Year: 2021

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Abstract: Objectives: (1) To correlate simultaneously recorded intra- and extracochlear electrocochleography (ECoChG) signals during electrode insertion into the cochlea, (2) to track changes in the ECoChG signal during insertion and removal of an electrode, and (3) to correlate the findings with the preoperative residual hearing. We hypothesized that intracochlear ECoChG recordings show signal changes not reflected in simultaneous extracochlear ECoChG recordings. Design: During cochlear implantation in human cochlear implant recipients, a short, slim, custom-made electrode was inserted and removed in a stepwise manner. At each step, ECoChG recordings were simultaneously recorded by an extracochlear electrode near the round window and via the inserted electrode. The acoustic stimulus was a 500 Hz tone burst at 110 to 130 dB SPL. Results: The mean amplitude difference between intra- and extracochlear ongoing ECoChG responses was 14 dB (range 9 to 24 dB; $n = 10$) at the beginning of insertion. Intracochlear ECoChG responses were larger in all cases. Extracochlear ECoChG responses remained stable while intracochlear recordings showed large variations regarding amplitude and phase during the electrode array insertion. Intracochlear signal changes during insertion were reversible with retraction of the electrode. There were only weak to moderate ($r_s = 0.006$ to 0.4), nonsignificant correlations of residual preoperative hearing with maximum amplitudes and amplitude changes during electrode insertion and removal in intracochlear recordings. Conclusions: Signals in intracochlear ECoChG recordings are reliably larger than ECoChG signals recorded simultaneously from an extracochlear location. Intracochlear ECoChG recordings show reversible amplitude and phase changes during insertion, not reflected in simultaneous extracochlear ECoChG recordings. Such changes are most likely due to the movement of the recording electrode in relation to the signal generators. Residual high-frequency hearing is associated with larger ECoChG signal amplitudes. Modeling of expected intracochlear ECoChG changes during electrode insertions may allow detection of cochlear trauma in the future.

DOI: <https://doi.org/10.1097/AUD.0000000000000935>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-189274>

Journal Article

Published Version

Originally published at:

Dalbert, Adrian; Sijgers, Leanne; Grosse, Julian; Veraguth, Dorothe; Roosli, Christof; Huber, Alexander; Pfiffner, Flurin (2021). Simultaneous Intra- and Extracochlear Electrocochleography During Electrode Insertion. *Ear and Hearing*, 42(2):414-424.

DOI: <https://doi.org/10.1097/AUD.0000000000000935>

Simultaneous Intra- and Extracochlear Electrocochleography During Electrode Insertion

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Alexander Huber,^{1,2} and Flurin Pfiffner^{1,2}

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Design: During cochlear implantation in human cochlear implant recipients, a short, slim, custom-made electrode was inserted and removed in a stepwise manner. At each step, ECoChG recordings were simultaneously recorded by an extracochlear electrode near the round window and via the inserted electrode. The acoustic stimulus was a 500 Hz tone burst at 110 to 130 dB SPL.

Results: The mean amplitude difference between intra- and extracochlear ongoing ECoChG responses was 14 dB (range 9 to 24 dB; $n = 10$) at the beginning of insertion. Intracochlear ECoChG responses were larger in all cases. Extracochlear ECoChG responses remained stable while intracochlear recordings showed large variations regarding amplitude and phase during the electrode array insertion. Intracochlear signal changes during insertion were reversible with retraction of the electrode. There were only weak to moderate ($r_s = 0.006$ to 0.4), nonsignificant correlations of residual preoperative hearing with maximum amplitudes and amplitude changes during electrode insertion and removal in intracochlear recordings.

Conclusions: Signals in intracochlear ECoChG recordings are reliably larger than ECoChG signals recorded simultaneously from an extracochlear location. Intracochlear ECoChG recordings show reversible amplitude and phase changes during insertion, not reflected in simultaneous extracochlear ECoChG recordings. Such changes are most likely due to the movement of the recording electrode in relation to the signal generators. Residual high-frequency hearing is associated with larger ECoChG signal amplitudes. Modeling of expected intracochlear ECoChG changes during electrode insertions may allow detection of cochlear trauma in the future.

