Rubinstein JT, Parkinson WS, Tyler RS, Gantz BJ. Residual speech recognition and cochlear implant performance: effects of implantation criteria. *Am J Otol*. 20(4):445–52. 199. [PubMed: 10431885]
5. Sharma A, Gilley PM, Dorman MF, Baldwin R. Deprivation-induced cortical reorganization in children with cochlear implants. *Int J Audiol*. 2007; 46(9):494–9. [PubMed: 17828665]
6. Caposeco A, Hickson L, Pedley K. Cochlear implant outcomes in adults and adolescents with early-onset hearing loss. *Ear Hear*. 2012; 33:209–220. [PubMed: 21934504]
7. Kaplan DM, Shipp DB, Chen JM, et al. Early-deafened adult cochlear implant users: Assessment of outcomes. *J Otolaryngol*. 2003; 32:245–249. [PubMed: 14587565]
8. van Dijkhuizen JN, Beers M, Boermans PP, Braire JJ, Frijns JH. Speech Intelligibility as a Predictor of Cochlear Implant Outcome in Prelingually Deafened Adults. *Ear Hear*. 2011; 32:445–58. [PubMed: 21258238]
9. Manrique M, Cervera-Paz FJ, Huarte A, et al. Cerebral auditory plasticity and cochlear implants. *Int J Pediatr Otorhinolaryngol*. 1999; 49(Suppl 1):193–197.
10. Wong RK, Chung E, Hui Y, et al. Speech perception and production performance of prelingually deafened adolescents after cochlear implantation. *Adv Otorhinolaryngol*. 2000; 57:373–376. [PubMed: 11892193]

11. Schramm D, Fitzpatrick E, Seguin C. Cochlear implantation for adolescents and adults with prelinguistic deafness. *Otol Neurotol.* 2002; 23:698–703. [PubMed: 12218622]
12. Waltzman SB, Roland JT Jr, Cohen NL. Delayed implantation in congenitally deaf children and adults. *Otol Neurotol.* 2002; 23:333–340. [PubMed: 11981391]
13. Teoh SW, Pisoni DB, Miyamoto RT. Cochlear implantation in adults with prelingual deafness. Part 1. Clinical results. *Laryngoscope.* 2004; 114:1536–1540. [PubMed: 15475777]
14. Santarelli R, De Filippi R, Genovese E, et al. Cochlear implantation outcome in prelingually deafened young adults. *Audiol Neurotol.* 2008; 13:257–265. [PubMed: 18259078]
15. Chee GH, Goldring JE, Shipp DB, et al. Benefits of cochlear implantation in early-deafened adults: The Toronto experience. *J Otolaryngol.* 2004; 33:26–31. [PubMed: 15291273]
16. Klop WM, Briaire JJ, Stiggelbout AM, Frijns JH. Cochlear implant outcomes and quality of life in adults with prelingual deafness. *Laryngoscope.* 2007; 117(11):1982–7. [PubMed: 17767086]
17. Noble JH, Labadie RF, Gifford RH, Dawant BM. Image-guidance enables new methods for customizing cochlear implant stimulation strategies. *IEEE Trans Neural Syst Rehabil Eng.* 2013; 21(5):820–9. [PubMed: 23529109]
18. Noble JH, Gifford RH, Hedley-Williams AJ, Dawant BM, Labadie RF. Clinical evaluation of an image-guided cochlear implant programming strategy. *Audiol Neurotol.* 2014; 19:400–11. [PubMed: 25402603]
19. Baer T, Moore BC. Effects of spectral smearing on the intelligibility of sentences in the presence of interfering speech. *J Acoust Soc Am.* 1994; 95:2277–2280. [PubMed: 8201124]
20. Moore BCJ, Glasberg BR. Simulation of the effects of loudness recruitment and threshold elevation on the intelligibility of speech in quiet and in a background of speech. *J Acoust Soc Am.* 1993; 94:2050–2062. [PubMed: 8227747]
21. Moore BC, Glasberg BR, Vickers DA. Simulation of the effects of loudness recruitment on the intelligibility of speech in noise. *Br J Audiol.* 1995; 29:131–143. [PubMed: 8574199]
22. Schuman TA, Noble JH, Wright CG, Wanna GB, Dawant B, Labadie RF. Anatomic Verification of a Novel, Non-rigid Registration Method for Precise Intrascalar Localization of Cochlear Implant Electrodes in Adult Human Temporal Bones Using Clinically-available Computerized Tomography. *Laryngoscope.* 2010; 120(11):2277–2283. [PubMed: 20939074]
23. Noble JH, Labadie RF, Majdani O, Dawant BM. Automatic segmentation of intra-cochlear anatomy in conventional CT. *IEEE Trans Biomed Eng.* 2011; 58(9):2625–32. [PubMed: 21708495]
24. Noble, JH.; Gifford, RH.; Labadie, RF.; Dawant, BM. Statistical Shape Model Segmentation and Frequency Mapping of Cochlear Implant Stimulation Targets in CT. In: Ayache, N., et al., editors. MICCAI 2012. 2012. p. 421-428. Part II, LNCS 7511
25. Reda FA, Noble JH, Labadie RF, Dawant BM. An artifact-robust, shape library-based algorithm for automatic segmentation of inner ear anatomy in post-cochlear-implantation CT. *Proc Soc Photo Opt Instrum Eng.* 2014 Mar 21;9034:90342V.
26. Reda FA, McRackan TR, Labadie RF, Dawant BM, Noble JH. Automatic segmentation of intra-cochlear anatomy in post-implantation CT of unilateral cochlear implant recipients. *Medical Image.* 2014; 18(3):605–15.
27. Zhao Y, Dawant BM, Labadie RF, Noble JH. Automatic localization of cochlear implant electrodes in CT. *Med Image Comput Comput Assist Interv.* 2014; 17(Pt 1):331–8. [PubMed: 25333135]
28. Noble, JH.; Dawant, BM. Automatic graph-based localization of cochlear implant electrodes in CT. In: Frangi, A., et al., editors. Proceedings of MICCAI 2015, Part II, Lect Notes in Comp. Sci. Vol. 9350. p. 152-159.
29. Friesen LM, Shannon RV, Baskent D, Wang X. Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hearing and cochlear implants. *J Acoust Soc Am.* 2001; 110:1150–1163. [PubMed: 11519582]
30. Garnham C, O'Driscoll M, Ramsden R, Saeed S. Speech understanding in noise with a Med-El COMBI 40+ cochlear implant using reduced channel sets. *Ear Hear.* 2002; 23:540–552. [PubMed: 12476091]

