Research article

The intraoperative relationship between intracochlear electrical field and excitability of the auditory nerve

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HIGHLIGHTS

- Intracochlear electrical field peak amplitude and width had an inverse relationship with eCAP thresholds.
- In large cochleae, the intracochlear electrical field peak amplitudes were shallower than in small cochleae.
- Intracochlear electrical fields with a high peak amplitude were also wide-spread along the electrode array.

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ABSTRACT

A limiting factor of cochlear implant (CI) technology is the electrode-contact overlapping spread of the electrode-generated intracochlear electrical field (EF). While the extent of the spread can be reduced with intracochlear ground electrodes, the stimulation level must be increased to reach similar loudness as with monopolar stimulation utilizing an extracochlear ground. In this study, we investigated the relationship between the monopolar intracochlear EF and the minimum stimulation level required for a measurable neural response assessed with electrically evoked compound action potential (eCAP) thresholds in intraoperative settings. Also, the effect of cochlear diameter on the intracochlear EF was evaluated, as narrower intracochlear EFs were found from larger than smaller cochleae in an earlier study.

A total of 171 ears of severely-to-profoundly hearing-impaired patients (ages 0.7–89 years; 42.5 ± 27.8 years, mean ± SD) implanted with a Cochlear Nucleus CI522 or CI622 implant and Slim Straight electrode array or with a Med-El Synchrony implant and Flex 28 electrode array were included in the study. Normal anatomy was established and cochlear diameter was measured for all patients from preoperative imaging. Intraoperative intracochlear EF and eCAP threshold measurements were measured for both Cochlear and Med-El devices with the CIs’ back-telemetry options, and EF and eCAP were compared for Cochlear devices.

The peak and width of the intracochlear EF correlated with each other ($r = 0.46$, $p < 0.001$, and $r = -0.29$, $p < 0.001$, respectively). The peak amplitudes of the intracochlear EF increased towards the apical part of the electrode array with both Cochlear ($r = 0.97$, $p < 0.001$) and Med-El ($r = 0.80$, $p = 0.002$) devices. The peak amplitudes of the intracochlear EF were shallower across the electrode array in large than in small cochleae ($p < 0.05$).

Our results indicate that the responsiveness of the cochlear nerve is not only dependent on neural health but is also affected by the physical environment of the electrode array, which can be assessed by measuring the intracochlear EF. Further studies are warranted to investigate the detailed characteristics of the intracochlear current spread in CI recipients with varying anatomical features of the cochlea and with electrode arrays with different locations in the scalae or related to the modiolus in the cochlea.

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1. Introduction

A cochlear implant (CI) helps patients with severe-to-profound hearing loss to perceive sound and communicate verbally. However, when compared to normal hearing, CI recipients suffer from diminished spectral resolution and poorer speech recognition, especially in background noise (Dorman and Gifford, 2017). The auditory sensation with a CI is ultimately generated by directly stimulating the spiral ganglion neurons (SGNs) in the inner ear with an electrode array. Depending on the model, an electrode array consists of 12–22 separate electrode contacts, which is a strikingly low number when compared to about 3 500 rows of tonotopically organized hair cells inside the cochlea. In addition, because of the substantial overlap between the electrode-generated spread of intracochlear electrical fields (EFs), CI recipients perform as their electrode arrays would have ten or less independent channels (Friesen et al., 2001).

Several approaches have been taken over the years to reduce channel interaction in CIs. Shortly after the development of the multichannel CI, a processing strategy was pioneered to interleave the spectrum of the sound signal by stimulating electrode contacts sequentially. The aim of this so-called continuous interleaved sampling (Wilson et al., 1991) was to minimize electrical interaction between electrode contacts, and it forms the basis of the most commonly used CI sound coding still today. Later attempts focused on placing the electrode array as near to the SGNs as possible. Perimodiolar placement has been shown to result in narrower neural excitation profiles when compared to lateral placement of the electrode array within the same cochlea (Cohen et al., 2003). More recently, there has been growing interest in current focusing by using the intracochlear electrodes to ground the stimulating current. With tripolar stimulation, where the adjacent electrodes of the stimulating electrode are used as grounds and the current loop is entirely intracochlear, the spread of the EF can be reduced potentially achieving narrower patterns of stimulated SGNs and improved speech recognition in complex listening situations (Snyder et al., 2004; Srinivasan et al., 2013; Padilla and Landsberger, 2016; Luo and Wu, 2016). However, to reach similar loudness levels as with monopolar stimulation with an extracochlear ground, the stimulating current in tripolar stimulation must be significantly increased (Landsberger et al., 2012), potentially debilitating the beneficial effects of current focusing (Morris and Pfingst, 2000).

To effectively detect the malfunctioning of a CI, the manufacturers have developed objective back-telemetry tests for device function (Hey et al., 2015). These measurements include the ability to record voltages at individual electrode contacts in response to current flow to estimate channel impedances and the spread of the intracochlear EF. With the former, the majority of short and open circuits can be detected (Hughes et al., 2004). Also, abnormally high impedances might be seen after meningitis related intracochlear fibrous tissue growth around the electrode array and ossification of the cochlea (Durisin et al., 2015; Helmstaedter et al., 2018). High contact impedances at the basal electrodes may reveal electrode migration out of the cochlea (Dietsz et al., 2016). Recordings of the EF are also used to assess more subtle abnormalities in the electrode array and its surroundings, such as tip fold-overs (Zuniga et al., 2017; Hoppe et al., 2022). With a complete insertion of the electrode array and without any cochlear pathologies, the most relevant patient-related factors affecting the intracochlear EF spread are believed to be cochlear dimensions and geometry (Bai et al., 2019; Lei et al., 2021), the placement of the electrode array (Shepherd et al., 1993), and the conductivity of the tissues in the ear (Briaire and Frijns, 2000; Nogueira et al., 2016).

