The spread of electric field within the cochlea is not predictive for speech perception: an analysis of different devices including custom-made electrodes for subtotal cochleectomy

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Abstract

Objective

Cochlear implants (CIs) can restore hearing not only in patients with profound hearing loss and deafness, but also in patients following tumour removal of intracochlear schwannomas. In such cases, design and placement differ from conventional electrode insertion, in which the cochlea remains filled with fluid. Despite these technical and surgical differences, previous studies have tended to show positive results in speech perception in tumour patients. The purpose of this study is to retrospectively evaluate the ability to predict speech recognition outcomes using individual electric field distributions based on different electrode designs and investigate special tumour cases.

Study design

In a retrospective analysis in a university tertiary center electric field distributions were compared between two groups of electrode designs implanted between 2009 and 2020 i.e., between lateral wall electrodes and custom-made perimodiolar electrode carriers from the same company. The voltage gradients were then correlated with speech recognition results.

Results

Differences in electrical field distributions were found between lateral wall electrodes and the custom-made perimodiolar electrodes, whereas a significant correlation to scores in speech recognition cannot be demonstrated.

Conclusion

Prediction of speech recognition outcome based solely on electric field propagation results seems not feasible, although significant differences in field distribution between electrode arrays can be clearly demonstrated. This observation and its relevance to hearing treatment and speech recognition should therefore be further investigated in upcoming studies.

Introduction

Cochlear implants (CIs) can restore hearing not only in patients with severe to profound hearing loss and deafness, but also in patients following tumour removal of intracochlear schwannomas, that are benign. These tumours originate in the peripheral branches of the eighth cranial nerve and often require surgical excision, resulting in partial or subtotal cochlear removal [1]. Interestingly, affected patients who were treated with CIs can potentially demonstrate comparable outcome performance as single-sided deafened CI users [1,2]. To evoke a sound perception in CI users, cochlear nerve fibres are stimulated by electrical current pulses along the electrode array. The amount and location of the excited nerve fibres depend on several parameters, such as the relative position of the electrode array in the cochlea, electrical impedances of the electrode-tissue-nerve connections, respective nerve sensitivity, parameters of the
stimulation pulses, and more. Without doubt, these factors influence intracochlear current flow and impede precise steering altogether, thus the resulting spread of excitation of nerve fibres can span about one third of the electrode array or even more [3,4]. Unfortunately, this undifferentiated distribution eventually leads to excitation of unaimed nerve fibers and thus to inaccurate auditory representation - still a limiting factor in current CI technology. Therefore, the enhancement of speech and music perception based on improved spatial resolution in CIs is widely discussed [5,6]. The CI induced current distribution and flow within the cochlea was modelled in several studies (see review 7), which is based on different influencing factors, e.g., electrical resistivity of the bone and tissue [8,9], electrical conductivity of the modiolus encapsulation [8], and changes in electrode-electrolyte interface by charge injection [7,10]. Instead, Choi et al. [11] used finite elements to model electrical impedances across the electrode array based on the assumption that the distance between electrode array and modiolus stays constant along its progression. However, the validity of this assumption has been questioned in the following studies [12,13]. However, using these insights, Mens [14] was able to show strong gradient related field distributions, where the apical to basal voltage propagation shows an increase in amplitude of about three times, thereby strongly emphasizing the necessity of further investigations into such mechanisms and effects. In addition to electrochemical and physiological factors one can hypothesize that the actual design of the CI electrode array influences the spread of electric field. During the last decades CI manufacturers developed and offered a variety of different electrode designs, e.g., long lateral wall arrays with the aim to cover the complete cochlear length and nerve fibres (MED-EL, Austria), shorter perimodiolar electrode arrays to decrease distance between carrier and nerve fibres (Cochlear, Australia), and others. Study results comparing the difference in word recognition between perimodiolar and lateral wall electrode designs finally base on the different electrical conditions within the cochlea show facilitated word recognition in perimodiolar arrays [6]. However, all these findings are based on the fact that the underlying anatomy of the cochlea is intact and its compartments remain fluid-filled. In contrast, in tumour patients with partial or subtotal cochleoectomy, the fluid-filled compartments are degraded and thus their contribution to the electric field distribution is impaired. Consequently, these patients could particularly benefit from precise control of the electric fields and thus from differential recruitment of the nerve fibres. For those patients, a perimodiolar electrode array was developed by Med-EL (Innsbruck, Austria) as a custom made device (CMD) based on the template of their common FORM19 electrode array [15]. To measure electrical impedances and voltage distributions CI manufacturers offer system integrated telemetry functions, that are commonly used in daily clinical routine to monitor correct implant functioning. One particular telemetry feature is the measurement of the intra-cochlear electric field or intra-cochlear current spread (ICCS) [16], labelled different for different manufacturers electrical field imaging (EFI) or transimpedance matrices (TIM) [17] or voltage matrices. All these tools measure the impedance and voltage gradient along the electrode array for the respective CI system, where values can then be used to calculate the voltage gradient along the nerve fibres. In MED-EL devices this measure is included in each routine impedance measure. Interestingly, significant peculiarities in the electrical field distribution were shown across different patient groups. For instance, Wagner et al. [2] observed smaller electric fields in Nucleus CI patients after partial or subtotal cochleoectomy for removal of intracochlear schwannoma compared to patients who underwent standard cochlear implantation through a round
window approach. Noteworthy, patients who underwent cochleectomy at cochlear implantation were able to demonstrate comparable or even better outcome in speech perception compared to the group with "normal" CI insertion [1]. Da Silva et al. [18] found that more precisely differentiated areas of recruited nerve fibres correlate with better outcomes in speech perception using spread of excitation measurements. However, the exact effects of stimulation field distributions are far from being understood. Therefore, it is of deeper interest of this study to further investigate the relationship of individual electrical field distributions with speech perception results. To facilitate a robust fundament for analysis two different types of electrode arrays were used, one group of commonly used electrode arrays as well as one group of special CMD electrode arrays (both provided by MED-EL), to provide capability in comparison based on their diverging designs. Further comparability is provided by the analysis of the discussed special patient group who underwent cochleectomy and were inserted using the CMDs. Fortunately, this combination offers an innovative and rare approach in research regarding this topic as these special arrays are one of a kind worldwide. Noteworthy, at the time of implantation only MED-EL implant technology allowed for postoperative MRI diagnostics, what was essential for the follow-up therapy of tumour patients. In summary, we expect to find differences in provided field distributions among the two investigated arrays based on their design and patient related anatomy as well as deeper insights into the relationship to speech performance outcomes.

