*IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*
*e-ISSN: 2278-2834, p- ISSN: 2278-8735.Volume 20, Issue 1, Ser. 1 (Jan. – Feb. 2025), PP 23-29*
*www.iosrjournals.org*

# Topographic Evaluation Of Spread Of Excitation In Cochlear Implants And Its Correlation With Neural Recovery Function

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***Abstract***
***Objectives:*** *to evaluate Spread of excitation (SOE) in adult and child implanted patients, along different regions of the cochlea (apical, medial and basal) through different stimulated electrodes, and compare it with Neural response telemetry (NRT) and recovery function (REC).*
***Methods:*** *Cross-sectional, descriptive and prospective study. The SOE, NRT and REC (evaluated through the function of the parameters T0, A and TAU) were evaluated in individuals undergoing CI surgery, divided into three groups according to the electrode stimulated in the cochlea region: apical, medial and basal.*
***Results****: 19 ears were evaluated. Data analysis showed significant differences between all measurements in cochlear regions, except REC TAU, with the most significant difference being in the SOE mm between the medial and apical regions. differences in eCAP measurements along the electrode array in the cochlea could be related both to the patient (etiology, shape and space within the cochlea, residual neuronal populations), and to factors related to the CI (electrode type, insertion mode, distance from electrode to modiolus and spiral ganglion).*
***Conclusion:*** *in our study, a significant difference was found in the measurement of SOE in different regions of the cochlea, this difference was more important when comparing the apical with the medial region, also affecting NRT and REC.*
***Keywords:*** *cochlear implants; neural response telemetry*

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Date of Submission: 02-02-2025 Date of Acceptance: 12-02-2025

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## I. Introduction

Various electrophysiological tests can be performed using cochlear implants (CI) to elicit stimulus and record responses.[1]

Neural Response Telemetry (NRT), measures the Electrically evoked compound action potential (ECAP), through which it is possible to obtain the recovery function of the auditory nerve (REC) and spread of excitation (SOE). These measurements reflect the refractory properties of the nerve (REC) and the measurement of the electric field and number of ganglion cells that fire with a stimulus given along the cochlea (SOE), allowing access to the interaction between CI electrodes and the auditory nerve.[2,3] Not many studies evaluated REC and SOE, especially considering electrodes along regions.

Our objective is to evaluate SOE, throughout different regions of the electrodes in the cochlea (apical, medial and basal), correlate SOE with NRT and SOE with REC, and to make comparisons between these measurements in different regions of the cochlea (apical, medial and basal).

## II. Methods

IRB approval was obtained. CAAE: 09895318.3.0000.5529. It was a cross-sectional, descriptive and prospective study.

Patients underwent CI with models from Cochlear Ltd, Australia, (see table 1) following the standard indications for surgery, all operated by the same surgeon, regardless of age (children and adults), and underwent intraoperative NRT, REC and SOE (at the time of surgery). Patients with syndromes, auditory neuropathy or other associated neurological impairments were excluded. All patients who underwent CI surgery during the period and in which the measurements were taken were included. The speech therapist included the patients and carried out measurements.

NRT, REC and SOE analysis was carried out using Custom Sound TM EP 5.0 software (Cochlear Corporation, Sydney, Australia) which controls the stimulation parameters and for recording and analyzing the

ECAP, installed on a microcomputer coupled to a programming system and the speech processor "CP810 Sound speech processor". Prior to the assessment of the neural response, Impedance Telemetry was tested, and values were ensured within limits accepted by the manufacturer to evaluate position, integrity and functionality of the electrodes.

In our service, the CI is introduced through the round window[4], therefore we do not perform routine imaging methods after CI surgery, except in isolated cases (such as cochlear malformation).

NRT procedure is as follows.[5, 6] ECAP is a wave formed by a negative peak (N1) with an approximate latency of 0.2ms and 0.4ms, followed by a positive peak (P2) with an approximate latency of up to 1ms. The amplitude of the response (N1 to P2) is proportional to the increase in stimulus intensity, which is measured in current units.[5] A valid neural response is considered to be the presence of a visible N1 peak accompanied by reproducibility in the tracing, absence of artifact or amplifier saturation. From the decrease in current, it is possible to trace the amplitude growth curve (current x amplitude) and determine the neural response threshold (NRT), expressed in current units (cu). NRT threshold (T-NRT) is the smallest current capable of generating an ECAP with an amplitude measurable by the software. The software has an automatic wave peak marker, however, it allows individual manipulation of the cursor. All ECAP assessments were confirmed by visual inspection and corrected when necessary. Then, NRT measurement (T-NRT, by AutoNRT) was performed on 5 or 9 electrodes. Current level (CL) at each electrode started at 170 current units (cu), with an interval of 6 cu between one stimulus and the next, until the maximum stimulation of 255 cu or until the T-NRT has been found. The parameters were default.