The spread of the intracochlear EF is purely a physical measure and can be recorded in saline and from cadavers and plastic cochlea models (de Rijk et al., 2020; Swaddiwudhipong et al., 2020). Therefore, to make inferences about the effect of the EF on auditory perception, its relationship with psychophysical loudness as well as with patterns of neural activation has been studied. The intracochlear EF seems to be similar between the different manufacturers (Swaddiwudhipong et al., 2020), despite slight differences in the measurement methods. In Cochlear (Sydney, Australia) devices the voltage is recorded for each stimulating and recording electrode pair separately, while in Advanced Bionics (Valencia, CA, USA) and Med-EI (Innsbruck, Austria) devices the EF distribution can be recorded simultaneously from all non-stimulated electrode contacts (Vanpoucke et al., 2004).

Berenstein et al. (2010) investigated loudness produced with monopolar stimulation and its combination with tripolar stimulation to estimate an effective field magnitude from the spread of intracochlear EF recordings. In EF measurements, the transimpedance recorded from the stimulating electrode includes a fast-decaying reactive component from the electrode-tissue interface and thus, Berenstein et al. (2010) assumed that the magnitude of the EF recorded at the stimulating electrode does not reach the neural components at its full potential. As it is impossible to record the transimpedance without the reactive component (effective transimpedance, Z_{ef}) at the location of the stimulating electrode, it has to be modeled based on the recordings from the rest of the electrodes (Berenstein et al., 2010) utilizing the knowledge of exponential decay of the intracochlear EF (Briaire and Frijns, 2000). Berenstein et al. (2010) found that loudness was determined by the Z_{ef}, and both loudness and the Z_{ef} increased with the stimulating current. In our earlier study (Söderqvist et al., 2021), we substituted the recorded transimpedance at the location of the stimulating electrode with a Z_{ef} to estimate an effective intracochlear EF (EF_{ef}), which allowed a more realistic comparison between the widths of the EF_{ef} and neural activation. We found that the profiles and widths of the EF_{ef} correlate with the patterns of the activated SGNs, as measured with the forward-masking paradigm for the spread of neural excitation.

Similarly, with impedance measurements, modern CIs can be used to record the excitability of the auditory nerve to electrical stimulation via the electrically evoked compound action potential (eCAP; Lai et al., 2002). The eCAP amplitude, defined as the potential difference between the negative and positive peaks in an eCAP recording, depicts the strength and synchrony of the SGN activation (Lai and Diller, 2000). As the eCAP amplitude increases with the stimulating current, an amplitude growth function (AGF) can be determined and further used to extrapolate the current level that elicits an eCAP amplitude of zero (eCAP threshold). Another method to determine the eCAP threshold is to repeat the eCAP measurement with a stimulation level around the assumed threshold level, and inspect what is the lowest current causing a visible eCAP over ground-noise level. A low eCAP threshold indicates that the cochlear nerve (CN) is easily excitable with electrical stimulation, but its correlation with the behavioral stimulation levels is moderate at best (Morita et al., 2003; Cafarelli Dees et al., 2005; Miller et al., 2008; Jeon et al., 2010). In animal models, the ears with better SGN survival possess steeper AGF slopes when compared to ears with sparse SGN density (Pfingst et al., 2015; Colesa et al., 2021). Also, it seems that the AGF slope is unaffected by intrascalar tissue growth (Swiderski et al., 2020). However, a similar relationship between neural health and eCAP thresholds has not been established.

The eCAP can be reliably measured from over 90% of CI recipients (Cafarelli Dees et al., 2005; Cooper et al., 2020). However, there is a great intersubject variability in eCAP thresholds, which is not explained by age or either duration or etiology of deafness (Morita et al., 2003; Cafarelli Dees et al., 2005; Jahn and Arenberg, 2020). Also, in lateral-wall electrode arrays, the eCAP thresholds are dependent on the recording location and tend to increase from apical to basal direction, which is a consistent finding between all devices (Cafarelli Dees et al., 2005; Telmesani and Said, 2015; Christov et al., 2019; Söderqvist et al., 2021). Further, both the eCAP and psychophysical threshold levels increase with the distance of an electrode from the modiolus (known as modiolar distance) or from the mid-modiolar axis (van Wermeskerken et al., 2009; Long et al., 2014; Davis et al., 2016; Mewes et al., 2020; Schwartz-Leyzac et al., 2020). The extent of neural activation is somewhat narrower in larger than in smaller cochleae (Söderqvist et al., 2021), which could be due to a larger volume of the scala tympani (ST) over which the intracochlear EF
decreases. On the other hand, a shallower decay of the intracochlear EF towards the apex has been detected in both modeling (Bai et al., 2019) and in vivo studies (Berenstein et al., 2010; Tang et al., 2011; Söderqvist et al., 2021), suggesting a physical background of the eCAP threshold variability at different sections of the electrode array.

