2015

Frequency-place map for electrical stimulation in cochlear implants: Change over time

K. Vermeire
Hofstra Northwell School of Medicine

D. M. Landsberger

P. H. Van de Heyning

M. Voormolen

A. Kleine Punte

See next page for additional authors

Recommended Citation

Vermeire K, Landsberger D, Van de Heyning P, Voormolen M, Kleine Punte A, Schatzer R, Zierhofer C. Frequency-place map for electrical stimulation in cochlear implants: Change over time. . 2015 Jan 01; 326():Article 586 [p.]. Available from: https://academicworks.medicine.hofstra.edu/articles/586. Free full text article.

Authors
K. Vermeire, D. M. Landsberger, P. H. Van de Heyning, M. Voormolen, A. Kleine Punte, R. Schatzer, and C. Zierhofer

HHS Public Access

Author manuscript

Hear Res. Author manuscript; available in PMC 2016 August 01.

Published in final edited form as:

Hear Res. 2015 August ; 326: 8–14. doi:10.1016/j.heares.2015.03.011.

FREQUENCY-PLACE MAP FOR ELECTRICAL STIMULATION IN COCHLEAR IMPLANTS: CHANGE OVER TIME

Katrien Vermeire[a,b], **David M. Landsberger**[c], **Paul H. Van de Heyning**[b], **Maurits Voormolen**[d], **Andrea Kleine Punte**[b], **Reinhold Schatzer**[e,*], and **Clemens Zierhofer**[e]

[a]C. Doppler Laboratory for Active Implantable Systems, Institute of Ion Physics and Applied Physics, University of Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria

[b]Univ. Dept. of Otorhinolaryngology, Head and Neck Surgery, University Hospital Antwerp, University of Antwerp, Wilrijkstraat 10, 2650 Edegem, Belgium

[c]Department of Otolaryngology, NYU School of Medicine, 550 1st Avenue NBV 5E5, New York, NY 10016, USA

[d]Univ. Dept. of Radiology, University Hospital Antwerp, University of Antwerp, Wilrijkstraat 10, 2650 Edegem, Belgium

[e]Institute of Mechatronics, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria

Abstract

The relationship between the place of electrical stimulation from a cochlear implant and the corresponding perceived pitch remains uncertain. Previous studies have estimated what the pitch corresponding to a particular location should be. However, perceptual verification is difficult because a subject needs both a cochlear implant and sufficient residual hearing to reliably compare electric and acoustic pitches. Additional complications can arise from the possibility that the pitch corresponding to an electrode may change as the auditory system adapts to a sound processor. In the following experiment, five subjects with normal or near-to-normal hearing in one ear and a cochlear implant with a long electrode array in the other ear were studied. Pitch matches were made between single electrode pulse trains and acoustic tones before activation of the speech processor to gain an estimate of the pitch provided by electrical stimulation at a given insertion angle without the influence of exposure to a sound processor. The pitch matches were repeated after 1, 3, 6, and 12 months of experience with the sound processor to evaluate the effect of adaptation over time. Pre-activation pitch matches were lower than would be estimated by a spiral ganglion pitch map. Deviations were largest for stimulation below 240° degrees and smallest above 480°. With experience, pitch matches shifted towards the frequency-to-electrode allocation. However, no statistically significant pitch shifts were observed over time. The likely explanation for the lack of pitch change is that the frequency-to-electrode allocations for the long electrode

Author Contact Details: Katrien Vermeire, Univ. Dept. of Otorhinolaryngology, Head and Neck Surgery, University Hospital Antwerp, Wilrijkstraat 10, 2650 Edegem, Belgium, kvermeire@gmail.com, +32 (0)477.24.32.14.

*Author Reinhold Schatzer is currently at MED-EL GmbH, Furstenweg 77a, 6020 Innsbruck, Austria

arrays were already similar to the pre-activation pitch matches. Minimal place pitch shifts over time suggest a minimal amount of perceptual remapping needed for the integration of electric and acoustic stimuli, which may contribute to shorter times to asymptotic performance.

Keywords

Cochlear Implants; Place Pitch; Adaptation; Psychophysics; Insertion Depth

1. Introduction

As more subjects with residual hearing (and subjects with more residual hearing) receive cochlear implants (CI), there are increased opportunities to compare the relationship between the pitch sensation produced by stimulating an electrode and that produced by an acoustic stimulus. The relationship between the place of stimulation and the corresponding perceived pitch is important for both an understanding of the auditory system and for optimally fitting a CI. It is plausible that a more precise allocation of pitch information from an electrode to the corresponding place might contribute to better overall performance, shorter times to asymptotic performance (Buchman et al., 2014), and an easier integration between acoustic and electric information.

Pitch matching of electric and acoustic stimuli is presumably dependent on both the amount and quality of the residual acoustic hearing as well as the subject's adaptation to their speech processing strategy and electrode frequency allocation with their CI. Several investigators have presented results from electric-acoustic pitch matching studies in experienced users of different CI systems with varying degrees of compromised residual hearing (Baumann and Nobbe, 2006; Boëx et al., 2006; Carlyon et al., 2010; Dorman et al., 2007; McDermott et al., 2009; Schatzer et al., 2014; Vermeire et al., 2008). Several of the studies found that the pitch elicited through stimulation of intracochlear electrodes is generally between one and two octaves lower than estimated by Greenwood's (1990) frequency-position function (Blamey et al., 1996; Boëx et al., 2006; Dorman et al., 2007). Blamey et al. (1996) conducted pitch-comparison experiments in 13 subjects with relatively poor hearing in their non-implanted ear. Results were quite variable across subjects, and the pitch elicited through stimulation of intracochlear electrodes was generally lower than estimated by Greenwood's frequency-place function. Boëx et al. (2006) and Dorman et al. (2007) tested subjects that had better hearing thresholds in the non-implanted ear. Thus, pitch-matching data were less compromised by hearing loss and abnormal cochlear function.

