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Place dependent stimulation rates improve pitch perception in cochlear implantees with single-sided deafness

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ABSTRACT

In normal hearing, the pitch of an acoustic tone can theoretically be encoded by either the place of stimulation in the cochlea or the corresponding rate of vibration. Thus spectral attributes and temporal fine structure of an acoustic signal are naturally correlated. Cochlear implants (CIs), neural prosthetic devices that restore hearing in the profoundly hearing impaired, currently disregard this mechanism; electrical stimulation is provided at fixed electrode positions with default place independent stimulation rate assignments. This does not account for individual cochlear encoding depending on electrode array placement, variations in insertion depth, and the proximity to nerve fibers. Encoding pitch in such manner delivers limited tonal information. Consequently, music appraisal in CI users is often rated cacophonic while speech perception in quiet is close to normal in top performers. We hypothesize that this limitation in electric stimulation is at least partially due to the mismatch between frequency and place encoding in CIs. In the present study, we determined individual electrode locations by analysis of cochlear radiographic images obtained after surgery and calculated place dependent stimulation rates according to models of the normal tonotopic function. Pitch matching in CI users with single-sided deafness shows that place dependent stimulation rates allow thus far unparalleled restoration of tonotopic pitch perception. Collapsed data of matched pitch frequencies as a function of calculated electrical stimulation rate were well fitted by linear regression ($R^2 = 0.878$). Sound processing strategies incorporating place dependent stimulation rates are expected to improve pitch perception in CI users.

1. Introduction

The anatomical and hydrodynamic properties of the cochlea are responsible for frequency-specific placement of highest amplitude of vibration (Békésy, 1949). Active movements of outer hair cells sharpen the pattern of vibration and enhance sensitivity and frequency selectivity in normal hearing (Sellick, 1982; Zwicker, 1979). Likewise, at each specific cochlear location, the basilar membrane vibrates with the corresponding rate. Therefore, the pitch of an acoustic signal is encoded simultaneously by place and corresponding rate of stimulation. Due to that inherent correlation of temporal and spectral attributes of acoustic signals, it is assumed that both mechanisms contribute to pitch perception. However, it is difficult to separate the impact of temporal and spectral attributes.

Cochlear implants (CIs), neural prosthetic devices that restore hearing in the profoundly hearing impaired, have been shown to provide great benefit in terms of speech perception in quiet. But pitch information as present in tonal languages or musical melodies is poorly perceived by the majority of CI users. Two abnormalities have been described in recent studies which impact electric pitch quality: a compressed and several octaves lowered frequency-electrode function, and frequency difference limens in electric pitch with equivalent electric frequency discrimination 24 times worse than normal-hearing (NH) controls (Baumann and Nobbe, 2006; Boex et al., 2006; Carlyon et al., 2010; Zeng et al., 2014). Zeng et al. (2014) hypothesized as cause for the disturbance of electric pitch a combination of broad electric field, distant intra-cochlear electrode placement, and non-uniform spiral ganglion cell

Abbreviations: CI, cochlear implant; NH, normal hearing; E, electrode; SSC, superior semicircular canal; V, vestibule reference; RW, round window; BT, basal turn; AT, apical turn; M, center of rotation (basal turn); M*, center of rotation (apical turn); x, insertion angle; OC, organ of Corti; SG, spiral ganglion; D/A, digital-to-analog; IQR, interquartile range

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distribution and survival, all of which are inherent to the electrode-nerve interface in contemporary cochlear implants.

In this study, we present a method of electric stimulation that improves CI user sensitivity to pitch information. The method is based on previous findings on the tonotopic representation of pitch information in NH subjects (Greenwood, 1961, 1990; Stakhovskaya et al., 2007) and takes both place and rate of stimulation into account. As a prerequisite, individual electrode locations were assessed by analysis of cochlear radiographic images obtained after surgery. According to the estimated angle of electrode insertion depth, electrical stimulation rate was adapted by application of a modified place-frequency function (Greenwood, 1961; Stakhovskaya et al., 2007).

2. Material and methods

2.1. Subjects

Eleven subjects with late-onset single-sided deafness and almost normal hearing in the unaffected ear participated in the study. Normal hearing was considered for pure-tone air conduction thresholds below 35 dB HL in the frequency range from 125 Hz to 4 kHz. The difference to bone conduction thresholds was below 15 dB HL in the same frequency range. All subjects were experienced CI users (range 7–40 months after implantation) with CONCERTO or SONATA devices (MED-EL, Innsbruck, Austria) and either the 28 mm FLEX28 electrode array ($n = 9$) or the 31.5 mm FLEXSOFT electrode array ($n = 2$). Subject demographical data are provided in Table 1. Pure-tone air conduction thresholds for the non-implanted ear and for the deaf ear with (i.e. aided threshold) or without the CI are shown in Fig. 1.

