Hearing Research 326 (2015) 8–14

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research paper

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

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A R T I C L E I N F O

Article history:
Received 12 November 2014
Received in revised form
19 March 2015
Accepted 23 March 2015
Available online 1 April 2015

A B S T R A C T

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 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.

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

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

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http://dx.doi.org/10.1016/j.heares.2015.03.011

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 and 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 Fig. 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 Fig. 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,