When frequency-place maps were constructed, most matches were approximately one octave lower than predicted by Greenwood. Baumann & Nobbe (2006), on the other hand, found pitch-matches that were on or above the Greenwood frequency-place function for the six most apical electrodes in six MED-EL COMBI 40+ users. Furthermore, a number of studies have examined acoustic-electric pitch matching in subjects with near-normal hearing in the non-implanted ear. Schatzer et al. (2014) conducted pitch-comparison experiments in eight experienced CI users with near-normal hearing in their non-implanted ear. Deviations of frequency-place functions relative to Greenwood were approximately half an octave at electrode insertion angles below 480°, increasing to an octave at higher angular locations.

Other studies found that in subjects with normal or near-normal hearing in the non-implanted ear, matches did not deviate consistently from the predictions of Greenwood's formula (Carlyon et al., 2010; Vermeire et al., 2008). Vermeire et al. (2008) performed pitch-scaling experiments with 14 subjects with functional hearing in the non-implanted ear. They found that electrical stimulation produced a frequency-place function that, on average, resembles Greenwood's function. In Carlyon et al. (2010), four CI users with normal hearing in the non-implanted ear compared pitch percepts of electrical and acoustic stimuli presented to the two ears. Results of these comparisons did not show a deviation of electrical pitch percepts from the predictions of Greenwood's cochlear frequency-to-place formula.

For experienced CI subjects, the perception of pitch of a given electrode might be influenced by the frequency range presented on that electrode by frequency allocation of their sound processor. The discrepancy between the frequency represented at a given cochlear location by a speech processor and the expected frequency at the equivalent location in the normal ear is increased when the insertion is shallow. Reiss et al. (2007; 2014) investigated the effects of place pitch adaptation over time to short Hybrid (mostly 10 mm) electrode arrays. Subjects with residual ipsilateral hearing and combined electric-acoustic stimulation pitch matched the most apical electrode of the shallow Hybrid insertion with their residual hearing. Although the predicted place-pitch frequency for the most apical electrode is between 2800 and 4700 Hz (Greenwood, 1990; Stakhovskaya et al., 2007), the corresponding pitch matches were found to deviate towards the frequency range allocated to the most apical electrodes in most subjects. Although pitch matches did not usually adapt completely to the allocated frequencies, place pitch percepts sometimes shifted by as much as 3 octaves from the Greenwood prediction towards the allocated frequencies, over a time frame of several months. These results suggest that while the mature auditory system has the ability to adapt greatly to deviations in place pitch, there are limitations to the amount of adaptation possible.

Similarly to Reiss et al. (2007; 2014), we have examined the effect of time on the changes in electrode place pitch. However, our study examined a very different patient population. Specifically, subjects had much longer and deeply inserted electrode arrays (either MED-EL FLEX^{SOFT} or MED-EL FLEX^{24} arrays with a maximum insertion angle ranging from 367° to 685°) and near normal hearing in the contralateral ear. Our initial pitch matches were made pre-activation, allowing estimates of electric place pitch across a large extent of the cochlea without compromise of limited acoustic input and the confounds of adaptation to a speech processing strategy. Subsequently, the pitch-matches were re-evaluated at 1, 3, 6, and 12 months to observe the stability of the percepts over time and the effects of adaptation to a deeply inserted electrode which provides a frequency allocation closer to the corrected estimate of place pitch (Stakhovskaya et al., 2007). While Reiss et al. (2014) investigated place pitch only for the most apical electrode due to the sloping hearing loss in their Hybrid-array subjects, we were able to longitudinally track place pitch percepts along the full electrode array, including at basal cochlear regions, as contralateral hearing thresholds in our subjects were ranging from normal to a moderate loss across frequencies. The study was approved by the University of Antwerp Ethics Committee.

2. Material and Methods

2.1 Subjects

Five adult subjects participated in this study. All subjects suffered from severe unilateral tinnitus resulting from ipsilateral sensorineural deafness. Demographic information about the participants can be found in Table 1. All subjects also participated in a previously reported study on the effectiveness of cochlear implantation as a treatment for unilateral tinnitus (Punte et al., 2011). Each of the subjects had a significant reduction of their tinnitus from stimulation by their implant.

All subjects were implanted with a MED-EL SONATA device with either a 31-mm FLEX^{SOFT} electrode (S1, S2, S4, and S5) or a 24-mm FLEX^{24} electrode (S3). All subjects had full insertions as confirmed by post-op radiography. The electrode insertion angles for all subjects are presented in Figure 1. The average age at the time of surgery was 57;7 years (range: 44;4 – 63;1 years) and the average duration of deafness was 5 years (range: 9 months – 9 years). All subjects had functional hearing in the contralateral ear. Individual audiograms of the contralateral ears are plotted in Figure 2.

2.2 Electrode design

Both FLEX^{SOFT} and FLEX^{24} arrays have 12 equally spaced electrodes. The length of the FLEX^{SOFT} array from the tip to the marker ring indicating full insertion into the cochlea is 31.5 mm. The contact spacing is 2.4 mm, resulting in an extent of 26.4 mm from the most apical electrode (E1) to the most basal electrode (E12). E1 has a distance of approximately 30 mm from the marker ring. The FLEX^{24} array has a length from tip to marker ring of 24 mm and a contact spacing of 1.9 mm, resulting in an active stimulation range of 20.9 mm. E1 has a distance of approximately 22.9 mm from the marker ring. Both electrode arrays are straight and highly flexible, which typically results in a lateral-wall placement inside the scala tympani. In MED-EL SONATA implants the reference electrode for monopolar stimulation is located on the implant housing.