Next, we used advanced NRT to create a new 'Recovery' series and chose 3 electrodes. Electrodes were divided according to their number into: apical (22-16), medial (15-8) and basal (7-1). Masking level was set to 10 units above the CL used for stimulation (probe level). Interpulse interval was set at 500μs and the stimulation speed was 80Hz in a series of 25μs per phase. REC uses 20 interval values between stimulus triggering at the masking electrode and stimulus triggering at the tested electrode (between 100 and 10000μs). Other parameters, such as amplifier gain, time interval between the end of the stimulus and response recording (defined as the number of artifacts to allow a better visualisation of N1 wave), and the distance between MP1 and MP2, were adjusted and modified.[5,7] Stimulus level used for REC recordings was an average of 20cu above the level at which the NRT was obtained at each stimulated electrode, minding to obtain neural response and to not cause saturation of the amplifier. The software transforms REC measurements into an exponential function, a mathematical model:[8] $F(MPI) = A(1-\exp[-\alpha(MPI-T0)])$, where 'A' is the maximum amplitude of the neural response at the maximum saturation level (μV), 'α' ("tau") is the recovery time constant during the relative refractory period (μs) and 'T0' corresponds to the absolute refractory period (μs).

SOE is measured with standard forward masking technique, using a fixed stimulating electrode and automatically varying the masking electrode around the target stimulus electrode. Current level was set at 10cu above eCAP threshold, stimulus pulse width of 25s and the stimulation rate at 40Hz. Interval between the masker and the target stimulus (interpeak interval - IPI) of 400s. In analyzing the result presented by the software, ECAP amplitudes below 4μV to 5μV were excluded considering that the base noise of the internal amplifier is around 2μV.[9]

Patients' medical records were evaluated regarding age, duration of hearing loss, sex, and etiology of hearing loss. The data obtained was analyzed with the IBM SPSS Statistics v.29.0 computer program. To evaluate correlation between the variables related to NRT, SOE and REC, Spearman correlation coefficients were estimated. Comparisons of the apical, medial and basal regions, in relation to each of the variables, were made using Friedman's non-parametric test. Normality of the variables was analysed using the Shapiro-Wilk test. Values of $p<0.05$ indicated statistical significance. For multiple comparisons of regions, p values were corrected by Bonferroni.

## III. Results

19 ears of 16 patients were evaluated for NRT, SOE and REC measurements, in the apical, medial and basal regions of the cochlea. Results can be seen in the tables 1-4. For each of the variables relating to NRT, SOE and REC, the three regions (apical, medial and basal) were compared.

In the analysis of the correlation of measurements, there was a strong correlation using the Spearman test for NRT X SOE CL (cu), NRT X REC CL (cu), SOE (mm) X REC t0 (us), SOE (mm) X REC A (uV) and SOE CL (cu) X REC CL (cu) (table 2). Of course, the REC CL and SOE CL (current levels) were set to 10 and 20 cu above the NRT, so it was an expected result. But the correlation between SOE and REC A was strong (r= 0,90) in the apical region.

When comparing the regions in relation to the measurements, it was observed that there was a significant difference for all measurements in each region. The only measure that did not show a difference between regions was REC TAU. (table 3)

For the variables that showed a significant difference, the regions were then compared two by two

(table 4). The most significant results were obtained when comparing the apical with the medial region, for NRT, SOE (mm), SOE CL (cu), and REC CL (cu). But we also found significance in SOE (mm) comparing medial and basal.