Key words: Cochlear implant, Cochlear implantation, Electrocochleography, Residual hearing.

(Ear & Hearing 2020;XX:00–00)

INTRODUCTION

In recent years, electrocochleography (ECoChG) has emerged as a tool to assess cochlear function before, during, and after cochlear implantation (Choudhury et al. 2012; Mandalà et al. 2012; Radeloff et al. 2012; Calloway et al. 2014; Campbell et al. 2015, 2016; Dalbert et al. 2015a, 2015b, 2016, 2018, 2019, 2020; Adunka et al. 2016; Bester et al. 2017; Harris et al. 2017a, 2017b; Giardina et al. 2018, 2019; Koka et al. 2018; Ramos-Macias et al. 2019; Riggs et al. 2019). Recordings

have been conducted from both intra- (Calloway et al. 2014) and extracochlear sites (Dalbert et al. 2015b), although considerably more studies have investigated intracochlear recordings. Published findings suggest that intracochlear ECoChG responses are usually larger than extracochlear responses (Calloway et al. 2014; Dalbert et al. 2015a). However, simultaneous ECoChG recordings from an intra- and an extracochlear location for comparison have not been attempted in human cochlear implant (CI) recipients.

Another advantage of intracochlear ECoChG is that it can be conducted through the CI itself (Campbell et al. 2015), which makes the recording less laborious and time-consuming. On the other hand, the main disadvantage of intracochlear ECoChG recording compared to extracochlear recording is that the recording electrode moves along the cochlea during insertion. Most likely, this movement itself leads to changes of the ECoChG signal (Giardina et al. 2019), which makes the interpretation of signal changes challenging. In intracochlear recordings, amplitude and phase changes occur regularly during insertion (Harris et al. 2017a; Giardina et al. 2019), but the correlation of these changes with cochlear trauma or changes of inner ear mechanics remains controversial (Campbell et al. 2016; Giardina et al. 2019).

Another difference between intra- and extracochlear ECoChG recordings is the location of the main contributors to the signal. In intracochlear ECoChG recordings, the main contributors to the signal are most likely in close proximity to the recording electrode, while signals recorded from outside the cochlea are probably generated over a wider area in the base of the cochlea (Campbell et al. 2017; Giardina et al. 2018, 2019; Dalbert et al. 2020).

In this study, intracochlear ECoChG recordings were performed with a short, slim, custom-made electrode array to minimize insertion trauma. Simultaneously, ECoChG signals were recorded from the promontory by a needle electrode. The aim of this study was (1) to correlate simultaneously recorded intra- and extracochlear ECoChG signals, (2) to track changes in the ECoChG signal during insertion and removal of an electrode array, and (3) to correlate intracochlear ECoChG response patterns with the preoperative residual hearing. This is the first case series of simultaneous intra- and extracochlear ECoChG recordings and the first description of ECoChG signal changes during removal of an electrode array in human CI recipients.

MATERIALS AND METHODS

The study was conducted in accordance with the terms of the Ethical Committee of Zurich (KEK-ZH-Nr. 2019-00007) and the Helsinki Declaration. Before surgery, written informed consent was obtained from all subjects. Twelve subjects (mean age 61 years, range 30 to 79 years) were included. All subjects except S4

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TABLE 1. Subject Demographics and Audiometric Findings