2.3 Determination of electrode positions

Postoperative radiographs were collected to determine the exact positions of the intracochlear electrodes. The radiographs were taken with the subject lying in a prone position on the angiography table (Angiostar plus, Siemens AG, Forchheim, Germany) and with the head tilted to the normal-hearing ear. The image of the intracochlear electrode array was made by directing the beam axis to the inner ear of the implanted side. The longitudinal and angular positions of the individual intracochlear electrodes were measured using the method described by Xu et al. (2000). Based on those measures, the electrode insertion angles were estimated by three independent observers and calculated in a similar manner to Boëx et al. (2006). The means from the three observations were taken as electrode insertion angles. As in Vermeire et al. (2008) and Schatzer et al. (2014), insertion angles were used to define apical, middle, and basal regions along each subject's electrode array. Electrodes with insertion angles up to 240° were assigned to the basal region, insertion angles beyond 480° to the apical region, and electrodes in between to the middle region.

2.4 Stimuli

The electric stimuli were single-electrode pulse trains consisting of un-ramped constant-amplitude biphasic pulses presented at 1500 pulses per second (pps) in monopolar configuration. The stimuli were delivered through a Research Interface Box II (RIB II, University of Innsbruck) and presented on one of eight electrodes (E 1–4, E6, E8, E10, E12) spanning the whole array. Pulse trains were 500 ms in duration. Pulse phase durations were 48.3 μs with an inter-phase gap of 2.1 μs. The stimulation rate used in this experiment was close to the mean clinical stimulation rate (1436 pps) for these patients. The selected phase duration was slightly longer than what was found in the clinical maps which had a maximum phase duration of 40.4 μs. The inter-phase gap was 2.1 μs in both the experimental stimuli and the clinical patient maps. The acoustic stimuli consisted of 500-ms pure tones which were faded in and out with 25 ms linear ramps. The tones were played through a standard PC sound card connected to circumaural headphones (Beyerdynamic DT150). The amplitude of the acoustic and electric stimuli was set according to the results of the loudness balancing (described below). All stimuli were clearly audible and comfortable.

2.5 Procedure

2.5.1 Loudness Balancing—Before collecting pitch-matching data, it was important to ensure that all acoustic and electric stimuli were of equal loudness. In order to obtain equally loud stimuli, a number of steps were taken. First, a rough pitch match was quickly estimated for a comfortably loud single-electrode pulse train for each of the 8 tested electrodes active in a patient’s map. The pitch-matched frequencies provided a rough estimate of the range of acoustic frequencies required for the experiment. Additionally, for each electrode stimulus, acoustic frequencies that were judged as distinctly higher and lower in pitch, respectively, were determined. Second, all of the acoustic stimuli were loudness balanced to the frequency roughly corresponding in pitch to that of a middle electrode (E6) at a comfortably loud level. Third, the loudness of each single-electrode pulse train was balanced to the loudness of the roughly corresponding acoustic frequency.

A two-interval procedure was used to obtain the informal pitch matches. The first interval contained a fixed single-electrode unmodulated pulse train presented at comfortable loudness. The second interval contained a pure-tone stimulus whose level and then frequency were repeatedly changed by the experimenter until it roughly matched the single-electrode stimulus both in loudness and pitch. The same procedure was used to bracket the electrode pitch and determine pure-tone frequencies perceived as distinctly higher and lower in pitch.

Loudness balancing of the acoustic stimuli was accomplished using a 1-up-1-down, two-interval two-alternative forced-choice (2I-2AFC) staircase procedure (Levitt, 1971). Subjects were asked to identify which of the two stimuli was quieter. One stimulus (the reference) was always presented at a fixed amplitude while the amplitude of the other stimulus (the target) was adjusted based on the subject’s response. The initial step size was 3 dB. After the first turning point, the step size decreased to 1 dB. The adaptive procedure ended after five reversals, and the arithmetic mean of the last four reversals was taken as the balanced loudness level. For the first acoustic loudness balancing, the comfortably loud presentation of the rough frequency estimate corresponding to E6 was used as the reference, and the target was one of the adjacent rough frequency estimates (i.e. the next one higher or lower in frequency.) The pattern of loudness balancing a frequency to the next adjacent frequency was repeated until all of the acoustic stimuli (those that were collected during the "rough estimate procedure") were balanced to a loudness equal to the original anchor point of the E6 frequency reference.

The amplitude of each single-electrode pulse train was adjusted to match the loudness of the corresponding acoustic stimulation. A 1-up-1-down, two-interval two-alternative forced-choice (2I-2AFC) staircase procedure was used with the acoustic stimulus as the reference and the electric stimulus as the target. Subjects were asked to identify which of the two stimuli was quieter. The amplitude of the electric stimulus was adjusted according the subject's response. The amplitude of the electric stimulus was changed by 3 current steps until the first reversal and by 1 current step afterwards. The adaptive procedure ended after five turning points, and the arithmetic mean of the last four turning points was taken as balanced loudness level.