Methods

Study design and patients

In a retrospective exploratory case-control study CI users with MED-EL devices were investigated. All patients were implanted between 02/2009 and 11/2020 at a tertiary university referral centre. All datasets were scanned for validity and included if a valid IFT measurement as well as a word recognition score test (Freiburger monosyllables and multisyllables at 65 dB under free field condition) were performed around 3 months after CI activation.

Datasets were grouped according to electrode array types (CMD, FORM 24, FLEX24, FLEX28, FLEXSOFT, STANDARD). Perimodiolar CMD electrode arrays were designed for patients with intracochlear, intravestibulocochlear and trans-modiolar schwannoma. Further details about this CMD electrode, the surgical procedure and audiological details are described by Plontke et al. [15]. There were no special age and sex restrictions. For analysis all data sets were anonymized. A safety assessment was given by the responsible institutional ethical review board (approval number: 2020-149).

Measurements

Build in impedance tests (IFT - Impedance and Field telemetry) and its measured voltage matrices using MAESTRO 9 software (MED-EL, Innsbruck, Austria) were analysed. For IFT a defined bi-phasic pulse with an amplitude of 302.4 cu and a phase duration of 24.2 µs was applied by all individual electrode
contacts respectively and the resulting voltage amplitudes between all electrode pairs were measured, individually. Each electrode contact contains an independent current source, thus using Ohm's law the impedance was calculated.

**Data processing**

All voltage matrices were exported from the MAESTRO 9 software (MED-EL, Innsbruck, Austria) as XML file, processed and analysed with a python 3 software script.

Datasets for all CI patients were clustered depending on used electrode array types. The individual plots were visually scanned for abnormalities, like deactivated electrode contacts or shortcuts. Patients with abnormal voltage matrices, based on histogram values, were excluded from further analysis. Patients with a high number (number in histogram > 22) of data points with very low voltage values (~0 V) are excluded. For each electrode array group, the mean voltage matrix was plotted. In addition, the line plots for the averaged CMD and the averaged standard group were plotted and discussed.

For each electrode array group, the spread of the electric field in basal and apical regions was investigated. The voltage at two neighbouring electrode contacts was plotted at electrode number 3 for basal investigation and the position of electrode number 9 of the CMD device. Due to different active electrode carrier length this is at electrode contact number 5 for FORM24 and FLEX24, at electrode contact number 4 for FLEX28, and at electrode contact number 3 for FLEXSOFT and STANDARD.

To analyse the correlation of word recognition score (WRS) and electric field the user's voltage matrices of all regular CI electrode arrays were grouped in good (WRS > 60%), medium (20% ≤ WRS ≤ 60%) and bad performers (WRS < 20%), and the voltage matrices were averaged.

