Influence of the spread of electric field on neural excitation in cochlear implant users: Transimpedance and spread of excitation measurements

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A R T I C L E   I N F O

Article history:
Received 27 January 2022
Revised 11 July 2022
Accepted 21 July 2022
Available online 23 July 2022

Keywords:
Cochllear implant
Intracochlear spread of electric field
Transimpedance
Spread of neural excitation
Electrically evoked compound action potential
Channel interaction

A B S T R A C T

Channel interactions caused by spread of the intracochlear electric field and, thus, the spread of neural excitation constrain frequency selectivity and speech recognition in cochlear implant (CI) users. Studying the influence of the spread of electric field (SEF) on the spread of excitation (SOE) can help us better understand the electrical-neural interface. The primary aim of this study was to examine the influence of the SEF on the SOE. In 38 Nucleus (Cochlear Ltd. Sydney, Australia) CI recipients, we assessed the spatial SEF by measuring the voltage drop (transimpedance) and the SOE through neural responses (electrically evoked compound action potentials [eCAPs]) along the electrode array. Transimpedance was recorded using the monopolar (MP2) mode as the stimulation and recording mode. Biphasic square-wave pulses with an amplitude of 110 CI and duration of 37 μs were used for stimulation. SOE was measured at the probe active electrodes E5, E13, and E18. The stimulation amplitudes were set individually to the thresholds of the neural response telemetry (T-NRT), which were measured by the AutoNRT protocol. The transimpedance half-widths were between 0.00 electrodes and 8.55 electrodes. The SOE half-widths reached values between 0.54 electrodes and 5.70 electrodes. Considering individual transimpedance and SOE half-widths, the SEF and SOE showed a significant positive correlation only at electrode E13. Furthermore, this study shows a significant negative correlation of the SEF and SOE in consideration of mean half-widths.

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1. Introduction

Multichannel cochlear implants (CIs) enable stimulation of the cochlear nerve in different regions. Consequently, the tonotopy of the cochlea is imitated and several auditory impressions created (van der Beek et al. 2012). The spectral resolution depends on the number of electrode contacts used. Each electrode induces an electric field in the cochlea that is centred around that electrode to stimulate a certain neural population. When the electric field is spread out, neurons associated with adjacent electrodes are also stimulated. This is called channel interaction and is considered a reason why speech recognition in quiet behaves asymmetrically if more than eight electrodes are used (Fishman et al. 1997; Friesen et al. 2001; Başkent 2006).

A potential objective estimation of the spread of electric field (SEF) within CI users is the voltage drop (transimpedance) along the electrode array (Wagner et al. 2020). Transimpedances are voltages between non-stimulating electrodes and the housing electrode normalised to the current at the stimulating electrode (Vanpoucke et al. 2012; Rijk et al. 2020). An equation for calculating the transimpedance is \( X_j = \frac{U_i}{I_j} \), where \( U_i \) is the voltage at electrode \( i \) and \( I_j \) is the current at stimulation electrode \( j \) \( (i; j \in \{E1, E22\}) \) (Rijk et al. 2020). If \( j \) equals \( i \), then \( X_j \) reflect the contact impedances.

The resulting spread of neural stimulation is assessed by measuring electrically evoked compound action potentials (eCAPs). Clinical research software from various manufacturers, such as Cochlear Ltd. (Custom Sound EP Software, Sydney, Australia) and MED-EL (MAESTRO, Innsbruck, Austria), offer tools to record spread of excitation (SOE) functions based on eCAPs. These measurements apply a technique called the ‘forward-masking subtraction paradigm’ (FMSP) to reduce artefacts. Therefore, masker and probe pulses are presented in four stimulation intervals: A, B, C, and D. The masker pulse uses the refractory period of neurons.
(Lai 1999) in which a neuron is insensitive (inactive) to new stimuli (Gekle et al. 2015). By skillfully executing and subtracting the stimulation intervals, the stimulation artefact and switch-on artefacts of the measuring amplifier are reduced. To measure SOE functions, the probe and recording active electrodes are fixed and the masker active electrode roams systematically through the electrodes. To simplify the principle of FMSP, just interval A and B are considered in Fig. 1. In interval A, only a probe pulse is presented, whereas in interval B a masker pulse is given before the probe pulse. If the masker and probe are not separated spatially, they stimulate the same population of spiral ganglion cells. All spiral ganglion cells are in the refractory period after the masker stimulus. In this case, only the stimulus artefact is recorded in interval B. This leads to minimal data and, thus, the eCAP amplitude reaches a maximum (see Fig. 1c). If the masker and probe are separated spatially by using different electrodes, they stimulate different populations of spiral ganglion cells. Some spiral ganglion cells are not inactivated by the masker and reply to the probe stimulus. Thus, the response in interval B increases compared to the first case, whereas eCAP amplitude decreases (compare Figs. 1b and 1c). Thus, the N1-P1 amplitude varies as shown in Fig. 1d. The SOE function describes the N1-P1 amplitude as a function of the masker active electrode (Lai 1999). In other words, the data points represent the overlap of the population of spiral ganglion cells stimulated by the masker and probe (Biesheuvel et al. 2016).