2.5.2 Pitch Matching—Pure tone frequencies that matched the pitches of the single-electrode pulse trains were measured with a 1-up-1-down, 2I-2AFC adaptive procedure. In a given trial, subjects were presented with a 500 ms electric stimulus, followed by a 500 ms acoustic pure tone presented to the contralateral ear separated by a 300 ms inter-stimulus interval. Subjects were asked to identify which sound was higher in pitch. The frequency of the acoustic stimulus was adaptively changed up or down depending on the response of the subject. To ensure a constant loudness, the level of each acoustic stimulus was linearly interpolated from the levels of the two closest acoustic frequencies that had been previously loudness balanced. An adaptive track ended after 11 reversals, and the geometric mean of the last eight reversals was taken as pure tone frequency match for that track. The initial acoustic step size was 24% of the target frequency and changed to 12% after the first reversal and further to the final step size of 6% after the third reversal. A minimum of four matching attempts per electrode were conducted, two each with different acoustic starting frequencies that were distinctly higher and lower than the electrode pitch (as roughly estimated prior to the experiment). Matching procedures from distinctly higher and lower starting frequencies were designated as down- and up-matching procedures or tracks, respectively. Appropriate starting frequencies for the down-matching procedure were between the frequencies previously noted as distinctively higher and an octave higher. This octave range was divided into semitones. Note that one semitone is 1/12th of an octave, or adjacent keys on a piano keyboard. The starting acoustic frequencies for down-matching were randomly selected from the semitones in this octave range. Similarly, starting acoustic frequencies for the up-matching trials were randomly selected from semitones between the frequency noted as distinctively lower and the octave below. Thus, the starting frequencies for the four matching procedures could vary over a range of more than two octaves. The electrode order and starting frequencies were randomized across subjects.

The experiment was repeated at several intervals (pre-activation and after 1, 3, 6, and 12 months of CI use) for each patient. Due to scheduling time limitations, patient S4 was not evaluated after 3 or 12 months of CI use. During the time of the study, the frequency allocations of the sound processors were not changed.

2.5.3 Data analysis—In order to identify reliable pitch matches, a post-hoc analysis was done. Data points were validated to ensure that pairs of up and down tracks converged to address potential bias concerns raised by Carlyon et al (2010). The correction was performed similarly to the correction described by Schatzer et al. (2014). The geometric mean of the frequency matches from converging pairs of up and down tracks was taken as the electrode pitch match.

One sample t-tests were used to determine if the pitch matched values deviated significantly from the spiral ganglion (SG) frequency map (Stakhovskaya et al., 2007). Similarly, one sample t-tests were also used to determine if the pitch matched values deviated significantly from the frequencies provided by the frequency allocation. Type I error correction for the multiple t-tests was performed using Rom's method (Rom, 1990). A two-way repeated measures ANOVA was used to look for significant differences in pitch matches across visits and cochlear regions. Post-hoc pairwise analysis for the ANOVA was conducted using the Holm-Sidak method.

3. Results

The pitch percepts from single electrode stimulation before initial activation were not influenced by adaptation to the specific properties of the speech processor. The acoustic frequencies that successfully pitch matched to each tested electrode for all subjects are plotted in Figure 3. As a reference, the SG frequency map estimating frequency along the spiral ganglion as adapted for rotation angle from the round window (Stakhovskaya et al., 2007) is also plotted (solid green line). Overall, the mean deviation of the place-pitch matches from the SG map estimate is 17.48 semitones (SE: 2.3), which was found to be significant (t_4=7.46, p=0.002). The data were reanalyzed for three different angular insertion regions corresponding to the cochlear base (below 240°), middle (between 240° and 480°), and apex (beyond 480°). Downward mean deviations were observed for all angular insertion regions (i.e. pitch matches were lower than predicted based on the SG frequency map). Specifically, the mean deviations from the spiral ganglion estimate were 29.04 semitones (SE: 8.5) in the basal region, 16.32 semitones (SE: 2.54) in the middle region, and 4.99 semitones (SE: 6.47) in the apical region. After Type I error correction using Rom's method (Rom, 1990), one-sample t-tests detected significant deviations from the SG frequency map in the middle region (Middle: t_3=6.43, p=0.008) but not in the basal or apical region (Base: t_4=3.42, p=0.027; Apex t_3=0.77, p=0.496).

The frequency-place functions derived from the across-ear electric-acoustic pitch matches that passed the sanity checks (Carlyon et al., 2010) are shown in Figure 4 for each time interval (pre-activation, 1, 3, 6, and 12 months post-activation). As a reference, both the corrected SG frequency map (solid green line) and frequency allocation (red dashed line) are plotted. It is worth noting that the default frequency allocation provides a closer match to the pre-activation pitch matches than the predicted SG frequency map, despite the listener not having had a chance to adapt to the frequency allocation. Nevertheless, a significant difference between the pre-activation matches and the frequency allocation is found (t_4=3.01, p=0.040). However, when examined separately for the basal, middle, and apical cochlear regions, no significant differences were detected from the frequency allocation. After experience with the cochlear implant and frequency allocation table (i.e. at the 1, 3, 6, and 12 month follow-up visits), no significant differences between pitch match and frequency allocation tables are observed, even before Type I error correction. Exact values are presented in Table 2.

To determine if there was a change in pitch matches over time, a two-way repeated measures ANOVA with cochlear region and visit as the two independent factors was conducted. Before the analysis, all frequency matches were log transformed. Average values were calculated for each cochlear region. Because no data were collected at 3 months and 12 months for subject S4, S4's data was excluded from the statistical analysis. Also subject S3 was excluded from the statistical analysis before S3 has a shallower insertion (FLEX^{24} electrode) so there were no electrodes in the apical region. A main effect of cochlear region was found ($F_{2,15}$ = 21.25, p = 0.007). Using the Holm-Sidak method all but the comparison between the apical and middle regions were found to be significant. A main effect of visit was not observed ($F_{4,15}$ = 2.78, p = 0.101).