The aim of this study was to investigate the relationship between the intracochlear EF in terms of peak amplitude (Zeff) and width with the responsiveness of the CN estimated via eCAP thresholds. As the profiles of the EF and neural excitation correlate (Söderqvist et al., 2021), the peak amplitude of the effective EF is related to psychophysical loudness (Berenstein et al., 2010) and eCAP amplitudes and loudness increase monotonically with stimulus current (Kirby et al., 2012), our hypothesis was that when a wide intracochlear EF with a high peak amplitude is generated by the stimulating electrode, less current is required to elicit a measurable neural response. In addition to the relationship between intracochlear EF and eCAP thresholds, we also evaluated the effects of cochlear diameter and CI manufacturer on the peak amplitude of the intracochlear EF. As in earlier studies narrow EFs and high eCAP thresholds were associated with large cochleae (Söderqvist et al., 2021, 2022), we expected to find shallower EF peaks from larger than smaller cochleae.

2. Methods

2.1. Study design and ethics

This was a retrospective cohort study approved by the institutional review board of the Hospital District of Helsinki and Uusimaa. Due to the retrospective nature of the study, the ethical committee and informed consent were not required by the Finnish national legislation.

2.2. Subjects

The study subjects consisted of two cohorts. In the first cohort, there were 99 consecutive severely-to-profoundly hearing-impaired patients (40 males and 59 females; ages 0.7–89 years; 35.8 ± 26.6 years, mean ± SD) implanted with a Cochlear Nucleus CI522 or CI622 implant and Slim Straight electrode array between January 2019 and December 2021. Twenty-three of the patients were implanted bilaterally, resulting in 122 implanted ears. Three ears were excluded from further analysis due to incomplete insertion or an open circuit in monopolar impedance measurements. The second cohort consisted of patients implanted with a Med-El Synchrony implant and Flex 28 electrode array between January 2015 and December 2021. Seventy-four ears of 71 severely-to-profoundly hearing-impaired patients were implanted with a Med-El device (25 males and 49 females; ages 3.4–85.1 years; 60.5 ± 18.8 years, mean ± SD). The intraoperative EF recordings were available from all study subjects. The eCAP thresholds were analyzed only from the recipients of Cochlear devices, as eCAP recordings were found only for 16 out of 74 ears with Med-El devices. Further, only three out of twelve electrode contacts had ten or more eCAP thresholds recorded. All patients were operated with the round window approach at Helsinki University Hospital at the Department of Otorhinolaryngology – Head and Neck Surgery. The following information was gathered: the age at the time of the surgery, the etiology of hearing loss, the size of the cochlea measured from computed tomography (CT) images, and the existence of an identifiable cochlear nerve in preoperative magnetic resonance images. The details of the patient demographics are described in Table 1 in the Appendix.

2.3. Intraoperative recordings

The intraoperative spread of the EF and eCAP thresholds were recorded from Cochlear devices via the transimpedance matrix (TIM) and automated neural response telemetry (AutoNRT) using the extrapolation method with the Custom Sound EP software. For Med-El devices, the EF spread was recorded via impedance field telemetry (IFT) with the Med-El Maestro software. All measurements were made during the final stages of the CI surgery after wound closure when the patient was still under general anesthesia. Prior to TIM measurements, the electrode array was conditioned by sweeping the contacts with 25 μs wide pulses at 230 current level (CL) to decrease the contact impedances with electrical stimulation (Newbold et al., 2011). For TIM, a maximum CL that did not exceed 230 CL and did not result in out-of-compliance or saturation was used and this was 207 ± 12.7 (mean ± SD) CL with a pulse width of 25 μs. For IFT, the charge was always 0.5 nanocoulombs (nC) and the pulse width was 26.7 μs.

The eCAP thresholds were measured with a pulse width of 25 μs and a rate of 250 Hz via AutoNRT and determined automatically by the measurement software. The recording electrode was two contacts apically from the stimulating electrode, with an exception for the two most apical electrodes, whose stimulation were recorded two contacts basally. From 113 to 117 out of 119 NRT recordings were available from each electrode. Electrode specific details are found in Table 2 in the Appendix.

2.4. Effective intracochlear electrical field

In the vicinity of the stimulating electrode the intracochlear EF decreases rapidly and linearly (Briaire and Frijns, 2000) likely due to the electrode-tissue interface (Berenstein et al., 2010). Further away from the stimulating electrode, which was estimated to be 0.4 mm by Berenstein et al. (2010), the decay of the EF is exponential. This information was used to compute an effective transimpedance (Zeff), which was thought to represent the transimpedance at the location of the neural tissue. In this study, the MATLAB (MathWorks, Natick, MA, USA) function fnmssearch was used to model Zeff and effective voltage (Ueff) based on the recorded values from the non-stimulated electrodes. These modeled values were used to substitute the corresponding monopolar value at the location of the stimulated electrode together with subtracting a dc offset from the modeled and recorded transimpedances to create an effective TIM (TIMeff) or IFT (IFTeff). Function fnpeaks, which finds a peak from a curve and computes its width, was used with halfheight as reference to estimate their 50% widths in millimeters along the electrode array similarly to Söderqvist et al. (2021). Also, a dc offset was deducted from Zeff and Ueff for further analysis.

Figure 1 illustrates examples of TIM and TIMeff (Figure 1A) as well as IFT and IFTeff (Figure 1B) with the corresponding 50% widths of the EFshapes. The modeling was considered successful if Zeff was between 0–2500 Ω, effective voltage (Ueff) between 0–1.5 V, TIM 50% width between 2–20 electrode contacts (1.82–18.2 mm), and IFT 50% width between 1–11 electrode contacts (1.93–21.23 mm). In total, 113–116 TIMeff and 28–73 IFTeff were modeled, as well as 109–116 TIMeff 50% widths were estimated from each electrode contact, respectively. The electrode-specific details are in Table 2 in the Appendix. Due to fewer electrode contacts in the Med-El electrode arrays, only 0–69 % of the IFTeff 50% widths were successfully computed (Table 2). Thus, the relationship between the IFTeff peak amplitude and 50% width was not analyzed further.