A correlation between the SEF and psychophysical parameters is desirable to adjust the SOE and SEF, e.g. by current focused stimulation (see Padilla and Landsberger 2016 for further readings), to
achieve a better hearing outcome after CI implantation. Relationships between the SEF and psychophysical parameters in patients with a standard electrode insertion has not been established. Similarly to the transimpedance measurements, the influence of the electrical field imaging and intracochlear impedance matrices (see Vanpoucke et al. 2012; Hey et al. 2015 for further readings) on speech recognition has rarely been studied to date. Wagner examined transimpedances in CI users after cochleeotomy, which was performed to remove an intracochlear schwannoma (tumour group, Wagner et al. 2020). The authors found a reduced SEF combined with better speech intelligibility in the tumour group in comparison to the control group. (Wagner et al. 2020) explained the better speech recognition performance in the tumour group by the narrow SEF. A cochleeotomy changes the anatomical structures and thus the position of the electrode array in comparison to a standard electrode insertion (Wagner et al. 2020).

In contrast to the relation of psychophysical parameters and the SEF, many studies examine correlations between psychophysical parameters and SOE shape (Biesheuvel et al. 2016; Hughes and Abbas 2006; Hughes 2008; van der Beek et al. 2012). van der Beek et al. recorded SOE curves at three electrodes: an apical, medial, and basal contact. For analysis, the SOE width was defined as the number of contacts from the stimulating electrode to the electrode where the normalised SOE function reached 60%. A significant correlation between monosyllabic word score and SOE width could not be verified (van der Beek et al. 2012). Contrary to that, da Silva could prove a negative correlation between the SOE width and speech perception (da Silva et al., 2020). They examined 43 CI users with different electrode arrays (perimodiolar and straight) by using SOE measurements and monosyllabic word tests. The SOE measurements were estimated by SOE width at 75% normalised amplitude in mm by applying a tool in the Custom Sound EP Software (Version 3.0).

Söderqvist examined the relation of the SEF and SOE by measuring transimpedances and eCAPs, intraoperatively. Both measurements were investigated by calculating and comparing transimpedance- and SOE widths at three electrodes (E6, E11, and E19). The authors found a correlation between the transimpedance- and SOE-widths in the apical region of the cochlea for lateral wall electrodes (Söderqvist et al. 2021). In order to further investigate and understand the influence of the SOE and the SEF on psychophysical parameters, the relationship between the SOE and the SEF should first be examined in more detail. For this reason, the primary aim of this study was to measure the SEF and SOE postoperatively using two available methods, transimpedance and eCAP measurements, and investigate the influence of the SEF on the SOE. In contrast to the study by Söderqvist, the measurements were performed postoperatively (Söderqvist et al. 2021). This may help us to understand the electrical-neural interface and to examine the influence of the SOE and SEF on psychophysical results which are also determined in the postoperative phase in a later step.

2. Material and methods

2.1. Study design and ethics

A monocentric, prospective, exploratory study was performed at the Department of Otorhinolaryngology, Head and Neck Surgery at the University Hospital Halle (Saale), Germany, from December 2020 to November 2021. Written informed consent was obtained from all patients before inclusion in the study. The study protocol was approved by the ethics committee of Martin Luther University Halle-Wittenberg (approval number: 2019-050).

2.2. Participants

Participants were included if they had received a Cochlear Nucleus implant (Clx12, Clx22, Clx32, or CI24(RE), Cochlear Ltd., Sydney, Australia). Exclusion criteria were inadvertent facial nerve stimulation, less than 20 intact electrode contacts, cochlear implantation after surgical removal of an intralabyrinthine schwannoma, a cardiac pacemaker, or an implant model that does not permit neural response telemetry (NRT).

2.3. Transimpedance recordings

Transimpedances were recorded postoperatively by using the transimpedance matrix (TIM) tool of Custom Sound EP Software (Version 6.0, Cochlear Ltd. 2020, Sydney, Australia). For stimulation, biphasic square-wave pulses with a pulse width of 37 µs and amplitude of 100 Cl (current level) were applied. The monopolar mode (MP2) was used for stimulation and recording. The voltage was recorded for each electrode after 37 µs which equates the measurement time point T6 in the Custom Sound EP Software. The measurement parameters were set in this way to ensure that all participants accepted the measurement and a clear transimpedance pattern occurred (no saturation or voltages in the magnitude of the noise floor (Cochlear Ltd. 2020)).