4. Discussion

The pre-activation pitch match settings provide an insight into the relationship between the place of electrical stimulation and the corresponding place pitch without the influence of adaptation to a sound processing strategy. Results suggest that the pitch perceptions reported by the subjects deviate from the place pitch estimates based on the spiral ganglion position (e.g. Stakhovskaya et al., 2007). Statistically significant deviations from the predicted place pitch are observed, with the greatest deviations observed in the middle and basal region. For a given angle of insertion, acoustic pitch matches tended to be lower in frequency than predicted by the Stakhovskaya et al. (2007) SG frequency map. Although there have been multiple reports of acoustic matches to single electrode stimulation, most previous reports have been limited by severely impaired acoustic hearing (e. g. Reiss et al., 2007; 2014; McDermott et al., 2009), adaptation to a speech coding strategy (e. g. Baumann et al., 2011; Schatzer et al., 2014; Zeng et al., 2014), or both (e. g. Blamey et al., 1996; Boëx et al., 2006). Carlyon et al. (2010) and McDermott et al. (2009) found place-pitch matches with inexperienced implant users to be closer to either the Greenwood (1990) organ of Corti estimate or the Stakhovskaya et al. (2007) spiral ganglion estimate. Our results are more consistent with previous findings from other groups in that the SG estimate overestimates electrical place pitch by approximately an octave for insertions below 480° (e.g. Blamey et al., 1996; Boëx et al., 2006; Dorman et al., 2007). Pitch matches were fairly stable across time; no significant main effect of visit was observed. By the first month post activation, deviations from the frequency allocation were small across all subjects. Perhaps this is because the default frequency allocation (red line in Figure 4) is similar to the predicted spiral ganglion map (green line in Figure 4) for all subjects with the long FLEX^{SOFT} array (S1, S2, S4, and S5). Therefore, the frequencies provided by each electrode using their speech processing strategy do not require a large shift in perceived place pitch.

For subject S3 (with the shorter FLEX^{24} array), the deviations between the frequency allocation and SG map increase with insertion angle. Pitch matches for S3's more apical electrodes lie stably across time between the predicted frequency by the SG map and the frequency presented by the frequency allocation. There are at least three potential explanations for this observation. One explanation is that the frequency place mismatch for these electrodes are too large for complete adaptation. A second explanation is that a year is not sufficient time for complete adaptation. A third explanation is that the subject hears a representation of pitch both at the frequency encoded by the SG map and the frequency allocation and therefore pitch match to a frequency between the two representations as a compromise. The deviations between SG map and frequency allocation are further exaggerated with the 10 mm Hybrid array subjects examined by Reiss et al. (2007, 2014). Some Hybrid subjects show close adaptation to the frequency allocation but nevertheless report greater frequency shifts than observed in S3. The Reiss et al. (2007, 2014) data in combination with the data presented in the current manuscript are consistent with the third explanation.

The magnitude of the deviations of frequency allocation from the natural tonotopic place may be relevant to performance with a cochlear implant. While it has been shown that subjects can adapt their place pitch maps to a frequency allocation (Fu et al., 2005; Reiss et al., 2014; Rosen et al., 1999), there seems to be a limit to the degree of adaptation available to a patient (Fu et al., 2002). Reiss et al. (2007) argue that "a closer match to the tonotopic place might allow implant subjects to reach asymptotic levels of speech performance faster after implantation." Indeed, recent data (Buchman et al., 2014) suggest that subjects with 31 mm MED-EL electrode arrays (and therefore presumably a closer match to the tonotopic place) both reach asymptotic performance more quickly, but also reach higher levels of performance than subjects with 24 mm MED-EL electrode arrays. It is however unclear if the difference in performance from these two arrays can be attributed to the apical stimulation, the presumably closer match to tonotopic place, or the reduced channel interaction from the increased spacing between adjacent contacts in the 31 mm array. Bilaterally deafened subjects might be more tolerant of place pitch shifts. With these subjects, a change in frequency allocation provides a shift in the world to which the subject can adapt. However, having frequency allocations approximating natural tonotopic place pitch may be even more important with single sided deafened subjects as the normal hearing ear will process frequencies at the correct tonotopic location. If there is a great place pitch mismatch between the electric and the acoustic hearing ears, it may be more difficult for subjects to fuse the percepts from both ears. A number of SSD patients at the Walter Reed National Military Medical Center report that switching to modified frequency allocations providing better place matches across ears than the default frequency provide better sound quality and fusion (Bernstein and Schuchman, 2015). It is worth noting that creating frequency allocations that matches place pitch to the normal ear typically requires shifting up the frequencies allocated to the most apical electrode. Therefore, if both matching place pitch and electric representation of low frequencies is important for an SSD patient, then a longer electrode array is recommended.

Acknowledgments

This work was supported by grants from NIH/NIDCD (R01 DC012152) and MED-EL Hearing Solutions. The authors would like to express their thanks and appreciation to the subjects for their time and effort. We gratefully acknowledge Daniel Visser, Andreas Krenmayr, and Mathias Kals for software development.

Abbreviations

2I-2AFC	Two Interval Two Alternative Forced Choice
ANOVA	Analysis of Variance
CI	Cochlear Implant
PPS	Pulses Per Second
SE	Standard Error of the Mean
SG	Spiral Ganglion

References

Baumann U, Nobbe A. The cochlear implant electrode-pitch function. Hear Res. 2006; 213:34–42. [PubMed: 16442249]

Baumann U, Rader T, Helbig S, Bahmer A. Pitch matching psychometrics in electric acoustic stimulation. Ear Hear. 2011; 32:656–62. [PubMed: 21869623]

Bernstein, JGW.; Schuchman, G. Cochlear implants for single-sided deafness: Clinical considerations for mapping. 3rd Annual Mid-Atlantic Seminar on Hearing; College Park, MD: University of Maryland; 2015.