2.5. Cochlear diameter and insertion angle

All patients were preoperatively imaged with a standard high-resolution computed tomography (CT) clinical protocol used in the Hospital District of Helsinki and Uusimaa. The diameter of the cochlea was evaluated by an otoradiologist from the reconstructed CT images of the cochlea as described by Alexiades et al. (2015). Even though the cochlea is a tapered structure, the cochlea diameter can be used to estimate the cochlear duct length with a linear equation (Alexiades et al., 2015). The mean ± SD cochlear diameters were 8.77 ± 0.35 and 8.81 ± 0.35 mm for Cochlear and Med-El groups, respectively.

To evaluate the effect of the cochlear diameter on the peak amplitude of the intracochlear EF, the ears were sorted into four groups according to
In this study, we investigated the characteristics of the intracochlear EF. Figure 2 presents the relationship between the modeled peak amplitude and 50% width of the effective intracochlear EF. In Figure 2A, $Z_{\text{eff}}$ is plotted against TIM$_{\text{eff}}$ 50% width. There appears to be a linear correlation between the two ($r = 0.46, p < 0.001$), indicating that intracochlear EFs with high peak amplitudes are also wide along the scala tympani (ST). When the means of the $Z_{\text{eff}}$ and TIM$_{\text{eff}}$ 50% width are plotted at individual electrode contacts (Figure 2B), there is a clear relationship between the peak and width of the intracochlear EF in all the other regions but the most apical section of the electrode array.

Figure 3 illustrates the comparison of $Z_{\text{eff}}$ and TIM$_{\text{eff}}$ 50% width with the corresponding eCAP thresholds. In Figure 3A, $Z_{\text{eff}}$ is plotted against eCAP thresholds. The eCAP thresholds decrease with the increase of $Z_{\text{eff}}$ ($r = -0.41, p < 0.001$), demonstrating that intracochlear EFs with high peak amplitudes are also wide along the scala tympani (ST). When the mean $Z_{\text{eff}}$ and TIM$_{\text{eff}}$ 50% width are plotted at individual electrode contacts (Figure 3B), an increase of eCAP thresholds and TIM$_{\text{eff}}$ 50% widths are seen in the apical section of the electrode array. However, from the middle to basal section of the electrode array their correlation seems to be inverse.

In order to study the effect of cochlear diameter on $Z_{\text{eff}}$, the cochleae were divided into four cochlear diameter groups (1–4 from smallest to
largest, respectively, Figure 4A.) The peak amplitude of the intracochlear EF field is generally lower in the group with the largest cochleae, which was confirmed with a two-way ANOVA revealing a significant main effect of cochlear diameter group ($F (3, 2475) = 10.6, p < 0.001$). The mean ± SEM Z_{\text{eff}} was 650 ± 12, 670 ± 7.9, 681 ± 7.6, and 596 ± 11 Ω, for groups 1–4 (from smallest to largest), respectively. A pair-wise comparison after a post-hoc correction with the Tukey method revealed no significant differences in Z_{\text{eff}} between the groups 1–3 ($p = 0.57, p = 0.17$, and $p = 0.77$ for comparisons between group 1 vs 2, 1 vs 3, and 2 vs 3, respectively). However, the mean Z_{\text{eff}} of the group with the largest cochlea was lower than in the rest of the groups ($p < 0.05$ for all), indicating that the effect of cochlear diameter may become only apparent after a certain threshold.

To investigate Cochlear and Med-El devices with different electrode array designs and a different number of active electrode contacts, we plotted the Z_{\text{eff}} and U_{\text{eff}} against the insertion angle rather than electrode number. This also allowed us to consider the effect of different cochlea sizes detected in Figure 3. As seen in Figure 4B, the mean U_{\text{eff}} remains...
relatively constant between insertion angles of 250–600° and then rapidly decreases, while \( Z_{\text{eff}} \) decreases more gradually towards the base of the cochlea. When the effect of the electrode location and the manufacturer on the relative distribution of the intracochlear EF was analyzed with a two-way ANOVA, there were significant main effects of insertion angle category and manufacturer, as well as an interaction between the two main effects (\( F (10,3285) = 140, F (1,3285) = 332, \) and \( F (10, 3285) = 35.5 \), respectively, \( p < 0.001 \) for all). In the post-hoc analyses, when the insertion angle was between 50–99 or 450–600, the relative distribution of \( E_{F\text{eff}} \) peaks were similar between the manufacturers. Between insertion angles of 100–449°, the relative \( E_{F\text{eff}} \) peaks were greater for Med-El than for Cochlear devices \( (p < 0.001 \) for all). However, when the correlation between the mean EF peak and the mean insertion angle of each insertion angle category was calculated, a general trend of lower EF peaks towards the base is apparent for both Cochlear \((r = 0.98, p < 0.001)\) and Med-El \((r = 0.77, p = 0.01)\).

