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Review

Deep electrode insertion and sound coding in cochlear implants

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ABSTRACT

Present-day cochlear implants demonstrate remarkable speech understanding performance despite the use of non-optimized coding strategies concerning the transmission of tonal information. Most systems rely on place pitch information despite possibly large deviations from correct tonotopic placement of stimulation sites. Low frequency information is limited as well because of the constant pulse rate stimulation generally used and, being even more restrictive, of the limited insertion depth of the electrodes. This results in a compromised perception of music and tonal languages.

Newly available flexible long straight electrodes permit deep insertion reaching the apical region with little or no insertion trauma. This article discusses the potential benefits of deep insertion which are obtained using pitch-locked temporal stimulation patterns. Besides the access to low frequency information, further advantages of deeply inserted long electrodes are the possibility to better approximate the correct tonotopic location of contacts, the coverage of a wider range of cochlear locations, and the somewhat reduced channel interaction due to the wider contact separation for a given number of channels.

A newly developed set of strategies has been shown to improve speech understanding in noise and to enhance sound quality by providing a more “natural” impression, which especially becomes obvious when listening to music.

The benefits of deep insertion should not, however, be compromised by structural damage during insertion. The small cross section and the high flexibility of the new electrodes can help to ensure less traumatic insertions as demonstrated by patients' hearing preservation rate.

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1. Introduction

A sound signal can be divided into two principal components, referred to as the envelope and the (temporal) fine structure (Hilbert, 1912). The envelope of a signal is defined by the Hilbert transform. It can be approximated by rectification followed by a low pass filter. The fine structure contains information about instantaneous frequency of a sound and is coded in the time domain via phase locking in the low frequencies. In speech and other acoustic signals, envelope and fine structure contribute differentially to the comprehension of sounds. Smith et al. (2002) and later Xu and Pfingst (2003) quantified these relative contributions as a function of the number of analyzed filter bands (corresponding to the number of channels in a cochlear implant). Results revealed that speech perception largely relies on the envelope of the sound whereas music and other tonal instances of sounds like prosody or tonal languages are mainly conveyed by the fine structure of the sound signal. This already hints at the improvements to be expected from apical temporal coding: “naturalness”, better performance with tonal languages, and more enjoyable perception of music. The degree of “naturalness” can be described by a single sided deaf subject by comparing the electrically versus the acoustically generated impression.

It is well known from physiology that – depending on frequency – sounds are not only coded in cochlear place but also in the temporal structure of neural responses, referred to as the time code. In natural hearing, low frequency sounds are coded both in place and time in the apical region of the cochlea. Sound frequency

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Abbreviations: EAS, electric-acoustic stimulation; CI, cochlear implant; CIS, continuous interleaved sampling; CIS+, CIS-variant; FSP, FS4, FS4-p, fine structure strategies; HDCIS, CIS-variant; HP, hearing preservation; SRT, speech reception threshold; MCL, most comfortable loudness; VEMP, vestibular evoked myogenic potential

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is thus not only coded in place but is also reflected in the temporal neural response pattern here. With increasing frequency, time coding vanishes, so that high-frequency sounds are only coded in place – the temporal response pattern of the neurons no longer reflects sound frequency. Temporal coding is produced by a mechanism that is usually referred to as phase locking, meaning that neural responses tend to arise at a certain point in time during each single period of the stimulus. With increasing frequency, phase locking and thus time coding vanish at frequencies beyond approximately 1.5 kHz.

In normal hearing, time coding and place coding usually covary in the cochlea so that it has been difficult to assess the importance for the low frequencies of either of these codes in isolation. Research using transposed tones (Oxenham et al., 2004), however, has demonstrated that when low-frequency sinusoids are presented to places in the cochlea that are tuned to higher frequencies, i.e. in the case of a mismatch between time code and place code, then pitch perception deteriorates dramatically when compared to the matched-time-place condition. In addition, the ability to extract the pitch (i.e. fundamental frequency) of a sound from a multitude of low-frequency harmonics disappears if these low-frequency harmonics are presented to high-frequency places in the cochlea. All in all, these results demonstrate the importance of frequency-place matching. Consequently, with electrical stimulation the mapping of frequency bands to location influences the "naturalness" of the elicited sensations.

2. Coding strategies

Strategies and algorithms for representing sounds through a cochlear implant have been a core challenge in cochlear implants from the early days. In the early '80's the more fundamental questions, like

monopolar or bipolar stimulation,
analog or pulsatile stimulation,
whole signal presentation or feature extraction,
fine temporal structure or place pitch
had to be addressed.

Our first design was a multichannel implant intended for pulsatile stimulation (I. Hochmair, 2013). Having been implanted in Dec. 1977, it was the first microelectronic multichannel cochlear implant (Fig. 1). It thus may be considered as the prototype of the modern cochlear implant. However, our experience with it led us to the conclusion that we needed a more signal-transparent system that would give us more flexibility in developing a viable coding strategy. To avoid percutaneous plugs, which are great for research but rather burdensome for the patient, we developed a passive transcutaneous four channel system which turned out to be our workhorse for the coming years. Since it allowed stimulation with any kind of pulsatile or analog waveform, it opened the door to a whole new realm of research possibilities. It was extensively used in our laboratory work to run psychoacoustic tests as well as to explore the possibilities of multichannel coding strategies. For the wearable processor only one channel was used. It took us almost 12 more years to reassume our original approach.