Blamey PJ, Dooley GJ, Parisi ES, Clark GM. Pitch comparisons of acoustically and electrically evoked auditory sensations. Hear Res. 1996; 99:139–50. [PubMed: 8970822]

Boëx C, Baud L, Cosendai G, Sigrist A, Kós MI. Acoustic to electric pitch comparisons in cochlear implant subjects with residual hearing. J Assoc Res Otolaryngol. 2006; 7:110–124. [PubMed: 16450213]

Buchman CA, Dillon MT, King ER, Adunka MC, Adunka OF, Pillsbury HC. Influence of Cochlear Implant Insertion Depth on Performance: A Prospective Randomized Trial. Otol Neurotol 2014. 2014 Aug 13. [Epub ahead of print].

Carlyon RP, Macherey O, Frijns JH, Axon PR, Kalkman RK, Boyle P, Baguley DM, Briggs J, Deeks JM, Briaire JJ, Barreau X, Dauman R. Pitch comparisons between electrical stimulation of a cochlear implant and acoustic stimuli presented to a normal-hearing contralateral ear. J Assoc Res Otolaryngol. 2010; 11:625–640. [PubMed: 20526727]

Dorman MF, Spahr T, Gifford R, Loiselle L, McKarns S, Holden T, Skinner M, Finley C. An electric frequency-to-place map for a cochlear implant patient with hearing in the nonimplanted ear. J Assoc Res Otolaryngol. 2007; 8:234–240. [PubMed: 17351713]

Fu QJ, Shannon RV, Galvin JJ III. Perceptual learning following changes in the frequency-to-electrode assignment with the Nucleus-22 cochlear implant. J Acoust Soc Am. 2002; 112:1664–74. [PubMed: 12398471]

Fu QJ, Nogaki G, Galvin JJ 3rd. Auditory training with spectrally shifted speech: implications for cochlear implant patient auditory rehabilitation. J Assoc Res Otolaryngol. 2005; 6:180–9. [PubMed: 15952053]

Greenwood DD. A cochlear frequency-position function for several species--29 years later. J Acoust Soc Am. 1990; 87:2592–2605. [PubMed: 2373794]

Levitt H. Transformed up-down methods in psychoacoustics. J Acoust Soc Am. 1971; 49(Suppl 2): 467. + [PubMed: 5541744]

McDermott H, Sucher C, Simpson A. Electro-acoustic stimulation. Acoustic and electric pitch comparisons. Audiol Neurootol. 2009; 14(Suppl 1):2–7. [PubMed: 19390169]

Punte AK, Vermeire K, Hofkens A, De Bodt M, De Ridder D, Van de Heyning P. Cochlear implantation as a durable tinnitus treatment in single-sided deafness. Cochlear Implants Int. 2011; 12(Suppl 1):S26–9. [PubMed: 21756468]

Reiss LA, Turner CW, Erenberg SR, Gantz BJ. Changes in pitch with a cochlear implant over time. J Assoc Res Otolaryngol. 2007; 8:241–57. [PubMed: 17347777]

Reiss LA, Turner CW, Karsten SA, Gantz BJ. Plasticity in human pitch perception induced by tonotopically mismatched electro-acoustic stimulation. Neuroscience. 2014; 256:43–52. [PubMed: 24157931]

Rom DM. A sequentially rejective test procedure based on a modified Bonferroni inequality. Biometrika. 1990; 77:663–665.

Rosen S, Faulkner A, Wilkinson L. Adaptation by normal listeners to upward spectral shifts of speech: implications for cochlear implants. J Acoust Soc Am. 1999; 106:3629–36. [PubMed: 10615701]

Schatzer R, Vermeire K, Visser D, Krenmayr A, Kals M, Voormolen M, Van de Heyning P, Zierhofer C. Electric-acoustic pitch comparisons in single-sided-deaf cochlear implant users: Frequency-place functions and rate pitch. Hear Res. 2014; 309:26–35. [PubMed: 24252455]

Stakhovskaya O, Sridhar D, Bonham BH, Leake PA. Frequency map for the human cochlear spiral ganglion: implications for cochlear implants. J Assoc Res Otolaryngol. 2007; 8:220–33. [PubMed: 17318276]

Vermeire K, Nobbe A, Schleich P, Nopp P, Voormolen MH, Van de Heyning PH. Neural tonotopy in cochlear implants: an evaluation in unilateral cochlear implant patients with unilateral deafness and tinnitus. Hear Res. 2008; 245:98–106. [PubMed: 18817861]

Xu J, Xu SA, Cohen LT, Clark GM. Cochlear view: postoperative radiography for cochlear implantation. Am J Otol. 2000; 21:49–56. [PubMed: 10651435]

Zeng FG, Tang Q, Lu T. Abnormal Pitch Perception Produced by Cochlear Implant Stimulation. PloS one. 2014; 9:e88662. [PubMed: 24551131]

Highlights

1. Pre-activation pitch matches deviate least from the spiral ganglion map in the apical region
2. Pitch matches were fairly stable over time; no significant main effect of visit was found
3. Frequency bands clinically mapped to long electrodes do not require large perceptual shifts