In Figure 5, the major finding of the present study is summarized with a sketch of the ST. Electrode insertion depth is plotted categorically as an estimated insertion angle along with the corresponding mean \( Z_{\text{eff}} \) and eCAP threshold for the Slim Straight electrode array. In the basal part of the electrode array with a shallow insertion depth, the intracoehlear EF (i.e., mean \( Z_{\text{eff}} \)) is low, and a high electrical current (in CL) is required to elicit a neural response. When moving along the electrode array towards to apex, the mean \( Z_{\text{eff}} \) increases while the eCAP threshold decreases, and there is a significant negative correlation between the two \((r = -0.95, p < 0.001)\).
4. Discussion

The aim of this study was to investigate the relationship between the electrode-generated intracochlear EF and the excitability of the CN. We also assessed how the peak of the intracochlear EF is affected by the cochlear diameter, which is assumed to correlate with the modiolar distance of lateral-wall electrodes and ST diameter (Hatsushika et al., 1990; Escudé et al., 2006). The ST is the desired location of the electrode array and is bordered by the basilar membrane and bone, which are poorly conductive essentially confining the electrode-generated EF in the intrascalar space (Briaire and Frijns, 2000). Therefore, it was expected that high-peaked intracochlear EFs are generally wide-spread. However, this is not true in the apex, where TIM 50% width decrease while $Z_{eff}$ increase. This may be due to the scarcity of data apically to the recording electrode, which may lead to a narrower TIM 50% width, as the width will be determined mostly by the basal part of the EF peak. In addition to computational inaccuracies, there may be current paths across the turns of the cochlea which may explain the discrepancy between TIM 50% width and $Z_{eff}$ in the apical part of the electrode array (Briaire and Frijns, 2006).

The inverse relationship between $M_{eff}$ and eCAP thresholds as well as the lower $Z_{eff}$ in larger than in smaller cochleae suggest that the neural excitability to electrical stimulation is dependent on the physical environment of the electrode array e.g., modiolar distance and scalar diameter. A previous modeling study found a sigmoid relationship between bone density and shallower decay of the intracochlear EF (Malherbe et al., 2015). Thus, high stimulation levels in conditions decreasing bone density, such as otosclerosis (Grayeli et al., 2004), may be required for sufficient loudness.

Generally, when the stimulation level is constant, the peak amplitudes of the generated intracochlear EFs increase towards the apex. A possible explanation for low peak amplitudes in the base is the current outflow from the round window, which may also be the case of a narrow TIM 50% width in the basal part of the ST (see Figure 3D). Based on our unpublished study, in which temporal bones were implanted with Slim Straight electrodes and cochlear dimensions were measured, the scala area decreases towards the apical end of the ST in line with Biedron et al. (2010). Thus, the local potential generated by a stimulated electrode might be greater in narrow than in larger ST due to the better conductivity of the perilymph than of the conductivity of the bone (Briaire and Frijns, 2000). Unfortunately, due to the lack of post-operative imaging in our patient cohort, the exact placement of the electrode arrays in the ST is unknown.

Contrary to an earlier study, where intracochlear EF recordings were similar between different manufacturers (Swadiiwudhipong et al., 2020), in our study the modeled EFs were different between Cochlear and Med-El devices. As the modeling function utilizes EF recordings from non-stimulating electrodes, a greater amount of recording electrodes likely leads to a more accurate estimate of the effective EF. Even though the distribution of the effective EF was different between the manufacturers, the general trend of increasing EF peak amplitude was apparent for both Cochlear and Med-El devices. As earlier studies have found that eCAP thresholds tend to decrease towards the apex also with Med-El CIs (Brill et al., 2009; Estienne et al., 2021), a similar relationship between the EF and eCAP thresholds likely could be found with Med-El as with Cochlear devices. However, future studies are warranted to confirm this assumption.

Finally, combining knowledge of individual cochlear anatomy, the properties of the intracochlear EF, and the responsiveness of the auditory nerve to electrical stimulation with audiometric measures will most likely result in more predictable CI outcomes, irrespective of the device brand. Although the exact electrode location was not available in this study due to the lack of postoperative imaging, the results highlight that the intracochlear EF and eCAP thresholds are linked and to some extent dependent on cochlear size in the intraoperative setting. This may help set the initial stimulation levels in cases with absent neural responses based on other individual measures, such as anatomy and the properties of the intracochlear EF. However, the eCAP thresholds tend to decrease within the first months after activation of the CI (Molisz et al., 2015) and thus, further studies investigating the eCAP thresholds and intracochlear EF in post-operative settings are warranted.

5. Conclusion

Intracochlear EFs with high peak amplitudes tend to spread widely along the ST. When the stimulating current generates an EF with a high and wide peak amplitude in EF measurements, less current is needed to excite the auditory nerve in eCAP measurements in the corresponding electrodes. The peak amplitude of the intracochlear EF is higher in the apex than in the base, and similar stimulation levels cause weaker EFs in larger than in smaller cochleae. The results suggest that the neural excitability to electrical stimulation is dependent on the physical environment of the electrode array, such as the dimensions of the cochlear.

Declarations

Author contribution statement

Samuel Söderqvist, M.D; Saku T. Sinkkonen; Ville Sivonen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
Appendix

Table 1. The patient demographics. If both ears from a single patient were included in the study, the right ear is marked with an “R” and left with an “L”.