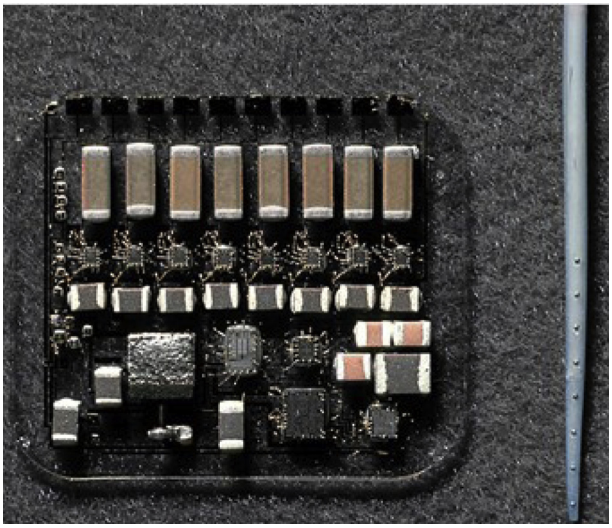

Fig. 1. 8-channel microelectronic cochlear implant together with scala tympani electrode. The substrate containing the electronic components was encased within a hermetic glass package and connected to the electrode and to the receiver coil (not shown here) via hermetic feed throughs.

To keep power consumption low, we had quickly decided to use monopolar stimulation, despite findings from animal experiments demonstrating the narrower stimulation range of bipolar stimulation. This decision more or less answered the remaining questions: a large current spread around intrascalar stimulation contacts is less amenable to multichannel stimulation providing place pitch, but rather to a single channel broadband stimulation signal (Hochmair-Desoyer et al., 1981). Our approach did not use a modulated 16 kHz carrier like the House single channel device, but used the broadband analog signal proper for stimulation. Dynamic range compression was achieved by a fast attack/slow release automatic gain control with an adjustable compression ratio. The frequency response was adjusted to closely fit the frequency characteristic of the particular channel/site used. This fitting was achieved by continuously presenting at MCL-level 10-s sweeps over the audio frequency range while simultaneously displaying the frequency response on screen. Thus the patient could on the spot indicate frequencies where adjustments were needed.

This strategy had to cope with the limited-benefit reputation of other single channel devices, but the speech understanding it provided was at least as good as, e.g. the widely promoted F0/F1/F2-strategy. This fact was recognized quite late, following the publication of independent test results by Tyler (1988). Video clips of subjects playing an instrument demonstrate astonishing music perception. This is not surprising in the light of the more recent findings (Smith et al., 2002; Xu and Pfingst, 2003).

Nevertheless, the lack of spectral information limited the achievable speech understanding. Attempts to provide place pitch information in addition to temporal coding by others and by us did not produce the expected improvements. This was either due to the increased channel interaction with simultaneous multichannel analog stimulation (Eddington, 1980), or due to the use of – against our better knowledge – feature extraction to determine channels, i.e. stimulation sites, according to formants F1 and F2 for a pitch-synchronous pulsatile stimulation signal in addition to the analog broadband channel (Zierhofer et al., 1993). A schematic representation is shown in Fig. 2.

The development of the Continuous Interleaved Sampling (CIS) strategy by Blake Wilson and colleagues in the early '90s (Wilson et al., 1991) was a breakthrough. Despite being deceptively simple compared to previous and contemporary feature-extraction strategies, CIS has nevertheless provided impressive improvements in speech perception with cochlear implants. CIS has practically developed into a standard, and the principles behind CIS (frequency analysis, envelope extraction, constant-rate stimulation) have been the foundation of almost every further development in this area. Its success can be at least partially attributed to three features:

* reduced influence of channel interaction due to non-simultaneous ("interleaved") pulsatile stimulation

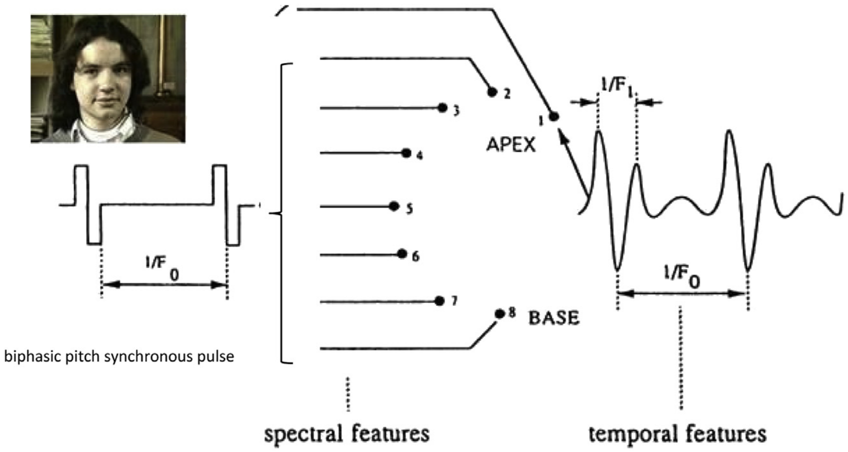

Fig. 2. Schematic of the multichannel implant designed for our strategy combining analog and pulsatile simulation (CAP-strategy). The analog signal was continually presented via the most apical channel, the other channels carrying pitch rate pulsatile signals were selected depending on the frequency of spectral maxima representing formants.

* filter banks with bell shaped frequency characteristics allow, due to the "virtual channel effect", a comparatively fine spectral resolution. Depending on the steepness of the filter slopes, the spread of excitation, and the CI-wearer's amplitude discrimination, up to 250 discernible bands are theoretically possible with a 12-channel electrode (Nobbe et al., 2007). These bands are, however, not to be confused with the number of physiologically independent channels.