2.4. SOE recordings

The SOE was measured for electrodes E5, E13, and E18 as the probe active electrodes with the advanced NRT plugin of Custom Sound EP Software. The stimulation amplitude of the probe and masker active electrode was set to the thresholds of the NRT (T-NRTs) determined by autoNRT in the Custom Sound EP Software for each tested person (Dziemba et al. 2016). The recording active electrode was separate from the probe active electrode by two electrode contacts in the apical direction (E7, E15, and E20). Berger showed that a larger pulse width in eCAP measurements results in softer sound perception compared to smaller pulse widths (Berger et al. 2017). Thus, the pulse width was set to 50 µs to obtain greater acceptance of the SOE measurement (Dziemba et al. 2016). During each of the three SOE test series, each electrode on the electrode array, excluding the recording active electrode, was the masker active electrode once. A 4 kHz low-pass filter was used for smoothing the eCAPs (Dziemba et al. 2016). N1-P1 amplitudes were found by using the peak-picker tool in the Custom Sound EP Software for the eCAP with the strongest neural response and clearest morphology. Afterwards, the peak-picker marker was set to the amplitude at the determined latency for individual eCAP recordings (Müller et al. 2020).

2.5. Characterisation of transimpedances and SOE functions

Transimpedance data points were linearly interpolated as a function of the recording active electrodes. Contact impedances were replaced by the maximum transimpedance value next to the contact impedance (see Fig. 2). The method for replacing the contact impedance was based on the research of Söderqvist, who used an optimised ‘effective impedance’ instead (Söderqvist et al. 2021). Transimpedance was corrected by an offset, which was determined separately for each participant. The offset was estimated by the minimum transimpedance value in the individual matrix and subtracted from all transimpedance values in the TIM (see Fig. 2).

Given that the triggering of action potentials depends on the absolute voltage (threshold potential) applied to neurons, transimpedance half-width $W_{l/2}$ was calculated at the absolute value of 0.52 kΩ for each participant at electrodes E5, E13, and E18. With the assumption that a threshold potential of 55 mV is necessary
to trigger an action potential (Seifert et al. 2005), an impedance of 0.52 kΩ (1 = 100 CL = 107 μA) arises from Ohm’s law. The half-width $W_{TI,a}$ was defined as the number of electrodes from the stimulation electrode to the point where the value of 0.52 kΩ was reached (see Fig. 2). For stimulation electrodes located more basal than electrode E1, the half-width was determined on the apical flank of the curve. For stimulation electrodes located more apical than electrode E1, the half-width was determined on the basal flank of the curve. The half-width was used to avoid cases where the transimpedance did not drop to the required value (van der Beek et al. 2012). If the maximum on the transimpedance curve did not reach the critical value of 0.52 kΩ, a half-width of 0 electrodes was assigned. As the transimpedances of different participants were comparable because of the same measuring parameters, a normalisation procedure was not necessary. SOE half-width $W_{SOE,r}$ was determined at a relative height of 50% of the peak.

To examine the correlation between $W_{TI,a}$ and $W_{SOE,r}$, as well as $W_{TI,a}$ and $W_{SOE,r}$, were analysed by linear regression. Spearman’s correlation coefficient was calculated to test for significance of the correlation between SOE and transimpedance half-widths. The mean half-widths $W_{TI,a}$ and $W_{SOE,r}$ were compared by Bonferroni-corrected paired $t$-tests. Alpha was set to 5%.

3. Results

Fifty-one patients with CI (18 males and 33 females) participated in this study. Transimpedance measurements were obtained for all participants. For 13 patients, the eCAP recordings could not be analysed because of uncomfortable loudness levels during autonRT or SOE measurement ($N = 6$) or due to facial nerve stimulation ($N = 1$). Six patients showed no neural responses. For the remaining 38 patients (16 males and 22 females), complete measurements were obtained. In two patients, the measurement could be performed bilaterally, resulting in 40 implanted ears being examined. The mean age of the analysed patients was (59 ± 19) years; the youngest participant was 12 years old and the oldest was 83 years old. Patients had been implanted between 2008 and 2021. All patients received a postoperative radiological evaluation of the implant position using either plain film or computed tomography to exclude electrode array tip fold-over or kinking. The patient characteristics are summarised in Table 1.