Subject	Age (yrs)	Sex	Side	Etiology of Hearing Loss	Low-frequency PTA	High-frequency PTA
S1	74	F	Left	Progressive idiopathic hearing loss	83	111
S2	30	F	Right	Progressive idiopathic hearing loss	72	101
S3	71	F	Left	Progressive idiopathic hearing loss	40	110
S4	79	M	Right	Fabry disease	73	85
S5	61	F	Left	Progressive idiopathic hearing loss	77	114
S6	76	M	Left	Progressive idiopathic hearing loss	68	116
S7	49	F	Right	Progressive idiopathic hearing loss	61	116
S8	38	M	Left	Progressive idiopathic hearing loss	52	112
S9	65	F	Right	Progressive idiopathic hearing loss	60	116
S10	73	M	Right	Progressive idiopathic hearing loss	78	101
S11	73	F	Right	Progressive hereditary hearing loss	40	108
S12	46	M	Right	Progressive idiopathic hearing loss	47	113

Low-frequency PTA was defined as the PTA from 0.125 to 0.5 kHz, high-frequency from 1 to 8 kHz.
PTA, pure-tone average.

and S11 had progressive idiopathic hearing loss. Subject S4 suffered from Fabry disease, and S11 had a progressive hereditary hearing loss. Subject demographics are summarized in Table 1.

Preoperative pure-tone audiograms were conducted within 1 month before surgery. They were performed according to ISO 8235-1. Threshold values were determined at 0.125, 0.25, 0.5, 1, 2, 4, and 8 kHz. If no response could be detected at the maximum output of the audiometer, the maximum output of the audiometer plus 5 dB was used to calculate the pure-tone average (PTA). The low-frequency PTA was defined as the PTA from 0.125 to 0.5 kHz, and the high-frequency PTA from 1 to 8 kHz. The definition for the low-frequency PTA was chosen according to Giardina et al. (2019). The hearing threshold at 1 kHz was included into the high-frequency PTA in view of the typical audiometric configurations in CI recipients with only minimal or no residual hearing in frequencies >1 kHz and consequently pronounced ceiling effects.

Surgery and Recording Technique

After induction of anesthesia, an insert earphone (Biologic Systems, Mundelein, IL, USA) was placed in the ear canal of the operated ear for acoustic stimulation. A custom-made electrode from MED-EL (Innsbruck, Austria) was used as the intracochlear recording electrode (Fig. 1). The electrode has three single contacts on an elongated silicone electrode array. The electrode array has a length of 18.3 mm with 4.2 mm contact separation. The diameter is 0.4×0.6 mm at the tip and 0.8 mm at the base. The electrode lead is 10.5 cm long and terminates with an Axon connector. The electrode was specifically designed for this study to achieve an atraumatic insertion.

After a standard transmastoid facial recess approach, the recording electrode was inserted through the round window in three steps. Each time a contact entered the cochlea, the insertion was paused and the electrode held in an unchanged position until the ECoChG recordings were completed. In the same way, the removal of the electrode was performed in a stepwise manner (except in S2 for whom no recordings were conducted during removal of the recording electrode), resulting in a total of five simultaneous ECoChG recordings. The estimated insertion angles at the three recording locations were 20°, 120°, and 220°, corresponding to the characteristic frequencies of approximately 16, 8, and 4 kHz, respectively (Greenwood 1961). After

complete removal of the recording electrode, the CI surgery was continued in standard fashion and the CI electrode was inserted using the established round window approach.

For extracochlear ECoChG recordings, a sterile disposable monopolar needle electrode (Neurosign, Ref 74512-100/24, Wales, UK) was placed on the promontory, adjacent to the round window, and left in an unchanged position for all recordings. For further details, we refer to previous publications (Dalbert et al. 2015b, 2016, 2019).

For intra- as well as extracochlear ECoChG recordings, surface electrodes in the contralateral retro-auricular region and on the forehead were used as negative and ground electrodes, respectively.