Being an envelope based strategy, largely ignoring temporal fine structure, CIS lacks low frequency code. This can affect music enjoyment and the communication in tonal languages. The pitch modulation apparent in non-resolved filter outputs may not be sufficient to replace the missing rate pitch.

A number of variants of CIS such as CIS+ and HDCIS have been implemented in cochlear implant systems today that, depending on the implementation of, e.g. the envelope extraction stage, provide varying degrees of temporal fine structure information in the low frequencies.

The importance of faithful low-frequency coding in time and place in connection with cochlear implants can be inferred from Electric-Acoustic Stimulation (EAS), i.e. the combination of acoustic stimulation and electric stimulation in individuals with good-to-moderate acoustic hearing in the low frequencies and severe-to-profound hearing loss in the mid-to-high frequencies. In contrast to CIS-like coding strategies such as CIS + or HDCIS, EAS provides users with both correct place and time coding in the low frequencies via acoustic stimulation and the normal physiological processes in the cochlea. Users of EAS on average show better speech perception in noise and music appreciation when compared to electrical stimulation alone using CIS-type coding strategies (Von Ilberg et al., 2011). EAS thus demonstrates the potential for improvements that could be made with cochlear implants using closer-to-natural coding of low-frequency sounds.

3. Electrical stimulation combining temporal and spectral fine structure

MED-EL has recently developed strategies, which, in contrast to fixed-rate envelope-based coding strategies, use the timing of stimulation to code the temporal structure of the sound signal in the low frequencies. These strategies were developed in an attempt to translate the lessons learned from broadband analog stimulation and from EAS into algorithms that allow individuals with little to no residual hearing to also benefit from improved low-frequency sound coding. In these strategies, series of stimulation pulses are triggered by zero-crossings in a low frequency channel's band-pass filter output, i.e. the fine structure of the sound signal in the respective frequency range (Zierhofer, 2003; Zierhofer and Schatzer, 2012). Thereby, such a strategy attempts to create phase locking by eliciting neural responses in synchrony with the fine structure of the sound signal. It goes beyond coding strategies with fixed-rate envelope-modulated stimulation. In contrast, pulse trains are rate modulated whereby the rate modulation follows instantaneous fine structure frequency. Place coding is provided by CIS or CIS-like stimulation for the higher frequencies.

The concept of encoding low-frequency components of sounds via rate modulations is supported by recent research in implant users with relatively good acoustic hearing in the non-implanted ear. Vandali et al. (2013) found a good match between the acoustic pitch produced by a complex harmonic tone and the electrical pitch produced by an unmodulated pulse train with a stimulation rate equal to the fundamental frequency of that tone, i.e. a rate-coded stimulus. In addition they found that the pitch produced by amplitude modulated pulse trains was generally higher than that for rate-coded stimuli with a pulse rate equal to the amplitude modulation rate. Thus, pulse rate coding seems to produce more natural pitches than coding via amplitude modulations, at least for relatively shallow amplitude modulations as presented in envelope-based coding strategies.

Particularly in combination with rate coding, the importance of frequency-place matching in normal hearing as discussed above also seems to hold in cochlear implants. Schatzer et al. (2014) showed in single-sided deaf cochlear implant users that the acoustic pitch produced by low-frequency pure tones can be best matched by stimulating electrodes located in the second turn at a rate that essentially equals pure tone frequency. These results suggest that the acoustic pitch of low-frequency tones can be recreated most reliably via a cochlear implant by using a combination of rate coding and stimulation in the second turn.

In this context, interesting results have recently been published in a case study by Prentiss et al. (2014). A patient with up-sloping hearing loss but otherwise preserved residual hearing across the entire audio frequency range in the implanted ear matched the pitch of acoustic pure tones ~~and~~ with that of an electrode stimulated with an unmodulated pulse train at varying rates. The results are shown in Fig. 3. These results carry some important implications although it is appreciated here that pitch matching in the

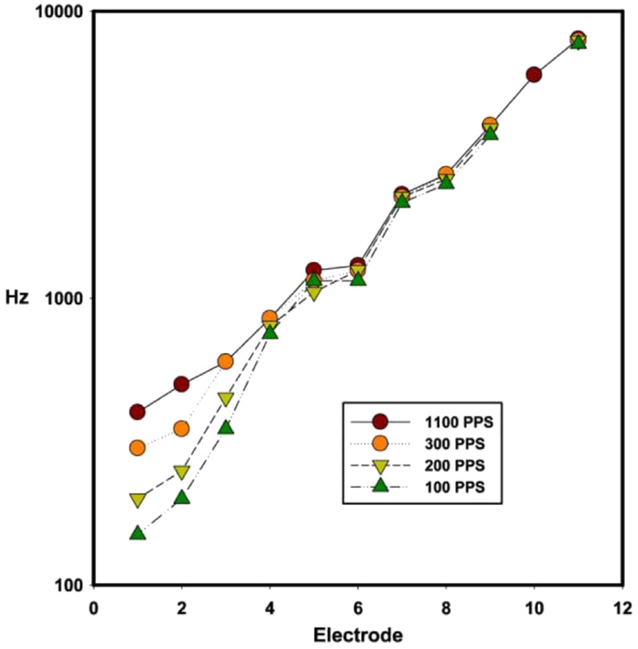

Fig. 3. The frequency of a pure tone presented acoustically, matched in pitch to the electrode pitch elicited by a pulse signal for four different pulse rates. Notice the strong dependence on the pulse rate in the apical region. Reproduced from Prentiss S, Staecker H, Wolford B. ‘Ipsilateral acoustic electric pitch matching: A case study of cochlear implantation in an up-sloping hearing loss with preserved hearing across multiple frequencies’, Cochlear Implants International, Volume 15 Issue 3 (May, 2014), pp. 161–165, Fig. 3., with permission of Maney Publishing (www.maneyonline.com/cim).