The SOE half-widths, i.e., the widths of SOE pattern $W_{SOE,r}$ at a relative height of 50% of the peak, were plotted as a function of transimpedance half-width $W_{TI,a}$ at the absolute value of 0.52 kΩ in Fig. 3 for electrodes E5, E13, and E18. At electrode E5, the $W_{TI,a}$ reached values between (0.00 ± 0.01) electrodes and (5.08 ± 0.01) electrodes. At electrode E13, the half-width was between (1.00 ± 0.01) electrodes and (6.04 ± 0.01) electrodes, and at electrode E18 between (0.00 ± 0.01) electrodes and (8.55 ± 0.01) electrodes. At electrodes E5 and E18, the half-widths $W_{SOE,E13}$ and $W_{SOE,E18}$ were randomly distributed and showed no significant correlation ($r_s = 0.062$, $p > 0.05$ and $r_s = 0.235$, $p < 0.05$). At electrode E13, the SOE half-widths increased with an increase in transimpedance half-width. Spearman’s correlation coefficient showed a weak significant correlation at electrode E13 ($r_s = 0.374$, $p < 0.05$).

The mean T-NRT calculated from T-NRTs, which were used as the stimulation level for the probe and masker active electrode was $167 ± 21$ CL at E5, $163 ± 17$ CL at E13, and $142 ± 18$ CL at E18. On average in all participants, the transimpedance offset was $(0.95 ± 0.06)$ kΩ. Fig. 4 shows the measure of central tendency and dispersion of transimpedances and SOEs determined separately for electrodes E5, E13, and E18. The mean SOE reached maximum values of $0.12 ± 0.06$ mV [median 0.12 mV], $0.18 ± 0.11$ mV [median 0.18 mV] and $0.12 ± 0.09$ mV [median 0.10 mV] at the probe active electrodes E5, E13, and E18, respectively. The mean transimpedance reached the maximum values of $2.02 ± 0.85$ kΩ [median 1.84 kΩ], $1.76 ± 0.39$ kΩ [median 1.69 kΩ] and (1.68

Fig. 2. Definition of transimpedance width at an absolute value of 0.52 kΩ ($W_{TI,a}$, black dashed line). Transimpedances were corrected by the determined offset. Data points are marked by filled circles. Solid lines show interpolated values. The cross marks the electrode where the width was measured.

Fig. 3. Relationship between width of SOE function $W_{SOE,r}$ and width of transimpedance $W_{TI,a}$ at an absolute value of 0.52 kΩ. Scatter plots were separated by the probe active electrodes and the stimulation electrodes E5 (left), E13 (middle), and E18 (right). Each data point equates to one participant. The dashed line marks equal widths, and the solid line shows the linear regression. The coefficient of determination $R^2$, the Spearman’s correlation coefficient $r_s$, and the $p$-value are noted on the diagrams.
Table 1