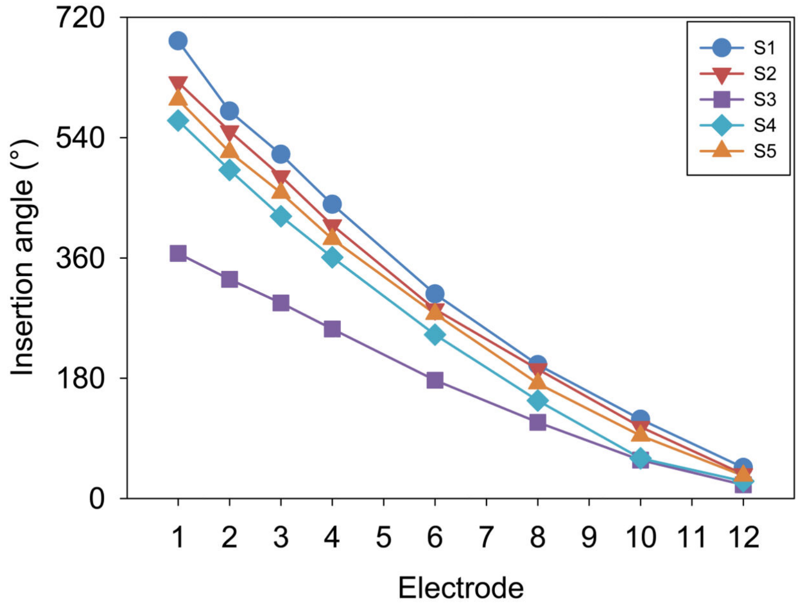

Figure 1.
Insertion angles for all 12 electrodes in each of the five subjects

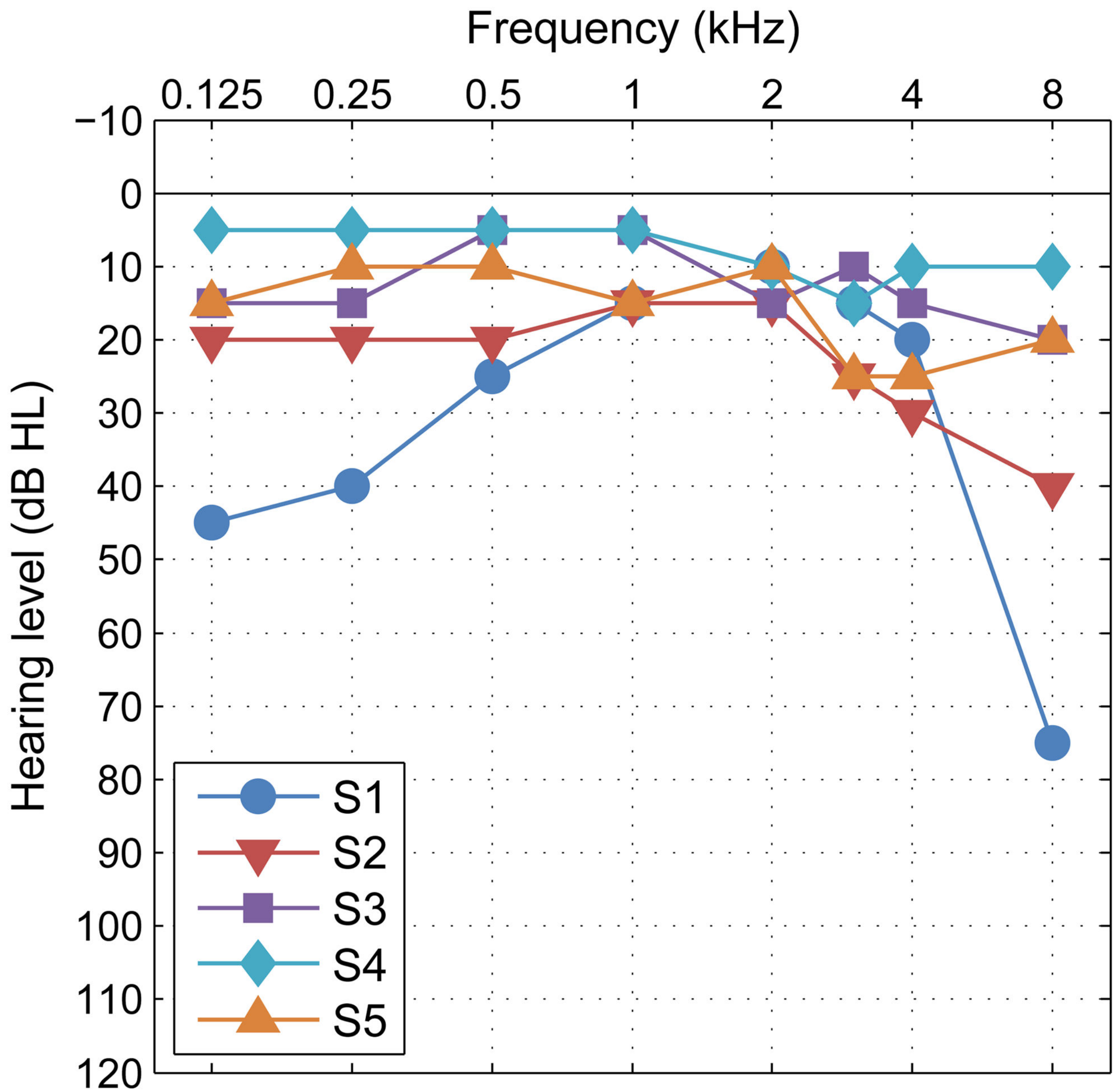

Figure 2.
Individual air-conduction pure-tone thresholds in the non-implanted ears