Electrococleography

For acoustic stimulation and ECoChG recording, a Biologic Navigator Pro (Biologic Systems) was used. After access to the promontory was established and the extracochlear recording electrode was in place, extracochlear ECoChG recording was performed (except with subjects S9, S10, and S11 in whom the first ECoChG recordings were conducted after opening the round window). If no clear response was visible, the measurement was terminated and the surgery continued according to the standard protocol without further ECoChG recordings. If a clear response was present, extracochlear ECoChG recordings were repeated after opening the round window. Then, simultaneous intra- and extracochlear recordings were conducted at five points during insertion and removal of the intracochlear recording electrode as described earlier. Finally, after removal of the intracochlear recording electrode, the insert earphone was disconnected from the loudspeaker and a final extracochlear

Fig. 1. The custom-made electrode used as the intracochlear recording electrode. The electrode has three single contacts (1, 2, and 3) with 4.2 mm contact separation. The diameter is 0.4×0.6 mm at the tip and 0.8 mm at the base. The electrode lead is 10.5 cm long and terminates with an Axon connector.

ECochG recording was made to assess possible electrical artifacts and the noise floor.

The acoustic stimulus was a 500 Hz sinusoidal tone burst at 110 to 130 dB SPL with alternating starting phases. The sound pressure in the ear canal was monitored by a microphone (ER-7C, Etymotic, Elk Grove Village, IL, USA) and visualized using an oscilloscope. The microphone was calibrated in an artificial ear canal. The measured sound pressure during surgery had to be within ± 10 dB of the intended sound pressure. All sound pressure levels mentioned in this article are the intended sound pressure values chosen in the Biologic Navigator Pro (Biologic Systems). The rise and fall times were 2 cycles shaped by a Blackman window and the plateau portion was 10 cycles. The total stimulus duration was 28 ms, and the recording window was 32 ms. Responses to 400 tone bursts were filtered and averaged. Responses to rarefaction and condensation tone bursts were stored separately. The high-pass filter was set at 10 Hz, and the low-pass filter was set at 3000 Hz.

Difference curves were obtained by subtracting responses with alternating starting phases, and sum curves were obtained by adding the responses. Postprocessing was done with MATLAB (MathWorks Inc., Natick, MA, USA), and data analysis was accomplished with GraphPad Prism (GraphPad Software Inc., La Jolla, CA, USA) and SPSS Statistics (Version 25, IBM Corp., Armonk, NY, USA). The data were exported from the Biologic Navigator Pro software using the AEP to ASCII software from Biologic Systems.

The spectrum of each response was obtained by a fast Fourier transform in an 8 to 24 ms time window. The time window was chosen to isolate the ongoing portion of the ECochG response from the compound action potential (CAP). The energy content was measured at the first and the second harmonic frequencies. For the rest of the article, if not otherwise stated, the amplitude of the ECochG response is defined as the sum of the first and second harmonic frequencies. Phase calculations were done in the difference curves. The CAP and the summating potential (SP) were assessed visually in the sum curve. To correlate preoperative hearing thresholds with amplitudes and amplitude changes of the ECochG signals, a Spearman rank correlation was performed. A p -value ≤ 0.05 was considered statistically significant.

RESULTS

Simultaneous intra- and extracochlear ECochG recordings were successfully performed in 10 subjects (S2, S3, S4, S5, S6, S8, S9, S10, S11, and S12). For subjects S1 and S7, the study was prematurely terminated as no clear signal was detectable in the first extracochlear ECochG recording.

The preoperative hearing thresholds of all subjects are shown in Figure 2. The mean hearing threshold at 0.5 kHz was 80 dB HL. All subjects had mean low-frequency thresholds from 0.125 to 0.5 kHz of < 80 dB HL. The low- and high-frequency PTAs for all subjects are summarized in Table 1. The mean signal-to-noise ratio between the first extracochlear ECochG recording and the noise recording was 17 dB (range 3 to 36 dB; Fig. 3). Electrical artifacts in the noise recordings with the frequency of the acoustic stimulus were visible in S4, S5, and S8.

Figure 4 shows all extracochlear ECochG recordings before (if available) and after opening of the round window. After opening the round window, the difference curve showed an

Fig. 2. Preoperative residual hearing in all subjects. The mean hearing threshold at 0.5 kHz was 80 dB HL.

average change of -0.6 dB (SD 3.6 dB; $n = 7$) and the sum curve an average increase of 1.4 dB (SD 2.8; $n = 7$). In all cases, clear responses in the difference curves as well as the sum curves were visible after opening the round window. However, in S10 the sum curve only showed a CAP but no ongoing response. A prominent increase of the response amplitude after opening the round window was detected only in the sum curve of S5 (increase of 6.8 dB).