For the CMD group, all four individual voltage matrices were shown, described, and discussed with respect to the individual speech perception improvement over the first year.

**Results**

The data base contained 168 patients (29 bilaterally implanted) with datasets. Patients who got their implant in another clinic as well as children who were too young for valid monosyllable tests after three months were excluded from analysis. A total of 134 patients (4 bilateral) and the four patients with custom-made devices were analysed. There were four patients with the CMD FORM19 electrode array, two with FORM24, nine with FLEX24, five with FLEXSOFT, 19 with Standard and 99 with the FLEX28 electrode array. The voltage matrix with the date of the three months testing (after implantation) was used.

Figure 1 shows the voltage matrices grouped for each specific electrode array type. A strong voltage decay next to the principal diagonal was observed. Compared to the perimodiolar CMD electrode arrays, larger voltage amplitudes and wider spreads of the electric field were found in all other electrode arrays.
Besides, the wider electric field was more prominent in the apical region compared to basal regions. The active stimulation range differed between 14.3 mm and 26.4 mm and lead to different stimulating sites in the cochlea.

Figure 2 shows the voltage decay for each electrode contact averaged for all standard electrode array types as well as for the perimodiolar CMD arrays. CMD arrays showed higher and more homogeneous amplitude deflections in the stimulation electrode contact over the whole array compared to the other electrode array types. The voltage drop to the neighboring electrode contact in the CMD device was higher compared to the other electrode arrays. That means the voltage in the neighboring electrode contacts was lower for the CMD device compared to the average of all other electrode arrays, especially in the apical regions (e.g., electrode contact number 2 to 1 and 3).

A closer insight in the comparison of apical and basal regions is given in Fig. 3. Differences in voltage deflections between the electrode contacts are in the magnitude of 0.1 V. For basal electrodes contacts the difference between CMD arrays and all other arrays were in the range of 0.02 V. The apical voltage amplitudes differed by about 0.06 V.

Figure 4 shows the mean voltage matrices for different word recognition score groups of CI users as average over all electrode array types. The dominating electrode array is FLEX28 because of the number of patients. Visually, the voltage distribution appears to be directly comparable between the performance groups. Figure 5A shows the electric field distribution for patients with a perimodiolar CMD CI electrode arrays after intracochlear schwannoma removal. A rapid decrease in voltage amplitude around the stimulating electrode contact and a rather homogenous spread over the whole cochlea was seen. The overall voltage spread differed about 0.1 V between patients ID1 and ID3. Asymmetries in the individual matrix were seen in all four CMD devices. Patients with a CMD electrode array showed an increase in monosyllabic word and multisyllabic number recognition scores in the first months of CI use and mostly fit to the “good” performance group (see Fig. 5B).

**Discussion**

The measured averaged voltage matrices for all common electrode arrays showed differences between basal and apical stimulating electrode contacts. A larger voltage gradient was observed for basal electrode contacts and is likely caused by a smaller electric spread in that cochlear region as predicted by several models describing the voltage in the cochlea [14]. These models assume a preferred current pathway through basal openings like the internal auditory canal, the vestibular system, the cochlear and vestibular aqueduct, and the oval as well as round window. This prediction particularly correlates with our findings for patients using a perimodiolar CMD electrode array after removal of an intracochlear tumour. After surgery, there is less fluid around and cartilage chips at the periphery of the perimodiolar electrode array, very likely fibrosis. So there is a different density and the current pathway is in apical regions as unopposed as in basal regions. Consequently, this changes electric characteristics. The CMD is pre-curved, thus it is closer to the modiolus than lateral wall electrode arrays, which means closer to the spiral
ganglion cells in Rosenthal’s canal than to the bone of the remnants of the cochlear capsule, which implies a smaller resistance and a higher voltage gradient. Another effect of the pre-curved structure of the array is a deeper insertion angle which is not further investigated. This is in accordance with the findings of different voltage spreads for the CMD electrode array compared to all others. A larger decrease in voltage at the stimulating electrode contact (Fig. 2) and, thus, a faster decrease in voltage in the surrounding electrode contacts (Fig. 3) can be explained by the unusual surrounding of the electrode, as well as the difference in basal and apical profile.

Beside the altered electrical characteristics of the surroundings after subtotal cochleocotomy, also the electrode array structure should be considered. The apical part of FLEX electrode arrays contains a FLEX-Tip with five single electrode contacts while STANDARD and FORM electrode arrays are made of paired contacts. Therefore, differences in electrical distributions could be expected for apical electrode contacts. We observed the smallest gradient and the highest voltages for the STANDARD electrode array whereas the FLEXSOFT and FLEX28 with almost the same length showed quite smaller voltage values in the adjacent electrode contacts (see Fig. 3). It needs to be pointed out, however, that it is not the real apical region that is plotted, because the correction to the “apical” FORM19 position was done, the longer electrode arrays are inserted much deeper in the cochlea.