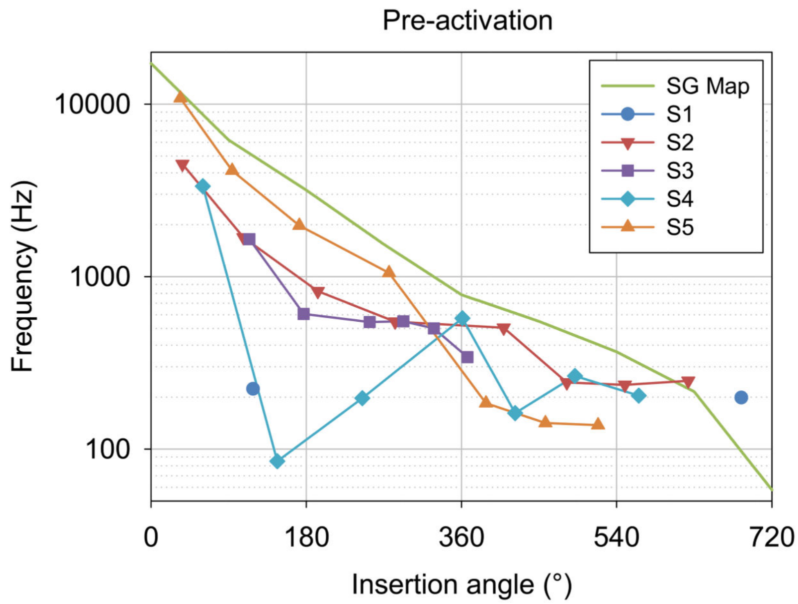

Figure 3.
Individual frequency-place functions for electrical stimulation in all five subjects at activation. The solid green line represents the spiral ganglion place-frequency as predicted by Stakhovskaya et al. (2007). Only 2 successful pre-activation matches were made for S1 so the two data points for S1 are not connected by a line.

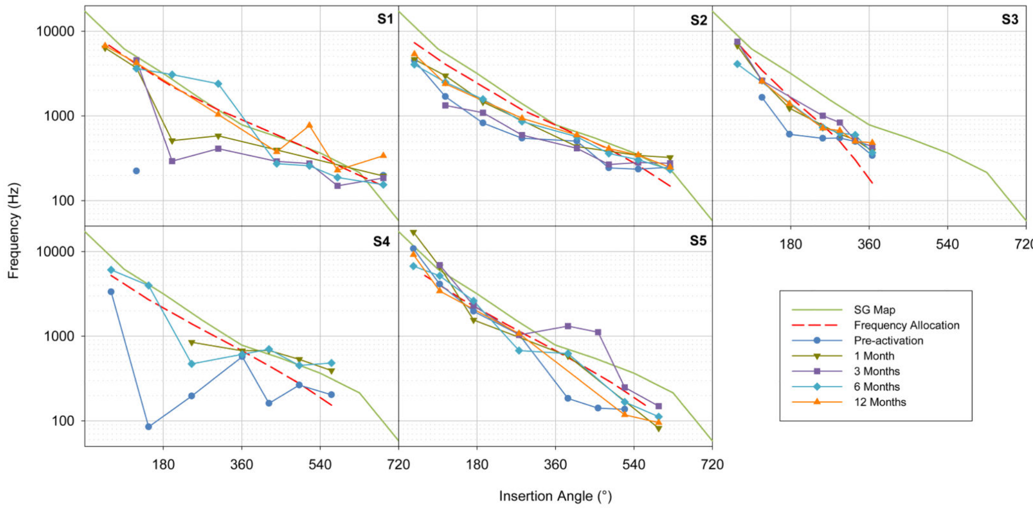

Figure 4.

Individual frequency-place functions for electrical stimulation in all five subjects. Each panel represents one of five subjects tested at the different test intervals. The solid green line represents the spiral ganglion place-frequency as predicted by Stakhovskaya et al. (2007). The dashed red line represents the frequency allocation for the corresponding subject.

Table 1

Subject demographics

Subject	Age at surgery [yrs;mo]	Duration of deafness at surgery [yrs]	Etiology	Implant & Electrode type	Implant ear	PTA (non-implanted ear in dB HL)
S1	58;8	7	Meniere	SONATA $FLEX^{SOFT}$	Left	17
S2	61;3	7	Meniere	SONATA $FLEX^{SOFT}$	Right	20
S3	60;10	0.75	Sudden SNHL	SONATA $FLEX^{24}$	Left	10
S4	44;4	9	Sudden SNHL	SONATA $FLEX^{SOFT}$	Left	7
S5	63;1	2	Sudden SNHL	SONATA $FLEX^{SOFT}$	Left	15
MEAN	57;7	5				

Table 2

Deviations in semitones from the frequency allocations are presented with standard error of the means in parenthesis. T-tests and corresponding p values are presented for each comparison. Results for the entire array as well as each cochlear region (Apical, Middle, and Basal) are presented for pre-activation, 1, 3, 6, and 12 months.

	Pre-activation	**1 month**	**3 months**	**6 months**	**12 months**
Base	22.32 (SE: 8.98)	4.89 (SE: 2.34)	4.46 (SE: 5.29)	2.01 (SE: 2.96)	2.92 (SE: 1.79)
	t(4)=2.49, p = 0.068	t(3)=1.127, p = 0.342	t(3)=1.41, p = 0.253	t(4)=0.68, p = 0.534	t(3)=1.648, p = 0.200
Middle	8.93 (SE: 4.84)	1.4 (SE: 3.19)	1.29 (SE: 6.48)	1.10 (SE: 2.18)	0.26 (SE: 2.8)
	t(3)=1.85, p = 0.162	t(4)=0.44, p = 0.684	t(3)=0.2, p = 0.855	t(4)=0.5, p = 0.642	t(3)=0.09, p = 0.932
Apex	1.2 (SE: 3.51)	−4.27 (SE: 5.22)	1.04 (SE: 1.71)	−1.54 (SE: 4.62)	−0.5 (SE: 5.69)
	t(3)=0.34, p = 0.754	t(4)=0.28, p = 0.795	t(3)=0.37, p = 0.737	t(4)=−0.05, p = 0.961	t(3)=0.205, p = 0.851
All	**11.20 (SE: 3.72)**	0.7 (SE: 1.76)	1.57 (SE: 4.25)	−0.10 (SE: 1.47)	−0.07 (SE: 1.76)
	t(4)=3.01, p = 0.040*	t(4)=−0.30, p = 0.977	t(3)=0.369, p = 0.737	t(4)=−0.071, p = 0.947	t(3)=−0.38p = 0.972