| ID  | Sex | Ear | Age,years | Aetiology and Pathology | Electrode | Age at Implantation, years | CI Experience, years |
|-----|-----|-----|-----------|-------------------------|-----------|---------------------------|----------------------|
| 001 | F   | R   | 79        | ISSNHL                  | CI422     | 72                        | 6.6                  |
| 002 | F   | R   | 67        | MD                      | CI632     | 67                        | 0.3                  |
| 003 | F   | L   | 83        | Cholesteatoma           | CI632     | 83                        | 0.7                  |
| 004 | F   | R   | 76        | Cholesteatoma           | CI632     | 76                        | 0.2                  |
| 005 | M   | L   | 48        | Scarlatica              | CI632     | 48                        | 0.2                  |
| 006 | F   | R   | 49        | pSNHL                   | CI632     | 49                        | 0.4                  |
| 007 | F   | L   | 54        | Otosclerosis            | CI612     | 54                        | 0.2                  |
| 009 | M   | R   | 61        | CVV + SNHL              | CI632     | 60                        | 0.8                  |
| 010 | F   | L   | 60        | pSNHL                   | CI632     | 59                        | 1.1                  |
| 012 | F   | L   | 65        | AOM + SNHL              | CI512     | 61                        | 3.4                  |
| 014 | F   | R   | 68        | ISSNHL                  | CI632     | 68                        | 0.25                 |
| 016 | F   | R   | 69        | ISSNHL                  | CI512     | 67                        | 1.9                  |
| 017 | M   | L   | 58        | ISSNHL                  | CI512     | 52                        | 6.4                  |
| 020 | M   | L   | 18        | Trauma                  | CI24(RE)  | 10                        | 8.1                  |
| 021 | F   | L   | 63        | pSNHL                   | CI312     | 61                        | 2.2                  |
| 022 | F   | L   | 67        | ISSNHL                  | CI632     | 67                        | 0.8                  |
| 023 | F   | L   | 16        | LVAS                    | CI612     | 15                        | 0.5                  |
| 024 | F   | L   | 68        | MD                      | CI632     | 67                        | 0.8                  |
| 025 | M   | L   | 73        | COM                     | CI24(RE)  | 65                        | 8.5                  |
| 025r| M   | R   | 73        | Cholesteatoma           | CI512     | 70                        | 3.5                  |
| 026 | M   | R   | 32        | IEM                     | CI632     | 31                        | 1.2                  |
| 034 | M   | R   | 78        | LVAS                    | CI612     | 78                        | 0.5                  |
| 035 | M   | R   | 52        | ISSNHL                  | CI632     | 50                        | 1.2                  |
| 036 | M   | L   | 12        | cSNHL                   | CI24(RE)  | 3                         | 8.9                  |
| 038 | F   | R   | 70        | Tympanoplasty           | CI632     | 68                        | 1.1                  |
| 039 | M   | L   | 70        | Post stapes surgery     | CI512     | 68                        | 2.0                  |
| 040 | M   | L   | 63        | pSNHL                   | CI632     | 61                        | 0.8                  |
| 041 | F   | L   | 55        | MD                      | CI632     | 55                        | 0.1                  |
| 042 | M   | L   | 78        | VS                      | CI632     | 78                        | 0.1                  |
| 044 | F   | L   | 61        | ISSNHL                  | CI512     | 58                        | 2.8                  |
| 045r| F   | R   | 23        | cSNHL                   | CI632     | 21                        | 1.2                  |
| 045l| F   | L   | 23        | cSNHL                   | CI632     | 23                        | 0.4                  |
| 046 | F   | L   | 72        | Cholesteatoma           | CI512     | 68                        | 4.2                  |
| 047 | F   | R   | 57        | ISSNHL                  | CI24(RE)  | 44                        | 12.5                 |
| 048 | M   | R   | 78        | Tympanoplasty           | CI512     | 74                        | 4.1                  |
| 049 | M   | L   | 67        | Otosclerosis            | CI632     | 66                        | 1.2                  |
| 051 | F   | L   | 55        | Cholesteatoma           | CI612     | 53                        | 1.8                  |
| 054 | M   | L   | 50        | pSNHL                   | CI512     | 48                        | 1.8                  |
| 057 | M   | R   | 54        | cSNHL                   | CI24(RE)  | 44                        | 10.0                 |
| 059 | F   | L   | 71        | Rubella                 | CI512     | 68                        | 2.8                  |

F: female; M: male; L: left; R: right; AOM + SNHL: acute otitis media with sensorineural hearing loss; c/pSNHL: congenital/progressive sensorineural hearing loss; CVD: central vestibular disorder; IEM: inner ear malformation; ILS: intralabyrinthine schwannoma; ISSNHL: idiopathic sudden sensorineural hearing loss; LVAS: large vestibular aqueduct syndrome; MD: Meniere’s disease; VS: vestibular schwannoma.

**Fig. 4.** Transimpedance (white) and spread of excitation (SOE, grey) functions for the stimulation/probe active electrodes E5, E13, and E18. Boxes show the lower and upper quartile (25th and 75th percentile) values. Horizontal lines mark the median, and crosses mark the mean. Whiskers show the statistical dispersion (1.5 × interquartile range). The transimpedance scale is shown on the left-hand side. The N1–P1 amplitude scale of the SOE was plotted on the right-hand side.
$± 0.29 \, \Omega$ [median 1.60 $\Omega$] at the stimulation electrodes E5, E13, and E18, respectively.

Fig. 5 shows the mean half-widths of transimpedances and SOE functions $W_{T1}$, a and $W_{SOE}$, r. On the left side of Fig. 5, widths were plotted as functions of the stimulation and probe active electrode. The transimpedance half-widths increased slightly towards the apical electrodes. The transimpedance half-width $W_{T1}$, a reached values between (2.54 $±$ 1.16) electrodes and (2.89 $±$ 1.59) electrodes. The mean half-widths of SOE function $W_{SOE}$, r decreased towards apical probe active electrodes and reached values between (1.63 $±$ 1.15) electrodes and (2.99 $±$ 1.24) electrodes. Significant differences between mean transimpedance and mean SOE half-widths were measured at the medial electrode contact E13 and apical electrode contact E18. On the right side of Fig. 5, mean half-widths of SOE function $W_{SOE}$, r were plotted as a function of the mean half-widths of transimpedance $W_{SOE}$, r and $W_{T1}$, a showed a significant negative correlation, with a Spearman’s correlation coefficient of $-1.000$ ($p < 0.05$).