apical turn of the cochlea can show greater variability compared to the basal and middle regions, as indicated in Schatzer et al. (2014). First, extending stimulation into the apical region of the cochlea expands the range of perceivable pitches. Second, the apical region of the cochlea seems to be particularly suited for rate coding since variations in pitch due to variations in rate are larger here than elsewhere in the cochlea. Third, similar to the results by Schatzer et al. (2014), reliable low-frequency pitches can only be produced by a cochlear implant when stimulating electrodes in the apical region of the cochlea at a rate that approximately corresponds to acoustic frequency. Thus, taking the results of Prentiss et al. (2014) and Schatzer et al. (2014) together one may conclude that low-frequency pitches of a different quality can be produced via a cochlear implant by combining stimulation of electrodes in the apical region and rate coding at low frequencies.

4. Extending electrical stimulation into the apical region

Long straight electrodes can be inserted more deeply than those that are perimodiolar and thus have the inherent advantage of extending the range of electrical stimulation into the apical region. Thus they not only provide a broader range of cochlear locations, but also allow much better place pitch match than any shorter electrode.

With short electrodes, like e.g. the perimodiolar pre-shaped electrodes with many contacts over a short distance mainly covering the basal turn, stimulation concepts assume that partial cortical remapping of frequencies will occur. Many implant patients report a “high, pitch” sound quality upon initial stimulation of the implant. A shallow insertion can be partially responsible for this initial perception. Over time, perception improves and is then often described as “normal,” or “more natural.” Studies (McDermott et al. (2009) and Reiss et al. (2014) show, that in adults pitch received through a cochlear implant changes with experience in a fairly systematic and predictable manner. Short electrode arrays produce a place mismatch, which some auditory systems can resolve to a greater or lesser degree. In fact, changes in perception can be dramatic, as much as 3 octaves, but this adaption can take years to occur. Over time, the implant recipient seems to compensate for distortions in frequency representation. Providing a higher percentage of cochlear coverage by extending electrodes into the apical region reduces the need for cortical remapping and might lead to a faster rate of learning with the implant. Dorman et al. (1997) found electrode arrays reaching the apical region provide a better initial place pitch match which positively affects the patient's asymptotic performance. More recently, Buchman et al. (2014) investigated the influence of electrode insertion length on cochlear implant performance. In a randomized, prospective study, subjects received either a MED-EL standard array or a MED-EL medium array and were followed for 1 year. Results indicate a trend for better performance at 6 months post-activation in subjects that received the standard array. This difference between treatment groups caused the IRB to halt subject recruitment. Data added retrospectively on standard array users confirmed the difference between the groups was significant.

Cochlear implants are designed to filter incoming signals into different frequency bands which are transmitted to intracochlear, tonotopically distributed electrodes (Fig. 4). Allocating frequency bands to electrode contacts in a way that the spectral information matches the tonotopic contact place is referred to as a “place pitch match”. There is a growing body of evidence to show that a better place pitch match leads to better sound quality and allows implant recipients to reach asymptotic levels of speech perception at faster rates. An additional contribution to better speech understanding could be due to the greater separation between electrodes, resulting in better channel separation and consequently in a larger number of physiologically effective independent channels, which rarely exceeded 8 with any brand of CI (Friesen et al., 2001; Dorman et al., 2006; Niparko, 2009).

Cochlear implant recipients with normal hearing or some degree of residual hearing in the contralateral ear provide insights into comparisons between pitch percepts elicited by electrical stimulation through the implant to those elicited by acoustic stimuli. Vermeire et al. (2008) studied 14 subjects implanted with MED-EL FLEXsoft (31 mm length) or medium (24 mm length) electrode array with functional hearing in the contralateral ear. Pitch scaling experiments were performed using single-electrode, constant-amplitude constant-rate stimuli in the implanted ear and acoustic sinusoids in the contralateral ear. Their results indicate that electrical stimulation produced by a frequency-place function, on average, resembles Greenwood's (1961) function plus or minus half an octave. (The Greenwood function is a map of characteristic frequencies onto cochlear place.) In other words, a good place pitch match was achieved with a long electrode array.

Landsberger et al. (2014) evaluated the perceptual distances between electrodes using multi-dimensional scaling in 14 subjects implanted with the MED-EL 31 mm standard or FLEXsoft array. Using this tool, the magnitude of perceptual difference between adjacent electrodes can be compared. Results show that there are perceptual differences between apical electrodes, although smaller than in the medial and basal region. Extending the range of stimulation (rate coded) into the apex increases the range of perceivable pitches, resulting in a wider range of pitches that can be perceived through a cochlear implant. Similar findings using a different test paradigm were reported by Hamzavi and Arnoldner (2006).

The better place pitch match achieved by a higher percentage of cochlear coverage in combination with fine structure is likely to

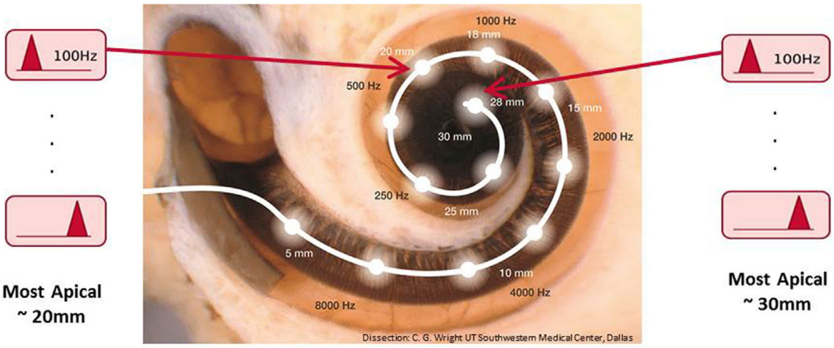

Fig. 4. Place pitch match is only possible with a sufficiently long electrode (in this case 30 mm long).

best suit the single sided deaf population due to the more natural low-frequency pitch provided by these two techniques. A closer match to the contralateral, normal hearing ear should ease the learning process and increase acceptance of the implant since the perceived frequency range via electrical stimulation more closely matches the frequency range of the normal ear.