In all cases, the first intracochlear ECochG recordings after insertion of one contact of the temporary recording electrode showed clear responses in the difference curve (Fig. 5). For subjects S2, S4, S6, and S11, clear responses were not observed in the sum curves.

Correlation of Intra- and Extracochlear ECochG Recordings With Signal Changes During Insertion/Removal of the Electrode Array

After insertion of the first contact of the recording electrode, the mean amplitude difference between intra- and extracochlear ECochG responses was 14 dB (range 9 to 24 dB) with a larger intracochlear response in all cases (Fig. 6).

Figure 7 shows two examples of intra- and extracochlear recorded difference curves during insertion and removal of the temporary electrode. On the left side, the recordings from subject S4 show a stable extracochlear signal, while in the intracochlear signal, a reversible increase and reversible change of the signal phase of 260° between an insertion depth of 120° and 220° is detectable. On the right side of Figure 7, the recordings of subject S8 are displayed. The ECochG signal remained stable in intra- as well as extracochlear recordings in this case.

Figure 8 summarizes the amplitude changes for intra- and extracochlear recordings in all subjects. The extracochlear ECochG responses showed minor amplitude changes during insertion and removal of the intracochlear recording electrode. Mean change between extracochlear recordings was 1.6 dB (SD 3.5 dB) in the difference curve and 0.5 dB (SD 4.3 dB) in the sum curve. In contrast, in intracochlear recordings, the difference curve as well as the sum curve showed large, mostly reversible variations during the procedure, which is shown in a mean change of -1.4 dB (SD 9 dB) in the difference curve and -0.1 dB (SD 8.2 dB) in the sum curve. The larger variation in intracochlear recordings is reflected in the markedly larger SD for the difference as well as the sum curve, the reversibility in

Fig. 3. The first extracochlear ECoG recording for each subject and the noise floor measured with a disconnected insert earphone speaker. The difference curves are shown. ECoG indicates electrocochleography; SNR, signal-to-noise ratio.

the overall small mean change. Exceptional were the findings in S6, in which the intracochlear difference curve showed an irreversible drop after the first recording and was not clearly detectable afterwards. This was accompanied by a reversible drop in the intracochlear sum curve at an insertion angle of 120° and stable extracochlear recordings throughout the procedure. The irreversible increase of the extracochlear difference curve in S5 should also be highlighted. After insertion of one electrode, the signal in the extracochlear difference curves shows an increase of 6.8 dB and remains stable afterwards. The intracochlear difference curve displays a reversible drop at the same time. The intra- and extracochlear sum curves show only slight changes in S5.

Changes in phase between the insertion steps are shown in Figure 9 for extra- as well as intracochlear recordings. The extracochlear recordings showed only minor phase changes. The mean change in phase was 15° (SD 18°) with the largest phase change being 83° (S4). Intracochlear recordings showed also in this regard a higher variability. The mean change in phase between recordings was 32° with a SD of 70° . Reversible abrupt changes of signal phase could be detected in S4 and S5 between the recordings at an insertion angle of 120° and 220° .

Correlation of ECoG Recordings With Preoperative Hearing

There were only weak to moderate, nonsignificant correlations between residual preoperative hearing and either maximum amplitudes or changes in amplitude during electrode insertion and removal (Table 2). However, good residual high-frequency hearing before surgery in S4 was associated with a reversible change of the polarity of the SP with increasing

insertion depth (Fig. 10). In all other subjects, the sum curves showed clearer signals with increasing insertion depth but no polarity change of the SP.