4. Discussion

The main aim of this study was to investigate the influence of the intracochlear SEF on the neural SOE in CI users by measuring the SOE and transimpedance half-widths (Söderqvist et al. 2021; van der Beek et al. 2012; Cohen et al. 2003). Given that the number of stimulated neurons depends on the absolute voltage (threshold potential), absolute transimpedance values were considered. The results of this study showed a significant positive correlation at the medial (E13) contact but no significance at the basal (E5) and apical (E18) electrodes (see Fig. 3). In addition, Söderqvist found a weak correlation between SOE and transimpedance widths at the basal (E6), medial (E11), and apical (E19) electrode contacts considering widths at the level of individual participants (Söderqvist et al. 2021). In our study, the dispersion of neural responses showed variable significance of correlations with the voltage drop. The positive correlation supports the hypothesis that a broader voltage drop is related to a broader excitation area. Possible reasons for the variable properties of the correlations are the methodological approach to SOE measurement and the individual anatomy of the cochleae. As the methodological approach to SOE measurement determines the overlap of masker and probe stimuli instead of their excitation areas (Biesheuvel et al. 2016), a stronger correlation between the widths of excitation density profiles and transimpedance is possible. Another explanation for the unexpected result is the discrepancy between a purely technical and physiological view. The transimpedance measurement is a purely technical consideration of the voltage drop between the electrodes, which is only influenced by the specific electrical resistance of the surrounding tissue. On the other hand, the SOE measurement records a large number of physiological processes that take place in and near the auditory nerve and are recorded by the electrode.

In our study, Slim Straight, Slim Modiolar, and Contour Advance electrodes were analysed. All electrode array models have the same number of electrode contacts (22 electrodes) but are distributed on different active lengths. The active length in Contour Advance and Slim Modiolar Electrodes is between 14 and 15 mm, whereas in Slim Straight Electrodes the active length is 19 to 20 mm (Cochlear Ltd. 2012). The variable active length in combination with a fixed number of electrode results in variability in the distance between individual electrode contacts. In addition to equidistantly distributed electrode contacts on different active lengths, the position of the electrode array within the cochlea relative to the modiolus must be considered. The Slim Straight electrodes have straight electrode arrays with a lateral wall position, which results in a larger distance between the electrode contacts and the spiral ganglion cells. In contrast, Slim Modiolar, as well as Contour Advance electrodes, have a precurved electrode array design to provide a perimodiolar position and bring the electrode contacts closer to the spiral ganglia (Grolman et al. 2009; Cochlear Ltd. 2012; Sturm et al. 2021). A close distance between electrodes and spiral ganglion would result in a narrow current spread and, therefore, a narrow spread of excitation (Kalkman et al. 2015). In our study population, no significant differences due to the electrode type could be determined. For this reason, the data of all subjects were compared and analysed, regardless of the implanted electrode. As only two subjects with a Slim Straight electrode participated in our study, future work should also focus on the effect of electrode type on the transimpedance and SOE pattern by analysing a study groups with an equal number of straight and precurved electrodes.

The tissue surrounding the electrode array depends on its intracochlear positioning, which is affected by the electrode array design. As transimpedances provide information about the tissue resistance around the implant (Král et al. 2021), the transimpedance pattern may be influenced by the electrode array design. However, an explicit examination of X-ray images to verify electrode position was not conducted in this study.
In contrast to the observation of individual half-widths, the mean SOE half-width WSOE, \( r \) over all participants showed a strong negative correlation with mean transimpedance half-width \( \bar{W}TI \), a at E5, E13, and E18 (see Fig. 5). This does not agree with the expectation that the SOE increases with the SEF. At the three analysed electrode contacts, large standard deviations were observed in the half-widths due to large patient-related differences in SOE and transimpedance measurements, as was obvious in the individual consideration of half-widths (see Fig. 3). Furthermore, transimpedance and eCAP measurements were performed at different stimulation levels and with different pulse widths. These parameters influence the half-widths and could cause the unexpected negative correlation (van der Beek et al. 2012). Moreover, only three electrodes were examined by SOE measurements, and an investigation of additional electrodes, in the best case an investigation of a full “eCAP matrix” (Söderqvist et al. 2021), could be meaningful to determine whether the half-widths of other electrodes fit the straight line from the linear regression.