5. Speech and music perception with rate coding strategies

Several coding strategies that use rate coding in the low frequencies combined with place coding across all frequencies – in the following referred to as fine structure strategies – were developed. They differ in the number of rate pitch stimulation channels (FSP, FS4) and whether they allow simultaneous stimulation on selected channels (FS4-p). In a number of studies, improvements were found in speech perception in both adults (Vermeire et al., 2010; Müller et al., 2012) and children (Lorens et al., 2010; Riss et al., 2011a), but more importantly, no degradation was found on average, when results were compared to the CIS + strategy. These results indicate that strategies combining rate coding in the low frequencies with place coding across all frequencies not only allow improved performance but are clinically a safe choice. One study (Riss et al., 2011b) indicated that at least short-term improvements with these strategies could also be due to the extended frequency range inherent to these strategies. The question, whether processing of the temporal fine structure needs to be re-learned by users that have been using fixed-rate envelope-modulated stimulation strategies, might be highlighted by a study by Vermeire et al. (2010) that found significantly improved speech perception with these new strategies only after one year of use. In a recent publication, Kleine Punte et al. (2014) reported a statistically significant mean SRT-improvement at two years after switching 25 subjects from HDCIS to FSP, albeit in a non-blind experimental setup. Another study (Magnusson et al., 2011) did not find any average improvement in speech perception with a fine structure strategy even after two years of use, however, in this study the fitting has not been optimized after switching from CIS+, which could also explain why – in contrast to Müller et al. (2012) (see below) – more subjects rated HDCIS significantly better for music.

With respect to the possible benefits of low-frequency rate coding within these new strategies, studies investigating music perception are of particular interest. Müller et al. (2012) found that among experienced cochlear implant users who had used a fine structure strategy for three months, 91% of the subjects reported that, in general, music sounded pleasant, with 64% saying it sounded fuller or more resonant in comparison to CIS+. Looi et al. (2011) found that when subjects were acclimatized to HDCIS, no difference in quality ratings existed between HDCIS and the tested FSP, but when subjects were acclimatized to FSP, they rated FSP closer to how they want their cochlear implant to sound, indicating that subjective satisfaction with sound quality can also depend on previous experiences. Recently presented results employing a test method that is relatively new to cochlear implants indicate improved perception of lower frequencies in musical pieces with FSP when compared to HDCIS. Using a method called CI-MUSHRA (Cochlear Implant-MUltiple Stimulus with Hidden Reference and Anchor), Roy et al. (2014) investigated to what degree normal hearing listeners and CI users experience changes in perception if these lower frequencies are filtered out from the musical pieces. They found that with FSP, subjects are equally sensitive to filtering out of low frequencies as normal hearing listeners, whereas with HDCIS they show reduced sensitivity. This finding suggests that these frequencies are less perceivable with HDCIS. In summary, these results indicate that with low-frequency rate coding, fine structure strategies can indeed provide improved sound quality and low frequency perception.

6. Electrodes

As has been shown above, a low frequency pitch rate signal must be applied to nerve fibers in the apical region in order to contribute

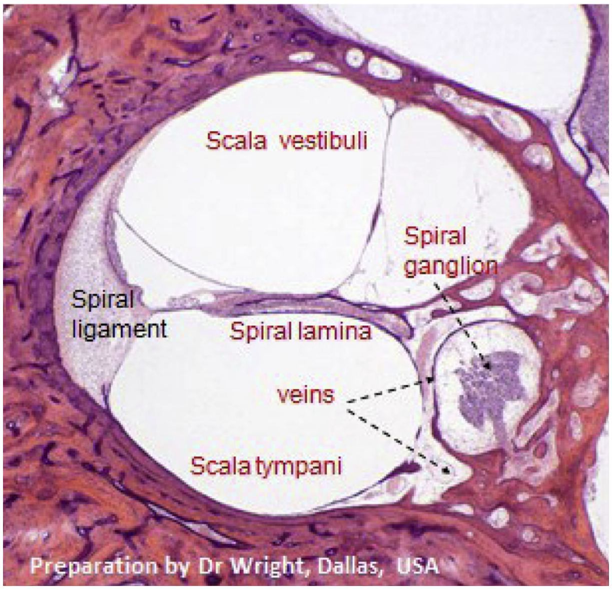

Fig. 5. Cross section of the cochlea (Celloidin stain). Preparation by Dr. C.G. Wright, UTSW, Dallas, USA.

to the naturalness of the percept. This requires electrodes which are long enough to reach this region. At the same time, they have to be thin and sufficiently flexible to not traumatize the delicate structures in the cochlea (Fig. 5).

Insertion of an electrode into the scala tympani is a fierce event: The round window membrane is incised, or a cochleostomy drilled, the tip and body of the electrode friction-rub against tissues lining the scala tympani exerting forces and pressure, especially as the cochlea becomes more tightly coiled. Venules lining the lateral wall are challenged (Wright and Roland, 2013) (Fig. 6).