DISCUSSION

This is the first report of simultaneous intra- and extracochlear ECoG recordings and the first description of ECoG signal changes during removal of an electrode array in human CI recipients. The aim of this study was to correlate simultaneously recorded intra- and extracochlear ECoG signals, to track changes of the ECoG signal during insertion and removal of an electrode array, and to correlate intracochlear ECoG response patterns with the preoperative residual hearing. Simultaneous extracochlear recordings were used to find out more about the mechanisms underlying changes of the intracochlear ECoG signals. We demonstrated that intracochlear ECoG recordings are reliably larger than ECoG signals recorded simultaneously from an extracochlear location and that intracochlear ECoG recordings show reversible amplitude and phase changes not reflected in extracochlear recordings.

Simultaneous Intra- and Extracochlear ECoG Recordings

Previous reports have described large variability between intra- and extracochlear ECoG signal amplitudes (Calloway et al. 2014; Dalbert et al. 2015a). Even smaller intracochlear signals compared to extracochlear ECoG signals have been described (Calloway et al. 2014). However, in our study, when simultaneously recorded with the same stimulation/recording device, intracochlear signals were larger in all cases, with the

Fig. 4. Extracochlear ECoG recordings before (if available) and after opening of the round window for all subjects. In the sum curves of S4, the assessment of the SP is illustrated. In the sum curves of S8, the window in which the CAP was assessed is marked. ECoG indicates electrocochleography; CAP, compound action potential; SP, summating potential.

smallest difference being 9 dB. The difference curve—usually the largest contributor to the ongoing ECoG signal—is much larger and more robust in intracochlear recordings. However,

this does not hold true to the same degree for the sum curve. Whereas the sum curve showed a clear response in all extracochlear recordings, in the initial intracochlear recordings with

Fig. 5. First intracochlear ECoChG recording after insertion of one contact of the temporary recording electrode for all subjects. For each subject, the difference (top) and the sum curves (bottom) are shown. ECoChG indicates electrocochleography.

only the first contact inserted, no clear sum curve responses were detectable for subjects S2, S4, S6, and S11. Our hypothesis is that in intracochlear recordings, the recording

electrode is much closer to the hair cells (the main generator of the difference curve response) compared to the extracochlear recording electrode. This is not true for neural elements

Fig. 6. Comparison of extra- and intracochlear ongoing ECoChG response amplitudes after insertion of one contact of the intracochlear recording electrode. The mean difference was 14 dB with a range from 9 (S6) to 24 dB (S8). The intracochlear ECoChG response was larger in all subjects. ECoChG indicates electrocochleography.

(usually the main generators of the sum curve). Neural elements are in intra- and extracochlear recordings not in direct proximity to the recording electrode. Consequently, the hair cell response components are larger in intracochlear recordings compared to extracochlear recordings, whereas the neural response components show less of a difference. In conclusion, in simultaneous ECoChG recordings, intracochlear responses recorded at the most basal part of the cochlea in the absence of trauma should be larger than extracochlear responses. If not, technical problems or differences between the recording systems used for intra- and extracochlear ECoChG recordings are most likely responsible.

Changes in the ECoChG Signal During Insertion/Removal of the Electrode Array

Previous studies analyzing intracochlear ECoChG recordings described different patterns of signal changes during insertion

(Harris et al. 2017a). The reasons for these signal changes remain controversial. Trauma, injury, or changes in inner ear mechanics due to the inserted electrode could lead to drops or increases in the ECoChG signal (DeMason et al. 2012). In this case, signal changes would represent changes in intracochlear conditions. However, the simple change of the position of the recording electrode relative to the generators of the signal could also lead to similar signal changes (Giardina et al. 2019). In such cases, ECoChG changes would not reflect a change of intracochlear conditions but rather recording artifacts.