As our study showed that mean transimpedance half-width \( \bar{W}TI \), a increased towards apical electrodes and mean SOE half-width WSOE, \( r \) decreased towards apical electrodes, differences between mean half-widths occurred at the medial and apical electrode contacts. The increasing SEF towards the apex can be caused by the tapering trend of the cochlea, which reduces the volume around apical electrodes (Biesheuvel et al. 2016). Söderqvist showed a significant difference between mean widths at basal and middle electrodes. He reported larger mean transimpedance widths than mean SOE widths at the middle electrode and smaller mean transimpedance widths than mean SOE widths at the basal electrode (Söderqvist et al. 2021). The different results of the two studies may be due to non-identical measurement parameters, such as stimulation level in transimpedance and SOE measurements (van der Beek et al. 2012), the use of other electrodes (E5, E11, and E19 instead of E5, E13, and E18), evaluation methods (e.g., using full or half-widths), intra- in comparison to postoperative measurement, and inclusion criteria (e.g., the electrode array models). From these five parameters, the stimulation level of the SOE has the greatest effect on the SOE shape. Based on our clinical experience, the stimulation level plays a subordinate role for the transimpedance shape while the stimulation level has a strong effect on the SOE shape. Since the electrode locations are pretty similar, especially taking into account individual differences in exact location, the choice of electrodes has less effect.

5. Conclusion

In summary, we identified a significant positive correlation between SEF and SOE on an individual level at medial electrode contact E13. When considering mean half-widths over all electrode contacts, we observed a significant negative correlation between SEF and SOE, but also a very large standard deviation. Therefore, the future work should focus on the dispersion of the electric field as a function of the individual position and the distance of the electrode array to the modiolus.

Funding Sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations of interest

None.

Credit authorship contribution statement

Anna C. Kopsch: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration. Torsten Rahne: Conceptualization, Methodology, Project administration, Writing – review & editing. Stefan K. Plontke: Writing – review & editing, Resources. Luise Wagner: Conceptualization, Methodology, Investigation, Writing – review & editing.

References

Başkent, Deniz, 2006. Speech recognition in normal hearing and sensorineural hearing loss as a function of the number of spectral channels. J. Acoust. Soc. Am. 120 (5), 2908–2925. doi:10.1121/1.2354017, Pt 1.
Berger, Klaus, Hocke, Thomas, Hessels, Horst, 2017. Laufzeitoptimierte messung von summenaktionspotentialen bei cochlea implantat trägern. Langy-smth-rino- otolocgie 96 (11), 780–786. doi:10.1055/s-0043-191292.
Biesheuvel, Jan Dirk, Briaire, Jeroen J., Frijns, Johan H.M., 2016. A novel algorithm to derive spread of excitation based on deconvolution. Ear. Hear. 37 (5), 572–581. doi:10.1097/AUD.0000000000000296.
Cochlear Ltd. (2012): Cochlear implant electrode comparison. Current electrodes offered by all manufacturers. Available online at https://www.cochlear.com/d229815ab-da4c-4c3c-a8f4-20416088459/ FUN1142_1554_JUL12_Electrode_Comparison4.pdf?MOD=AJPERES&CACHEID= ROOTWORKSPACE%2b229815ab-da4c-4c3c-a8f4-20416088459-fBKB.
Cochlear Ltd. (2020): Custom Sound EP Software. Version 6.0. User Guide.
Cohern, Laurence T., Richardson, Louise M., Saunders, Elaine, Cowan, Robert C., 2003. Spatial spread of neural excitation in cochlear implant recipients: comparison of improved ECAP method and psychophysical forward masking. Hear. Res. 179 (1–2), 72–87. doi:10.1016/S0369-8559(03)0056-0.
Da Silva, Coutinho, Juliana, Goffi-Gomez, Maria Valéria Schmidt, Magalhães, Ana Tereza, Tsuji, Robinson Koji, Bento, Ricardo Ferreira, 2020. Is the spread of eCAP width correlated to the speech recognition in cochlear implant users? Eur. Arch. Otorhinolaryngol. doi:10.1007/s00405-020-08629-9.
Dziembowski, Olivier C., Mir-Salim, Parweis, Müller, Alexander, 2016. Vergleichswerte elektrophysiologischer Messungen zur intraoperativen Lagekontrolle bei verschiede- nen Oto-Celektroden. Ztschrift für Audiologi (55) 50–56 2016.
Fishman, K.E., Shannon, R.V., Slatery, W.H., 1997. Speech recognition as a function of the number of electrodes used in the SPEAK cochlear implant speech processor. J. Speech Lang. Hearing. Res. 40 (5), 1201–1215. doi:10.1044/jshl-1200.1201.
Friesen, L.M., Shannon, R.V., Başkent, D., Wang, X., 2001. Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hear- ing and cochlear implants. J. Acoust. Soc. Am. 110 (2), 1150–1163. doi:10.1121/1.1381538.
Gekke, Michael, Wischmeyer, Erhard, Gründer, Stefan, Petersen, Marlen, 2015. Taschenlehrbuch Physiologie. With assistance of Michael Gekke. 2., überarbeitete Aufl. Georg Thieme Verlag, Stuttgart.
Grolman, Wilko, Maat, Albert, Verdamin, Froukje, Simis, Yvonne, Carelens, Bart, Peeling, Nicole, Tang, Rinze A., 2009. Spread of excitation measurements for the detection of electrode artery foldovers: a prospective study comparing 3-dimensional rotational x-ray and intraoperative spread of excitation measurements. Otol. Neurotol. 30 (1), 27–33. doi:10.1177/1945940608318157.
Hey, Matthias, Bönke, Britta, Dillier, Norbert, Hoppe, Ulrich, Esklsson, Gunnar, Löwen, Karolina, et al., 2015. The Intra-Cochlear Impedance-Matrix (IM) test for the Nucleus cochlear implant. Biomedizinische Technik Biomed. Eng. 60 (2), 123–133. doi:10.1515/bmt-2014-0058.
Hughes, Michelle L., 2008. A re-evaluation of the relation between physiological channel interaction and electrode pitch ranking in cochlear implants. J. Acoust. Soc. Am. 124 (5), 2771–2784. doi:10.1121/1.2990710.
Hughes, Michelle L., Abbas, Paul J., 2006. The relation between electrophysiologic channel interaction and electrode pitch ranking in cochlear implant recipients. J. Acoust. Soc. Am. 119 (3), 1527–1537. doi:10.1121/1.2163273.
Kalkman, Randy K., Briaire, Jeroen J., Frijns, Johan H.M., 2015. Current focusing in cochlear implants: an analysis of neural recruitment in a computational model. In: Hearing Research 322, 139–151. doi:10.1016/j.heares.2014.12.004.
Kral, Andrej, Aplin, Felix; Maier, Hannes (Eds.) (2021): Prostheses For the Brain: Academic Press.
Lai, W. (1999): An NRT Cookbook: guidelines for Making NRT Measurements, Version 2.04: cochlear AG. Available online at https://books.google.de/books?id= 8GgAAAAYAAAJ.
Müller, Alexander,; Kropp, Miriam H., Mir-Salim, Parweis, Aristeidou, Aristotleis; Dziemb, Oliver, C., 2020. Intraoperatives Tip-Folderover-Screening mittels Spread of Excitation Messungen. Z Med Phys 30.1036/j.jemedi.2020.07.0024.
Padilla, Monica,; Landsberger, David M., 2016. Reduction in spread of excitation from current focusing at multiple cochlear locations in cochlear implant users. Hear. Res. 333, 98–107. doi:10.1016/j.heares.2016.01.002.
Rijk, Simone R., de, Tam, Vu C., Carlyon, Robert P., Bance, Manohar, L., 2020. Detection of Extracochlear Electrodes in Cochlear Implants with Electric Field Imaging/Transimpedance Measurements: a Human Cadaver Study. Ear. Hear. 41 (5), 1196–1207. doi:10.1097/AUD.0000000000000837.