In the early days of cochlear implantation, CI indications were for profoundly deaf patients many of whom had been afflicted with deafness for decades. The cochlea was considered a dead organ. There was little concern about cochlear structure preservation except for spiral ganglion cells and axons, the declared target of electrical stimulation at that time. Peripheral processes in the form of dendrites were assumed to be absent or severely depleted from base to apex.

As indications for CIs changed to include young and very young children who will be implanted and reimplanted several times in their lifetime and whose neural tissue is most likely pristine from peripheral to proximal neural processes, it has then become of the utmost importance to preserve structure as much as possible. Considering the progressing human life expectancy it can be stated that the probability of CI replacement in the young and very young population is close to 100%, for all devices and all manufacturers, and most likely more than once in a lifetime. With the introduction of fully implantable CIs most likely necessitating battery replacement every 10 years or less, it is essential that the electrode array insertion and explantation processes do not accumulate tissue and neural damage. There is evidence, that with soft and flexible electrodes, explantation and re-implantation can be accomplished with hearing preservation the second time around, when residual hearing was present first time around (Helbig et al., 2013; Jayawardena et al., 2012; Kamat et al., 2011). Hearing preservation after re-implantation was unthinkable two decades ago.

Structure preservation has become a significant topic in the field of cochlear implantation. It refers to minimizing the interference of the electrode insertion process with the most delicate tissues of the inner ear (Fig. 5). The tissues at risk during electrode insertion are the spiral ligament and stria vascularis, osseous spiral lamina, basilar membrane and organ of Corti, neurites where present (peripheral processes), spiral ganglion cells and axons behind the bony modiolar wall, and the venous blood supply (A. A Eshraghi, 2006).

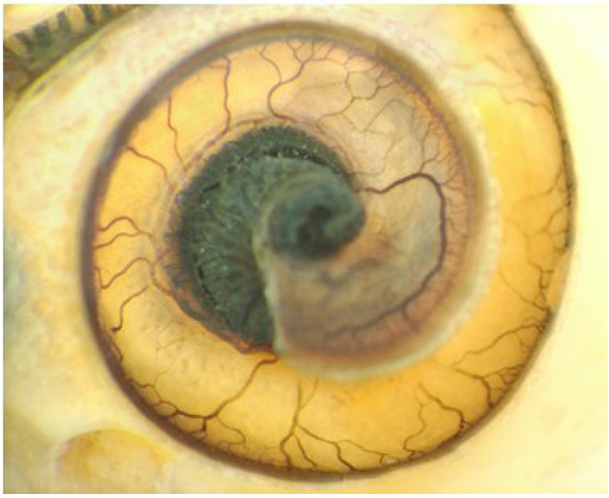

Fig. 6. Dissected cochlea with scala vestibule partition removed exposing venules draining the spiral ligament in the scala tympani. The center of the photograph shows the osmium stained modiolus. Preparation by Dr. C.G. Wright, UTSW, Dallas, USA.

Reliable structure preservation after electrode insertion could extend the indications for cochlear implants to much less severe deafness and more residual hearing, tinnitus, and for inner ear interventional drug therapy (Erixon et al., 2012). Theoretically, a high degree of structural preservation after electrode insertion or removal does not preclude the reversibility of cochlear implantation through gene and stem cell therapies, even in some decades from now. There are however no therapies which can repair structural damage to the cochlea. The research field of stem cell and gene therapies for the inner ear to correct hearing loss is evolving rapidly with approved clinical trials under way specifically for the treatment of specific hearing losses.

6.1. *Structure preservation demonstrated by hearing preservation*

Structure preservation in hearing preservation surgery can be demonstrated by evaluating post-op residual hearing. The importance and demonstration of structure preservation could not have been established without the initial rise of hearing preservation electrodes and surgical techniques (von Ilberg et al., 2011). CI electrodes and surgical techniques designed for hearing preservation and for combined electric acoustic stimulation (EAS) or partial deafness treatment (Skarzynski, 2007) not only require the preservation of the fragile scala tympani tissue from base to apical region, they also require minimal interference with micro structures, mainly inner and sometime outer hair cells. Furthermore, hearing preservation as a subset of structure preservation requires the maintenance of the endocochlear potential. Hearing preservation of whatever measurable degree demonstrates that the electrode is strictly in the scala tympani without translocation. This is true even if residual hearing is lost some time after surgery. Post-op loss of residual hearing in EAS cases is caused by indirect actions of the electrodes since the region of residual hearing lost in most of the cases is distal to the electrode tip (Jolly et al., 2010). Deep electrode insertion, however, does not preclude conservation of residual hearing. Surgical skill has advanced considerably during the last several years. There are now several publications reporting preservation of residual hearing (i.e. preservation of micro and macro structures) with deep insertion electrodes up to 28 or even 31 mm in length (Usami et al., 2011; Helbig et al., 2011; Mick et al., 2014; Skarzynski et al.,. 2011; Mandalà et al.,. 2012; Tamir et al., 2013). Hearing preservation in patients with some pre-op residual hearing continues to increase and is now reaching 90–95% of patients when free fitting lateral wall electrodes of different length have been used (Fig. 7). While the maximum post-op period of observation for these patients did not exceed 12–13 months, it should be noted that any level of residual hearing immediately or shortly post-op demonstrate that the electrode did not translocate. Another way to infer structure preservation in patients with little or no residual hearing is to observe and compare saccular functions between pre and post-op. Vestibular evoked myogenic potential (VEMP) and caloric function, if they are unaffected, could testify for the insertion quality. Post-op dizziness could indicate an undesirable event caused by electrode insertion (Tsukada et al., 2013).