Our findings correlate with previously published results with regard to the large variability of intracochlear ECoChG signals during insertion of an electrode array (Giardina et al. 2019). However, for the first time, we could demonstrate that these ECoChG changes are not reflected in simultaneous extracochlear recordings. Extracochlear ECoChG signals remained for the most part stable with regard to amplitude and phase during intracochlear signal changes. Therefore, we conclude that trauma, injury, or changes in inner ear mechanics are probably not the cause for a great part of the detected intracochlear signal changes. Rather, our results suggest that the movement of the recording electrode alone can cause increases or drops in the intracochlear ECoChG signal with and without phase changes. Besides the already mentioned stability of the extracochlear ECoChG recordings, two additional things support this hypothesis: 1) we used a short, flexible electrode, which is highly unlikely to cause intracochlear trauma or injury and 2) changes of the intracochlear ECoChG signal were in all but one subject (S6) reversible with retraction of the temporary electrode.

Despite the fact that extracochlear recordings remained stable for the most part, the findings in S5 have to be discussed in further detail. In S5, the extracochlear difference curve increased (+6.8 dB) after insertion of one electrode. This was

Fig. 7. Examples of simultaneous intra- and extracochlear ECoChG recordings in S4 and S8 during insertion and removal of the recording electrode. Only the difference curve is shown for each recording. Note the difference scales between intra- and extracochlear recordings. ECoChG indicates electrocochleography.

Fig. 8. Amplitude changes during insertion and removal of the temporary recording electrode. The extracochlear responses (difference and sum curves) remained relatively stable throughout the procedure, while the intracochlear responses showed large reversible amplitude changes in both the difference and the sum curves. Dotted lines represent unclear ECoG signals. Note the difference scales between intra- and extracochlear recordings. ECoG indicates electrocochleography.

Fig. 9. Phase changes during insertion and removal of the temporary recording electrode. In the extracochlear ECoG recordings, only small phase changes were detectable. In the intracochlear recordings, S4 and S5 showed abrupt reversible phase shifts with increasing insertion depth. ECoG indicates electrocochleography.

TABLE 2. Correlation of Residual Preoperative Hearing With Maximum Amplitudes and Amplitude Changes During Electrode Insertion and Removal

		Low-frequency PTA	High-frequency PTA
Maximum intracochlear ECoG response	Difference curve	$r_s = 0.09, p = 0.8, n = 10^*$	$r_s = 0.4, p = 0.3, n = 10^*$
	Sum curve	$r_s = 0.4, p = 0.3, n = 9^*$	$r_s = 0.4, p = 0.4, n = 9^*$
Maximum intracochlear ECoG amplitude change during insertion/removal	Difference curve	$r_s = 0.01, p = 0.9, n = 10^*$	$r_s = 0.006, p = 0.9, n = 10^*$
	Sum curve	$r_s = 0.1, p = 0.7, n = 10^*$	$r_s = 0.3, p = 0.4, n = 10$

Low-frequency PTA was defined as the PTA from 0.125 to 0.5 kHz, high-frequency from 1 to 8 kHz.

*Spearman rank correlation.

ECoG, electrocochleography; PTA, pure-tone average.

accompanied by a reversible drop in the intracochlear difference curve (Fig. 8). As we have placed the extracochlear recording electrode in close proximity to the round window, direct contact to the perilymph would be a possible explanation for the increase of the extracochlear signal. Furthermore, the abrupt loss of some perilymph around the location of the intracochlear recording electrode could explain the temporary drop of the intracochlear difference curve. As an alternative explanation for increases of the extracochlear signal, changes of cochlear mechanics have been proposed (Dalbert et al. 2015b, 2019; Adunka et al. 2016). Overall, the underlying mechanisms remain controversial, but it has to be noted that such increases

may influence the sensitivity of extracochlear recordings, as amplitude drops could be concealed.

Another limitation of the presented study is the stepwise manner in which the ECoG recordings were performed. A continuous ECoG recording is able to detect transient fluctuations not assessable by the here presented method. Such transient fluctuations of the ECoG signal have been associated with poorer postoperative residual hearing (Campbell et al. 2016).