| ID | Cochlear diameter (mm) | Age  | Ear  | Hearing loss etiology |
|----|------------------------|------|------|-----------------------|
| 1  | 8.10                   | 44.8 | Right| Unknown               |
| 2R | 9.0                    | 42.1 | Right| Unknown               |
| 2L | 9.8                    | 44.0 | Left | Unknown               |
| 3  | 9.2                    | 21.6 | Right| Unknown               |
| 4  | 8.6                    | 53.8 | Left | Unknown               |
| 5  | 9.0                    | 57.3 | Right| Unknown               |
| 6  | 9.0                    | 37.8 | Left | Unknown               |
| 7  | 8.7                    | 50.8 | Left | Unknown               |
| 8R | 8.6                    | 45.7 | Left | Unknown               |
| 8L | 8.5                    | 46.4 | Right| Unknown               |
| 9  | 8.1                    | 82.0 | Right| Unknown               |
| 10 | 7.9                    | 4.7  | Left | Unknown               |
| 11 | -                      | 16.9 | Right| Unknown               |
| 12R| 9.3                    | 0.8  | Right| Unknown               |
| 12L| 9.3                    | 0.8  | Left | Unknown               |
| 13 | 9.1                    | 6.5  | Right| Unknown               |
| 14R| 9.3                    | 0.7  | Right| Connexin-mutation     |
| 14L| 9.0                    | 0.7  | Left | Connexin-mutation     |
| 15 | 8.5                    | 15.1 | Left | Unknown               |
| 16 | 8.4                    | 64.3 | Right| Unknown               |
| 17 | 8.7                    | 58.9 | Right| Unknown               |
| 18 | 8.7                    | 39.7 | Left | Unknown               |
| 19 | 8.6                    | 24.8 | Right| Unknown               |
| 20 | 8.5                    | 45.6 | Right| Unknown               |
| 21 | 8.0                    | 60.5 | Left | Unknown               |
| 22 | 9.0                    | 47.1 | Left | Unknown               |
| 23 | 8.4                    | 41.9 | Left | Unknown               |
| 24R| 8.3                    | 47.1 | Right| Unknown               |
| 24L| 8.6                    | 45.6 | Left | Unknown               |
| 25 | 9.0                    | 35.4 | Right| Meningitis            |
| 26 | 8.6                    | 79.8 | Left | Meniere               |
| 27R| 8.9                    | 3.8  | Right| Unknown               |
| 27L| 8.9                    | 3.8  | Left | Unknown               |
| 28 | 8.5                    | 5.5  | Left | Unknown               |
| 29 | 8.7                    | 2.2  | Right| Unknown               |
| 30 | 8.5                    | 11.7 | Right| Unknown               |
| 31 | 8.4                    | 3.9  | Right| Unknown               |
| 32 | 8.9                    | 5.4  | Right| Connexin              |
| 33 | 8.2                    | 23.1 | Right| Unknown               |
| 34 | 9.2                    | 52.9 | Right| Maternal rubella      |
| 35 | 8.1                    | 56.0 | Left | Usher                 |
| 36 | 8.7                    | 57.0 | Left | Unknown               |
| 37 | -                      | 75.7 | Left | Unknown               |
| 38 | 8.9                    | 58.3 | Right| Unknown               |
| 39 | 8.9                    | 14.2 | Left | Unknown               |
| 40 | 8.2                    | 10.6 | Right| Unknown               |
| 41R| 8.8                    | 0.8  | Right| Unknown               |
| 41L| 9.1                    | 0.8  | Left | Unknown               |
| 42R| 8.9                    | 1.1  | Right| Maternal CMV          |
| 42L| 8.9                    | 1.1  | Left | Maternal CMV          |
| 43 | 7.7                    | 1.3  | Right| Cochlear nerve hypoplasia |
| 44 | 9.1                    | 4.4  | Left | Unknown               |
| 45R| 8.5                    | 1.0  | Right| Unknown               |
| 45L| 8.7                    | 1.0  | Left | Unknown               |
| 46R| 8.9                    | 1.1  | Right| Unknown               |
| 46L| 8.1                    | 1.1  | Left | Unknown               |

(continued on next page)
Table 1 (continued)

| ID   | Cochlear diameter (mm) | Age   | Ear   | Hearing loss etiology |
|------|------------------------|-------|-------|-----------------------|
| 47R  | 8.9                    | 0.9   | Right | Unknown               |
| 47L  | 8.8                    | 0.9   | Left  | Unknown               |
| 48R  | 8.5                    | 0.8   | Right | Unknown               |
| 48L  | 8.6                    | 0.8   | Left  | Unknown               |
| 49R  | 8.8                    | 12.6  | Right | Asphyxia              |
| 49L  | 8.8                    | 13.6  | Left  | Unknown               |
| 50   | 8.8                    | 17.3  | Right | Unknown               |
| 51R  | 9.5                    | 0.9   | Right | Unknown               |
| 51L  | 9.5                    | 0.9   | Left  | Unknown               |
| 52   | 8.9                    | 27.5  | Left  | Unknown               |
| 53   | 9.4                    | 50.7  | Right | Unknown               |
| 54R  | 8.7                    | 46.0  | Left  | Otosclerosis          |
| 54L  | 8.7                    | 45.7  | Left  | Otosclerosis          |
| 55   | 8.9                    | 38.7  | Left  | Meniere               |
| 56   | 8.9                    | 60.5  | Left  | Unknown               |
| 57   | 8.8                    | 42.2  | Left  | Unknown               |
| 58   | 8.6                    | 54.5  | Left  | Unknown               |
| 59R  | 8.4                    | 50.7  | Right | Otosclerosis          |
| 59L  | 9.0                    | 50.4  | Left  | Otosclerosis          |
| 60   | 9.0                    | 60.1  | Right | Unknown               |
| 61R  | 8.5                    | 54.8  | Right | Unknown               |
| 61L  | 8.5                    | 55.5  | Left  | Unknown               |
| 62   | 8.0                    | 49.0  | Right | Unknown               |
| 63   | 8.7                    | 36.2  | Right | Meningitis            |
| 64   | 8.9                    | 55.6  | Right | Unknown               |
| 65   | 8.7                    | 32.8  | Left  | Meniere               |
| 66   | 8.7                    | 78.3  | Left  | Unknown               |
| 67   | 9.0                    | 77.9  | Left  | Unknown               |
| 68   | 9.1                    | 53.3  | Left  | Otosclerosis          |
| 69   | 8.5                    | 55.0  | Left  | Unknown               |
| 70   | 8.6                    | 42.1  | Right | Unknown               |
| 71   | 8.5                    | 66.6  | Left  | Unknown               |
| 72   | 8.8                    | 25.8  | Right | Unknown               |
| 73   | 8.7                    | 67.0  | Right | Unknown               |
| 74   | 9.0                    | 50.8  | Left  | Otosclerosis          |
| 75   | 8.9                    | 25.1  | Left  | Unknown               |
| 76   | 9.2                    | 89.9  | Right | Chronic otitis media |
| 77   | 8.9                    | 34.4  | Left  | Unknown               |
| 78   | 8.2                    | 68.2  | Left  | Unknown               |
| 79   | 9.3                    | 71.4  | Left  | Unknown               |
| 80   | 9.0                    | 69.1  | Left  | Unknown               |
| 81   | 8.0                    | 54.1  | Right | Preterm birth         |
| 82   | 9.1                    | 74.3  | Left  | Meniere               |
| 83   | 9.2                    | 57.9  | Right | Meniere               |
| 84   | 9.3                    | 74.2  | Right | Unknown               |
| 85   | 9.3                    | 35.2  | Left  | Renal insufficiency   |
| 86   | 8.7                    | 34.7  | Left  | Unknown               |
| 87   | 8.8                    | 66.5  | Right | Unknown               |
| 88   | 8.4                    | 0.9   | Right | Connexin-mutation     |
| 89R  | 8.5                    | 0.9   | Left  | Connexin-mutation     |
| 90R  | 8.4                    | 0.9   | Right | Unknown               |
| 90L  | 8.4                    | 2.0   | Right | Unknown               |
| 91R  | 8.5                    | 0.9   | Right | Unknown               |
| 91L  | 8.5                    | 0.9   | Left  | Unknown               |
| 92R  | 8.8                    | 3.9   | Right | Unknown               |
| 92L  | 9.1                    | 3.9   | Left  | Unknown               |
| 93   | 9.1                    | 5.3   | Right | Unknown               |
| 94R  | 8.2                    | 1.2   | Right | Unknown               |