31. MSTB: The New Minimum Speech Test Battery. 2011. http://www.auditorypotential.com/MSTB_Nav.html
32. Gifford RH, Hedley-Williams A, Spahr AJ. Clinical assessment of spectral modulation detection for cochlear implant recipients: a non-language based measure of performance outcomes. *Int J Audiol*. 2014; 53(3):159–64. [PubMed: 24456178]
33. Drennan WR, Won JH, Nie K, Jameyson E, Rubinstein JT. Sensitivity of psychophysical measures to signal processor modifications in cochlear implant users. *Hear Res*. 2010; 262:1–8. [PubMed: 20144699]
34. Drennan WR, Anderson ES, Won JH, Rubenstein JT. Validation of a clinical assessment of spectral-ripple resolution for cochlear implant users. *Ear Hear*. 2014; 35:e92–e98. [PubMed: 24552679]
35. Gifford RH, Hedley-Williams A, Spahr AJ. Clinical assessment of spectral modulation detection for adult cochlear implant recipients: a non-language based measure of performance outcomes. *Audiol Neurotol*. 2014; 53:159–164.
36. Henry BA, Turner CW. The resolution of complex spectral patterns by cochlear implant and normal-hearing listeners. *J Acoust Soc Am*. 2003; 113:2861–2873. [PubMed: 12765402]
37. Saoji AA, Litvak LM, Spahr AJ, Eddins DA. Spectral modulation detection and vowel and consonant identifications in cochlear implant listeners. *J Acoust Soc Am*. 2009; 126:955–958. [PubMed: 19739707]
38. Cox RM, Alexander GC. The abbreviated profile of hearing aid benefit. *Ear Hear*. 1995; 16:176–186. [PubMed: 7789669]
39. Gatehouse S, Noble W. The speech, spatial and qualities of hearing scale (SSQ). *Int J Audiol*. 2004; 43:85–99. [PubMed: 15035561]
40. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap) – a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform*. 2009; 42:377–381. [PubMed: 18929686]
41. Jethanamest D, Tan CT, Fitzgerald MB, Svirsky MA. A new software tool to optimize frequency table selection for cochlear implants. *Otol Neurotol*. 2010; 31(8):1242–7. [PubMed: 20729774]
42. Dwyer, RT.; Spahr, AJ.; Agrawal, S.; Hetlinger, C.; Holder, JT.; Gifford, RH. Participant-generated Programs for Advanced Bionics Recipients: Speech Recognition, Sound Quality, and Satisfaction. 14th Symposium on Cochlear Implants in Children; Nashville, TN. December 11–13, 2014;
43. Kral A, Tillein J, Heid S, Hartmann R, Klinke R. Postnatal cortical development in congenital auditory deprivation. *Cereb Cortex*. 2005; 15:552–562. [PubMed: 15319310]
44. Kral A, Sharma A. Developmental neuroplasticity after cochlear implantation. *Trends Neurosci*. 2012; 35:111–122. [PubMed: 22104561]
45. Neville H, Bavelier D. Human brain plasticity: evidence from sensory deprivation and language experience. *Prog Brain Res*. 2002; 138:177–188. [PubMed: 12432770]
46. Sharma A, Dorman MF. Central auditory development in children with cochlear implants: clinical implications. *Adv Otorhinolaryngol*. 2006; 64:66–68. [PubMed: 16891837]
47. Sharma A, Nash AA, Dorman M. Cortical development, plasticity and re-organization in children with cochlear implants. *J Commun Disord*. 2009; 42:272–279. [PubMed: 19380150]
48. Olulade OA, Koo DS, LaSasso CJ, Eden GF. Neuroanatomical profiles of deafness in the context of native language experience. *J Neurosci*. 2014; 34:5613–5620. [PubMed: 24741051]
49. Petersen B, Gjedde A, Wallentin M, Vuust P. Cortical Plasticity after Cochlear Implantation. *Neural Plasticity*. 2013; 2013:31852.
50. Litvak LM, Spahr AJ, Saoji A, Fridman GY. Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners. *J Acoust Soc Am*. 2007; 122:982–991. [PubMed: 17672646]
51. Spahr AJ, Saoji A, Litvak LM, Dorman MF. Spectral cues for understanding speech in quiet and in noise. *Cochlear Implants International*. 2011; 12:S66–S69. [PubMed: 21756477]
52. Tyler RS, Preece JP, Lansing CR, Otto SR, Gantz BJ. Previous experience as a confounding factor in comparing cochlear-implant processing schemes. *J Speech Hear Res*. 1986; 29:282–287. [PubMed: 3755194]