Hearing Research 424 (2022) 108591
A.C. Kopsch, T. Rahne, S.K. Plontke et al.
Seifter, Julian, Ratner, Austin, Sloane, David. 2005. Concepts in Medical Physiology. Lippincott Williams & Wilkins, Philadelphia, Pa. Available online at.
Söderqvist, Samuel, Lamminmäki, Satu, Aarnisalo, Antti, Hirvonen, Timo, Sinkkonen, Saku T., Sivonen, Ville. 2021. Intraoperative transimpedance and spread of excitation profile correlations with a lateral-wall cochlear implant electrode array. Hear. Res. 405, 108235. doi:10.1016/j.heares.2021.108235.
Sturm, Joshua J., Patel, Vir, Dibelius, Greg; Kuhlmey, Megan; Kim, Ana H. 2021. Comparative performance of lateral wall and perimodiolar cochlear implant arrays. Otol. Neurotol. 42 (4), 532–539. doi:10.1097/MAO.0000000000002997.
van der Beek, Feddo, B., Briaire, Jeroen J., Frijns, Johan H.M. 2012. Effects of parameter manipulations on spread of excitation measured with electrically-evoked compound action potentials. Int. J. Audiol. 51 (6), 465–474. doi:10.3109/14992027.2011.653446.
Vanpoucke, Filiep J., Boermans, Peter-Paul, B., Frijns, Johannes H., 2012. Assessing the placement of a cochlear electrode array by multidimensional scaling. In: IEEE transactions on bio-medical engineering, 59, pp. 307–310. doi:10.1109/TBME.2011.2173398.
Wagner, Luise; Plontke, Stefan K., Fröhlich, Laura; Rahne, Torsten, 2020. Reduced spread of electric field after surgical removal of intracochlear schwannoma and cochlear implantation. Otol. Neurotol. 41 (10), e1297–e1303. doi:10.1097/MAO.0000000000002884.