In conclusion, our results support the notion that intracochlear ECoG signals recorded by a moving recording electrode are highly complex signals and that not all amplitude and phase changes during the insertion of an electrode represent

Fig. 10. Changes of the sum curves of the ECoG responses compared to high-frequency hearing before surgery. Good residual high-frequency hearing in S4 was associated with a reversible change of the polarity of the SP with increasing insertion depth. In all other subjects (S2 and S6 are shown as examples), the sum curves showed clearer signals with increasing insertion depth but no polarity change. The polarity of the SP is marked by + or – in S2 and S4. ECoG indicates electrocochleography; PTA, pure-tone average; SP, summating potential.

cochlear trauma or injury, but sometimes are rather caused by a change of the recording location within the cochlea.

Correlation of Intracochlear ECochG Response Patterns and Preoperative Residual Hearing

As discussed earlier, intracochlear ECochG signals are highly complex, and changes in amplitude and phase can be due to the movement of the recording electrode alone. Consequently, to be able to detect trauma during insertion by a moving intracochlear recording electrode, one would have to be able to determine the expected ECochG changes in advance. If a deviation of the expected pattern would occur during insertion, a change of intracochlear conditions could be deduced.

Therefore, the data were analyzed to determine if there was significant correlation between the residual preoperative hearing with either maximum amplitudes or changes of the amplitude during tracking. However, all correlations were weak to moderate and nonsignificant, ranging from $r_s = 0.006$ to 0.4. The best correlation was between the maximum amplitude and the high-frequency residual hearing. Better high-frequency hearing was therefore associated with larger maximum ECochG signals. This is probably because intracochlear recording electrodes mainly pick up responses from local generators around the recording electrode (Campbell et al. 2017; Dalbert et al. 2020). Because the short electrodes used in this study only reached high-frequency regions, signals from this region were mainly recorded. The better high-frequency hearing represents more intact structures in this region, which again explains the larger signals.

An interesting finding was the change of the polarity of the SP between the recording points at 120° and 240° in the intracochlear recordings of S4. In all other subjects, the SP was more clearly detectable with increasing insertion depth but did not change polarity. Compared to the rest of the study population, S4 was the subject with by far the best residual high-frequency hearing. Helmstaedter et al. (2018) demonstrated in guinea pigs that passing of signal generators leads to a polarity change of the SP. Therefore, as subject S4 had some remaining residual hearing at 4 and 8 kHz (Fig. 2) which represent the characteristic frequencies at the recording locations with an insertion angle of 120° and 240°, the polarity change of the SP could be due to the approach to new signal generators or even the passing of signal generators. The high intensity used for acoustic stimulation probably leads to a wide spread of the activation towards the base of the cochlea which makes an activation of the cochlea at this high frequencies likely, despite the fact that the acoustic stimulus had a frequency of 0.5 kHz.

In conclusion, the preoperative residual hearing seems to be associated with certain findings in intracochlear ECochG findings. However, to be able to detect trauma in the future, better modeling of expected intracochlear ECochG changes during insertion is necessary.

CONCLUSION

Intracochlear ECochG signals are reliably larger than ECochG signals recorded from an extracochlear location. Intracochlear ECochG recordings show reversible amplitude and phase changes during electrode insertions, not reflected in simultaneous extracochlear ECochG recordings. Such changes can be due to the movement of the recording electrode in relation to the signal generators. Residual high-frequency hearing is associated with larger intracochlear ECochG signal amplitudes.

ACKNOWLEDGMENTS

The authors would like to thank Markus Binzer and Marek Polak from MED-EL for their continuous support and valuable assistance throughout this project.

The study was partially funded by MED-EL, Innsbruck, Austria.

A.D. designed and performed experiments, analyzed data, and wrote the article; L.S., J.G., and D.V. performed experiments and provided critical revision; C.R. and A.H. performed the CI surgeries and provided critical revision; F.P. designed and performed experiments, provided statistical analysis, and contributed to writing the article. All authors discussed the results and implications and commented on the manuscript at all stages.

The authors have no conflicts of interest to disclose.

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Received March 25, 2020; accepted June 26, 2020.

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