6.2. *Structure damage demonstrated by post-op imaging*

Of recent interest worldwide has been post-op imaging able to demonstrate the electrode position intra scala after insertion (Aschendorff, 2011). New imaging modalities such as cone beam computer tomography use reduced radiation while preserving a detailed view of electrode position within the inner ear (Martinez-Monedero et al., 2011). Major structural damage can be inferred when the electrode is reported to dislocate from one scala to the other (A Eshraghi, 2006). Some pre-shaped electrodes inserted

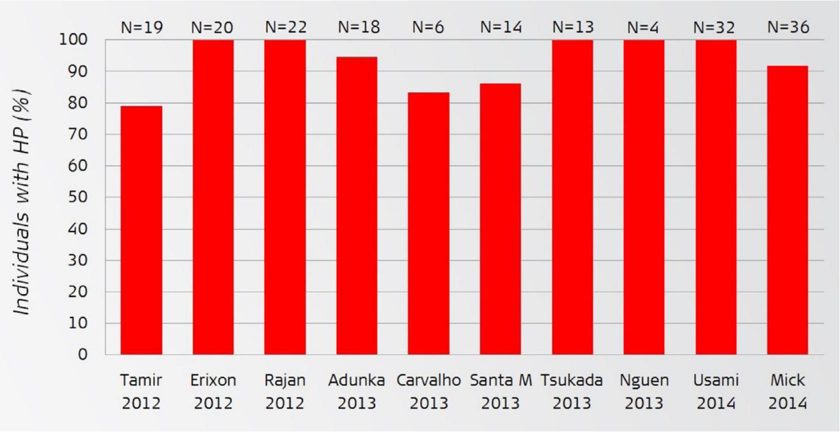

Fig. 7. Percentage of individuals with hearing preservation in recently published literature.

through cochleostomy translocate about 50% of the time when the literature is scrutinized (Finley et al., 2008; Wanna et al., 2011; Aschendorff et al., 2011; Holden et al., 2013; Wanna et al., 2014).

Translocation can happen even in the hands of the best surgeons. The reported rate of translocations is an unacceptable situation for patients, adults and children. While post-op imaging studies for deeply inserted long electrodes are not specifically available it is important to note that any amount of residual hearing present immediately post-op infers that the electrode is in scala tympani and has not translocated into scala vestibuli through ruptures and fractures of the structures separating the scalae. The endocochlear potential must be intact. Importantly, the deep insertion of short electrode designed for basal turn has proven detrimental to both scala location and performance of patients (Finley et al., 2008). Temporal bone studies and insertion force measurements in models are of limited but important value to demonstrate the pre-market behavior of a new electrode design. They cannot, however, replace post market evaluation: residual hearing preservation, VEMPS, and imaging to assess final electrode location.

6.3. Methods for structure preservation

The surgical approach is essential for structure as well as for hearing preservation. Slow insertion through the round window membrane with lateral wall electrodes is becoming the standard approach in many centers (Rajan et al., 2013). Interestingly, round window membrane electrode insertion was assumed to be unfavourable for HP, even though it became systematically used in one large centre with remarkable results (Skarżyński et al., 2003). Historically, round window insertion was the original way to insert electrodes until rigid banded electrodes causing difficulties and incomplete insertions were introduced. The cochleostomy approach to enter the cochlea was introduced as soft surgery specifically for the rigid electrode with banded contacts (Cohen, 1997).

One problem with the cochleostomy approach is the lack of consensus where it should be initiated (Adunka et al., 2007). When drilling a cochleostomy into the best guessed location there is often the possibility of basilar membrane perforation and mixing of endolymph and perilymph leading to loss of endocochlear potential. The best method to open the round window membrane is under intense discussion. Ending electrode insertion at the point of first serious resistance is essential for structure preservation.

Recent data shows that the cochlear duct length (scala tympani length measured at the organ of Corti) can vary by 40% between shortest and longest cochleae (Hardy, 1938; Lee et al., 2010) (Fig. 8). Just one electrode length will not give equivalent cochlear coverage for all patients. Even a medium length electrode of 24 mm may be too long for a very short cochlear duct length while a long electrode of 31 mm will be too short for completely covering the longest cochlear duct length. Pre-op imaging and simple radiographic measurement of the diameter of the basal turn of the cochlea can infer the cochlear duct length and help in choosing the right electrode for a specific patient (Escude et al., 2006; Alexiades, 2012). For the EAS patient, the cochlear duct length is an important parameter in choosing an electrode length which does not overlap with the residual hearing region. Personalized and tailored medicine for cochlear implantation is becoming a reality and requires electrodes of different lengths (Fig. 9). The documented cochlear duct length variation implies that the modiolus dimension will also vary within the same proportion (Avci et al., 2014), which makes a single pre-shaped electrode curvature fitting all modiolar shapes essentially impossible. In addition to macrostructure preservation during electrode insertion, the damage to microstructure could eventually be better controlled using drug eluting electrodes. Dexamethasone can be mixed with silicone and controlled elution within perilymph is documented (Farahmand et al., 2010). With corticosteroids, inflammatory processes caused by electrode insertion could be reduced in magnitude and in time, and protection of sensory epithelium enhanced (van de Water et al., 2010). Hearing preservation level and stability using corticosteroids have been demonstrated in one controlled study (Rajan et al., 2012).