(continued on next page)
Table 1 (continued)

Patients with Cochlear C522 and C622 with Slim Straight electrode array

| ID  | Cochlear diameter (mm) | Age | Ear | Hearing loss etiology      |
|-----|------------------------|-----|-----|-----------------------------|
| 94L | 8.4                    | 1.2 | Left| Unknown                     |
| 95R | 8.6                    | 2.4 | Right| Unknown                     |
| 95L | 8.6                    | 2.4 | Left| Unknown                     |
| 96L | 8.2                    | 1.0 | Right| Unknown                     |
| 96R | 8.2                    | 1.0 | Left| Unknown                     |

Patients with Med-El Synchrony with Flex 28 electrode array

| ID  | Cochlear diameter (mm) | Age | Ear | Hearing loss etiology      |
|-----|------------------------|-----|-----|-----------------------------|
| 1   | 8.3                    | 83.7| Right| Presbycusis                 |
| 2   | 8.8                    | 74.2| Right| Unknown                     |
| 3   | 8.8                    | 75.0| Right| Meningitis                  |
| 4   | 8.9                    | 77.7| Right| Meniere                     |
| 5   | 8.8                    | 78.0| Left | Sudden deafness             |
| 6   | 8.6                    | 25.8| Left | Unknown                     |
| 7R  | 8.5                    | 58.3| Right| Unknown                     |
| 7L  | 8.8                    | 54.6| Left | Unknown                     |
| 8   | 9.7                    | 81.6| Left | Sudden deafness             |
| 9   | 8.7                    | 73.8| Right| Unknown                     |
| 10  | 8.7                    | 84.2| Left | Unknown                     |
| 11  | 8.8                    | 57.4| Left | Usher                       |
| 12  | 8.2                    | 83.0| Right| Unknown                     |
| 13  | 8.9                    | 63.4| Left | Unknown                     |
| 14  | 8.9                    | 46.4| Right| Unknown                     |
| 15  | 8.9                    | 83.5| Right| Sudden deafness             |
| 16  | 8.9                    | 76.5| Right| Unknown                     |
| 17  | 8.5                    | 72.5| Left | Cochlear nerve aplasia      |
| 18  | 9.6                    | 61.1| Right| Unknown                     |
| 19  | 9.1                    | 76.4| Right| Unknown                     |
| 20  | 9.4                    | 70.1| Right| Unknown                     |
| 21  | 8.5                    | 56.5| Right| Unknown                     |
| 22  | 8.4                    | 77.8| Right| Unknown                     |
| 23  | 8.0                    | 51.9| Left | Unknown                     |
| 24R | 8.7                    | 32.5| Right| Unknown                     |
| 24L | 8.8                    | 34.7| Left | Unknown                     |
| 25  | 8.9                    | 59.5| Right| Unknown                     |
| 26  | 8.7                    | 84.1| Left | Unknown                     |
| 27  | 9.4                    | 53.4| Right| Unknown                     |
| 28  | 9.0                    | 83.8| Left | Unknown                     |
| 29  | 8.3                    | 67.0| Right| Unknown                     |
| 30  | 8.6                    | 76.0| Left | Unknown                     |
| 31  | 8.6                    | 27.3| Left | Unknown                     |
| 32  | 9.1                    | 64.1| Right| Unknown                     |
| 33  | 9.3                    | 50.3| Right| Unknown                     |
| 34  | 8.4                    | 73.9| Left | Unknown                     |
| 35  | 9.5                    | 79.0| Right| Unknown                     |
| 36  | 8.7                    | 41.7| Right| Unknown                     |
| 37  | 8.6                    | 67.6| Left | Otosclerosis                |
| 38  | 8.2                    | 74.8| Right| Unknown                     |
| 39  | 9.1                    | 72.7| Right| Unknown                     |
| 40  | 8.5                    | 35.6| Left | Unknown                     |
| 41  | 8.5                    | 65.6| Left | Meniere                     |
| 42  | 8.8                    | 74.6| Left | Unknown                     |
| 43  | 8.4                    | 74.8| Right| Unknown                     |
| 44  | 8.6                    | 80.5| Right| Unknown                     |
| 45  | 8.6                    | 45.2| Right| Unknown                     |
| 46  | 8.9                    | 42.4| Right| Usher                       |
| 47  | 8.9                    | 50.0| Right| Usher                       |
| 48R | 8.4                    | 56.1| Right| Meniere                     |
| 48L | 8.5                    | 54.3| Left | Meniere                     |