Figure 1. Output of image-processing algorithms show (top panel) 3-D rendering of position of electrode array relative to the modiolus and (bottom panel) graphical plot of the distance from each electrode (y-axis) to the modiolus (x-axis). In this example, electrodes 6, 8, 10, 11, 13, and 15 have been deactivated as their neighbors are closer to their intended stimulation site than their neighbor.

Figure 2. Histogram of percentage of electrodes deactivated (x-axis) for Cochlear (top left panel), Advanced Bionics (top right panel), and Medel (bottom panel) devices.

Figure 3.

Individual data for audiological testing before (x-axis) and after (y-axis) IGCIP for CNC words, BKB-SIN, and AZ BIO in both quiet and +10dB signal to noise ratio. In these graphs, the diagonal dotted line represents no change from pre to post and values that fall above the diagonal represent improvement and those below represent worsening (although the opposite is true for the BKB-SIN curve where decreases, found below the diagonal, represent an improvement). The thin, curved lines show 95% confidence intervals.

Figure 4. Individual data for audiological testing before (x-axis) and after (y-axis) IGCIP for SMD at both 1 cycle/oct (top panel) and 0.5 cycle/oct (bottom panel).. In these graphs, the diagonal dotted line represents no change from pre to post and values that fall above the diagonal represent improvement and those below represent worsening. The thin, curved lines show 95% confidence intervals.

Table I

	Pre IGCIP	Post IGCIP	p-value
CNC Words (n=29)	31.52 ± 22.94	30.96 ± 24.42	0.39
AzBio Quiet (n=29)	39.10 ± 29.06	38.83 ± 30.07	0.46
AzBio +10 dB SNR (n=17)	34.24 ± 25.27	33.59 ± 24.33	0.44
BKB-SIN (n=29)	16.78 ± 6.17	17.86 ± 4.86	0.07
SMD 0.5 cyc/oct (n=25)	45.52 ± 18.60	52.04 ± 20.19	0.02
SMD 1.0 cyc/oct (n=25)	40.51 ± 20.46	46.49 ± 17.52	0.07

Table II

	Pre IGCIP	Post IGCIP	p-value
APHAB (n=26)	48.20 ± 21.68	46.95 ± 16.97	0.2
APHAB EC (n=26)	33.15 ± 29.75	28.25 ± 22.31	0.07
APHAB RV (n=26)	56.84 ± 26.07	56.77 ± 22.48	0.36
APHAB BN (n=26)	54.31 ± 18.00	54.44 ± 17.04	0.28
APHAB AV (n=26)	37.28 ± 27.86	37.11 ± 26.71	0.38
SSQ Total (n=26)	4.66 ± 2.09	4.68 ± 1.91	0.49
SSQ Speech (n=26)	4.53 ± 2.06	4.59 ± 1.89	0.40
SSQ Spatial (n=26)	4.00 ± 2.38	4.27 ± 2.21	0.15
SSQ Qualities (n=25)	5.31 ± 2.11	5.29 ± 2.34	0.47