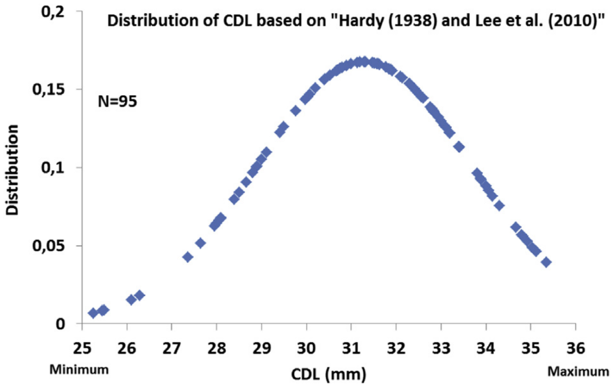

Fig. 8. Distribution and variation of cochlear duct length (CDL) based on 95 specimen (Hardy, 1938; Lee et al., 2010). The cochlear duct length can vary between 25 and 35 mm.

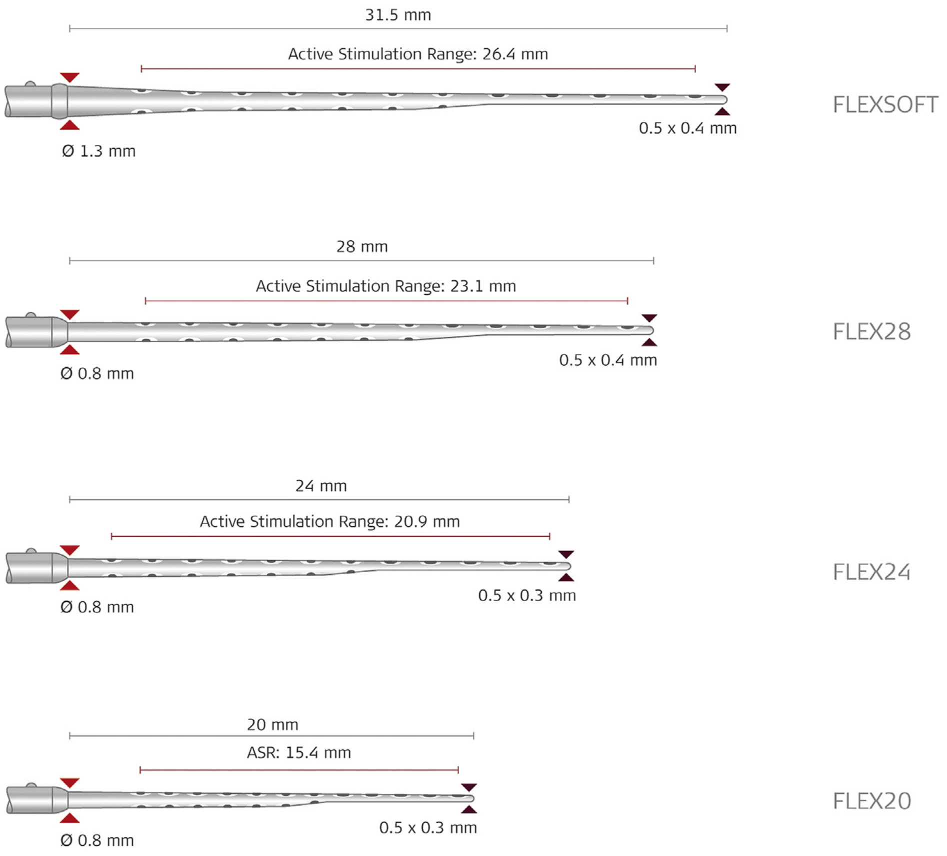

Fig. 9. Electrodes of different lengths able to provide a personalized solution for hearing loss, cochlear duct length, and EAS cases.

6.4. *Electrode design features essential for structure preservation*

In order to avoid electrode trauma, free fitting lateral wall electrodes have been designed with super flexible mechanical properties in the initial segment of the array (front 1/3 of the array). With proper design, the super flexible properties do not compromise insertion depth and position on the lateral wall, even for deep insertion. The thin super flexible front end makes it virtually impossible for the electrode tip to penetrate through the stiffer basilar membrane. Super flexible atraumatic electrodes require a unique "narrow pitch" wavy wiring shape to reduce insertion forces while inserting deeply into the scala tympani. In contrast, straight wires in the electrode array combined with numerous and close contacts increase the perforation strength even when a smaller electrode diameter is used. The inclusion of a stiffener at the base to increase pushability can increase deviation of the electrode with ensuing trauma to basilar membrane and spiral lamina, as well as causing loss of residual hearing when present. In addition, stiff electrodes would have a propensity to disrupt the venous system which drains venous blood from the lateral wall by rupturing vessels and causing local hemorrhages. This is why none of the FLEX- and other electrodes of MED-EL include a basal stiffener and include only wave shaped wires.

6.5. *Performance advantages with structure preservation*

For all cochlear implant electrodes correlations between performance and the degree of structure preservation need to be investigated thoroughly. Recent literature (Carlson et al., 2011; Wanna et al., 2014) addresses this issue. There appears to be better CI-performance, as measured with speech audiometry, when some residual hearing was conserved, as opposed to loss of residual hearing. And there are reports of significantly better performance when all electrodes are engaged in scala tympani compared to translocation cases (Finley et al., 2008; Holden et al., 2013).

7. Conclusion

The present goal with super flexible straight electrodes inserted through the round window membrane is to comfortably achieve structure and hearing preservation with medium insertion length as well as with deep insertion electrodes. To reach the apical region of the cochlea, where rate pitch is effective in carrying low pitch fine frequency information, is a prerequisite for the application of fine structure strategies providing both high temporal as well as high spectral resolution. These strategies, combined with the better place pitch match as a consequence of the complete cochlear coverage inherent with long electrodes, result in a more "natural" hearing, greater enjoyment of music, and improved communication capabilities.

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