(continued on next page)
### Table 1 (continued)

| ID  | Cochlear diameter (mm) | Age | Ear | Hearing loss etiology |
|-----|------------------------|-----|-----|-----------------------|
| 49  | 9.0                    | 59.9| Left| Unknown               |
| 50  | 8.8                    | 68.0| Right| Unknown               |
| 51  | 8.9                    | 75.0| Left| Unknown               |
| 52  | 8.9                    | 39.0| Left| Unknown               |
| 53  | 9.3                    | 40.7| Right| Unknown              |
| 54  | 9.2                    | 21.4| Left| Unknown              |
| 55  | 9.1                    | 58.8| Right| Unknown             |
| 56  | 9.2                    | 56.3| Left| Unknown             |
| 57  | 8.9                    | 39.1| Left| Unknown             |
| 58  | 9.3                    | 23.9| Left| Meningitis        |
| 59  | 8.6                    | 35.5| Right| Meningitis       |
| 60  | 9.2                    | 49.8| Right| Unknown         |
| 61  | 8.5                    | 75.0| Right| Meningitis  |
| 62  | 8.8                    | 76.2| Left| Unknown         |
| 63  | 8.9                    | 66.6| Left| Unknown         |
| 64  | 8.8                    | 48.9| Left| Usher            |
| 65  | 8.6                    | 62.4| Left| Unknown         |
| 66  | 8.8                    | 69.6| Left| Sudden deafness|
| 67  | 8.3                    | 68.7| Left| Unknown       |
| 68  | 9.6                    | 71.8| Right| Meningitis       |
| 69  | 9.0                    | 85.1| Left| Unknown       |
| 70  | -                      | 17.7| Left| Unknown       |
| 71  | 8.9                    | 3.4 | Left| Connexin mutation |

### Table 2
The number of available TIM\textsubscript{eff} and IFT\textsubscript{eff} from each electrode contact. For TIM\textsubscript{eff}, the corresponding 50\% widths and cCAP thresholds are also shown. The electrodes are arranged from the apical to basal direction, which is from 22 to 1 in Cochlear devices and the opposite in Med-El devices.

#### Cochlear CS22 and C622 with Slim Straight electrode array

| Electrode | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 |
|------------|----|----|----|----|----|----|----|----|
| Zeff       | 98 | 98 | 97 | 98 | 97 | 97 | 96 | 96 |
| NRT        | 96 | 96 | 96 | 96 | 97 | 97 | 97 | 95 |
| Both       | 94 | 95 | 94 | 96 | 94 | 94 | 94 | 92 |
| Electrode  | 14 | 13 | 12 | 11 | 10 | 9  | 8  |    |
| Zeff       | 96 | 95 | 96 | 96 | 96 | 97 | 96 |    |
| NRT        | 95 | 96 | 96 | 98 | 98 | 98 | 97 |    |
| Both       | 92 | 92 | 94 | 94 | 94 | 96 | 94 |    |
| Electrode  | 7  | 6  | 5  | 4  | 4  | 2  | 1  |    |
| Zeff       | 96 | 96 | 96 | 96 | 96 | 95 | 94 |    |
| NRT        | 97 | 97 | 97 | 97 | 96 | 97 | 98 |    |
| Both       | 94 | 92 | 94 | 93 | 92 | 93 | 93 |    |

#### Med-El Synchrony with Flex 28 electrode array

| Electrode | 1  | 2  | 3  | 4  | 5  | 6  |
|------------|----|----|----|----|----|----|
| IFT\textsubscript{eff} | 86 | 89 | 91 | 88 | 73 | 53 |
| IFT\textsubscript{eff} 50\% width | 0 | 35 | 65 | 62 | 50 | 23 |
| Electrode | 7  | 8  | 9  | 10 | 11 | 12 |
| IFT\textsubscript{eff} | 36 | 69 | 88 | 97 | 97 | 96 |
| IFT\textsubscript{eff} 50\% width | 16 | 34 | 50 | 55 | 69 | 0 |

### Table 3
The number of available Z\textsubscript{eff} and U\textsubscript{eff} in each insertion angle category.

| Insertion angle | 50-99 | 100-149 | 150-199 | 200-249 | 250-299 | 300-349 | 350-399 | 400-449 | 450-499 | 500-600 |
|----------------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Zeff count     | 461   | 410     | 355     | 328     | 274     | 264     | 254     | 235     | 186     | 159     |
| Ueff count     | 151   | 137     | 94      | 104     | 87      | 78      | 71      | 65      | 59      | 30      |

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