For CMD CI users, asymmetries were observed in the voltage matrices. These were somehow unexpected and cannot be explained in detail so far. One could suspect a difference of the measured values because of independent current sources within the electrode array and different conductivities depending on electrode surroundings and current direction. The explanation for the dark blue spot in the matrix of ID 1 (see Fig. 5A) is a decoding error. This was investigated by the manufacturer. It might be due to a bad coupling during the measurement and cannot be erased afterwards. What stays unexplained is the difference in overall voltage between ID 1 and the three other CMD voltage matrices. It might be the location of the tumour in the modiolus that influences the voltage distribution in that way.

**Speech perception**

The electrical field distribution as measured by the voltage matrices was not different among the included good and bad CI performers. Figure 4 shows almost equal field distributions for CI users with good and poor speech perception. An effect of voltage gradients on speech perception was not found in this cohort. One reason might be the only small variation between the electric distributions for different electrode array types considering the surrounding conditions are comparable.

Users with perimodiolar CMD electrode array showed a slightly better speech perception than the average of all other CI users (Fig. 5B). This difference might be based on the close perimodiolar position of the pre-curved electrode array, what is one of the most significant differences compared to lateral wall electrode arrays. Also the surrounding characteristics might influence voltage distribution. After subtotal cochleocotomy, the surrounding electrochemical conditions would rather be resistive than conductive.
The role of both factors could not be separately analysed in this study but could be investigated in further studies comparing different electrode array shapes.

The observed increased speech perception in the small group of CMD CI users correlates to the usually observed growth within the first months after CI use if audioverbal therapy is applied. A correlation of that increase to a smaller or larger voltage distribution cannot be seen in the analysed case series so far.

**Conclusion**

In this study, voltage matrices in CI users with different surgical techniques and electrode array types were analysed. A difference between perimodiolar (precurved, “modiolus hugging”) electrode arrays in patients after subtotal cochleectomies and electrode array close to the lateral wall was found. Electrode arrays closer to the modiolus showed smaller field distributions and therefore the potential to achieve a more focused electrical stimulation of the neurons. No effect of electric field distribution on speech perception was seen in this patient cohort. Further investigations comparing different electrode array types will bring more insights in this interesting topic.

**Declarations**

**Acknowledgment**

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**Confirmation**

We confirm that all methods were carried out in accordance to common regulations and the protocol that was approved by the ethical review board of the medical faculty of the Martin-Luther-University Halle-Wittenberg (approval number: 2020-149).

**References**


**Figures**

![Electrode array types](image)

**Figure 1**

*Mean voltage matrices grouped for each electrode array type (FORM24 n= 2, FLEX24 n=9, FLEX28 n=99, FLEXSOFT n=6, STANDARD n=19)*
Figure 2

Voltage for each stimulation pair of electrode contacts. Perimodiolar CMD devices (green) and all other common electrodes arrays averaged (grey). Error bars indicate the standard deviation.
**Figure 3**

Voltages between the stimulating and adjacent electrode contacts as average across basal (left) and apical (right) stimulating electrode contacts (green: common electrode arrays, single dots: FORM24, line-dot: FLEX24, dashed line: FLEX28, dotted: FLEXSOFT, solid line: STANDARD, red: CMD).

**Figure 4**

Mean voltage matrices for different word recognition score groups of CI users after 3 months, averaged over all common electrode array types. WRS better than 60% \((n = 25)\), 20-60% \((n = 78)\) and less than 20% \((n = 31)\).

**Figure 5**
A Matrices for four patients with a perimodiolar CMD for use after surgical removal of intralabyrinthine schwannomas (ILS). ID1 transmodiolar, intravestibulo-cochlear (basal turn) ILS. In this patient, the modular and fundal tumour parts were not removed in order to enable hearing rehabilitation with CI. ID2: intracochlear (middle turn and apex) ILS. ID3: intracochlear (basal and middle turn) ILS. ID4: intravestibulo-cochlear (basal, middle and apical turn) ILS. Measures after three months are shown. For detailed pictures of electrode array position see Plontke et al. 2020a.

B Word recognition score of CMD users. Dotted lines show the 20% and 60% WRS line as separation between good and bad performers. ID1: green, ID2: yellow (not German speaking), ID3: red, ID4: blue. The grey line shows the averaged monosyllabic word and the black averaged multisyllabic number score for the CMD. The grey square is the averaged WRS for all users of common electrode array types.