The experiments described here were part of a study titled in German "Tonhöhenvergleiche und Hörleistung bei Cochlea-Implantat-Trägern mit einseitiger Taubheit" [Pitch comparison and assessment of hearing in single-sided-deafness cochlear implant users], approved by the local ethics committee (J.W.-Goethe-University Frankfurt, IRB number 209/13). In addition to the pitch matching experiment, the subjects participated in several other tests concerned with sound localization and speech perception in noise. All participants signed an informed consent formular and received an allowence for their expenses.

2.2. Insertion angle estimation

Postoperative X-ray images acquired with Stenvers' projection

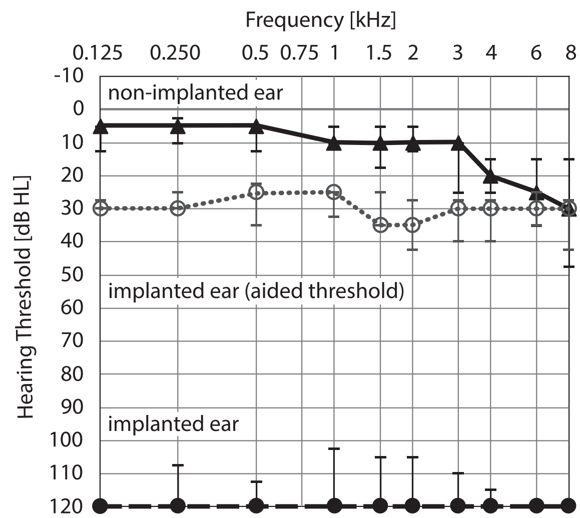

Fig. 1. Air conduction pure-tone audiograms (medians and interquartile ranges) for the non-implanted ear and for the deaf ear with (aided threshold) or without using the CI.

(cochlear view, Xu et al., 2000), which demonstrate the petrous temporal bone, were used to determine the insertion angle for each electrode (Fig. 2B). Fig. 3 schematically shows how the insertion angle of each electrode was assessed: the point at which the electrode array (E) crossed a reference line between the superior semicircular canal (SSC) and the center of the vestibule reference (V) was determined as a geometric zero reference (Boex et al., 2006; Cohen et al., 1996; Xu et al., 2000). This point corresponds to the round window (RW) and the insertion point of the electrode array into the cochlea. The central axis in the cochlea, the modiolus, served as center of rotation. Two centers of rotation exist due to the helical geometry of the cochlea: the center of rotation of the basal turn (BT) which starts at the RW is denoted by M, and that of the apical turn (AT) by M*. The insertion angle $\boldsymbol{x}$ of each stimulating electrode was measured by clockwise rotation starting at the geometric zero reference (Verbist et al., 2010).

2.3. Frequency mapping

The percentage distance (or percentage length) of the organ of Corti (OC) or the spiral ganglion (SG) of the cochlea as a function of the insertion angle from the round window was previously formulated (Stakhovskaya et al., 2007) as:

Table 1
Subject demographics. Freiburger monosyllables tested in aided condition (with CI) at 65 dB SPL (distance to speaker 1.2 m), double blocking of the normal hearing ear provided by insert foam protectors combined with additional ear muff. Implants manufactured by MED-EL, Austria. Straight flexible electrode arrays of either 28 mm (FLEX28) or 31.5 mm (FLEXSOFT). See Table 2 for corresponding individual depth of insertion.

Subject	Age at surgery [years]	Duration of functional deafness [years]	Duration of implant use [months]	Sex	Ear implanted	FMS with implant [%]	Implant type	Electrode type	Etiology
S01	43	4	30	M	R	75	CONCERTO	FLEXSOFT	Sudden hearing loss
S02	45	1	7	F	R	75	CONCERTO	FLEX28	Sensorineural hearing loss
S03	68	18	10	F	L	45	CONCERTO	FLEX28	Sudden hearing loss
S04	70	3	10	M	R	85	CONCERTO	FLEX28	Infection
S05	68	>2[a]	26	M	L	85	CONCERTO	FLEXSOFT	Sudden hearing loss
S06	62	>2[a]	12	F	R	85	CONCERTO	FLEX28	Sensorineural hearing loss
S07	69	4	40	F	R	50	SONATA	FLEXSOFT	Sudden hearing loss
S08	38	1	23	M	R	75	CONCERTO	FLEX28	Sudden hearing loss
S09	44	2	23	M	L	60	CONCERTO	FLEX28	Sudden hearing loss
S10	31	>2[a]	12	F	L	15	CONCERTO	FLEX28	Cholesteatoma
S11	28	8	11	F	R	90	CONCERTO	FLEX28	Sudden hearing loss

[a] At least 2 years of functional deafness. F, female; M, male. L, left; R, right; FMS Freiburger monosyllables Speech Test.