## IV. Discussion

Each Electrophysiological measure has its implications, be it clinically or for research purposes. Electrophysiological measures of the eCAP amplitudes measured at different spatial separations between masker- and probe-electrode can be used to assess channel interaction at the electrode-neural interface (SOE). The smaller the masking effect (e.g., as a result of a greater distance between the probe and the masking electrode), the smaller the ECAP response.[10] SOE patterns can be used to approximate spatial resolution within the electrically stimulated cochlea.[11]

SOE can provide useful information about channel interaction at the electrode-neural interface, which leaves the possibility for new applications beyond speech perception or electrode discrimination in CI users.[12] For example, it can potentially be used to protect against bending electrode arrays during surgery[13] especially when there is no access to imaging, or to determine the position of electrodes in relation to the spiral ganglion.[14,15] The exact location of the electrode array within the cochlea is an important factor for hearing outcomes. We normally use electrophysiological tests to confirm location, reserving imaging tests for exceptions.

One of the factors that can impact CI performance is the quality of electrical stimulation generated by the device. Electrode arrays are designed considering ideal intracochlear positioning, and each electrode must tonotopically stimulate different nerve pathways, adopting a predefined frequency bandwidth. High-frequency signals are delivered to basal electrodes and low-frequency sounds to apical electrodes, in a logarithmic function. However, in CI surgery, the assembly is inserted blindly into the cochlea. Effectiveness of electrical stimulation will be affected by electrode positioning within the cochlea. Therefore, it is assumed that an electrode with suboptimal positioning and more distant from the modiolus than its neighbor may affect the propagation of excitation within the cochlea, increasing the interaction of the channels or overlapping areas of neural activation. Furthermore, overlapping electrodes involved in bending may also contribute to channel interaction, which can lead to spectral smearing of the signal and poorer speech understanding, especially in noisy environments.[16]

Many studies[17-19] believe that reducing interaction between channels (more selective stimulation) would improve speech recognition. Theoretically, the greater the interaction, the worse the frequency identification results.[3,12] However, the correlation between SOE and performance is not well understood. On the other hand, the restricted number of physical electrodes in an CI limits the amount of spectral information that can be represented by the device. Various methods for improving spectral representations have been investigated, including the use of "virtual channels" recruiting populations of neurons slightly different from those activated by individual physical electrode contacts (with the theoretical advantage of improved spectral representation of the stimulus and potentially improved speech perception).[3] Stickney et al.[20] mentions that this is an important cause of variability in speech recognition results among CI users, with higher levels of channel interaction associated with worse performance.

However, increasing the number of available electrodes beyond eight does not increase performance, suggesting that channel interaction makes adjacent electrodes less distinguishable.[17] A smaller distance between electrodes and spiral ganglion would result in a smaller current dispersion and therefore a smaller SOE[21] and vice versa, the greater the distance, the greater the dispersion. In our study, the SOE mm was greater in the medial region, in relation to apical and basal, therefore it could be concluded that there is a greater distance between electrodes and the spiral ganglion in the medial region, in this sample. The wider SOE found in straight implants may be a reflection of more fibers recruited, resulting in worse channel separation. As the electrode is further away from the modiolus, the electric current tends to disperse more and reach a greater number of ganglion cells, increasing the amplitude.[17] In our study we had 10 slim straight and 9 contour advanced electrodes. The sample size did not allow evaluations based on this aspect.

Da Silva et al.[22] evaluated 323 ears, dividing into pre and postlingual, and straight and perimodiolar arrays, and concluded that different factors influence SOE and REC. The authors performed measurements only on electrode 11 (medial). In our study, we did not divide the groups according to the duration of deafness or type of electrode, we also measured the SOE and REC in each region of the electrode.

NRT current level correlated (with statistical significance) with the current level for REC and also for SOE, in all regions, as well as the required current level to elicit REC and SOE from each other in the apical and basal regions. SOE mm correlated with REC t0 and REC A in the apical region, and only with REC t0 in the basal region. When comparing regions in relation to measures, the only measure that did not show a difference between regions was REC TAU.

The biggest differences found, in two-by-two comparisons, were between apical and medial regions:

NRT was greater in the medial than apical region, SOE mm was greater in the medial than apical region, SOE CL was greater in the medial than apical region. REC CL was greater in the medial than apical region and greater in the basal than apical region. REC t0 was greater in the medial region than in the apical region, but greater in the medial region than in the basal region. REC A was higher in the medial region than in the basal region. At the base of the cochlea, generally, the surviving neural population tends to be smaller, requiring more energy for stimulation. In our study, REC CL was higher in the basal region compared to the apical region, but also in the medial region compared to the apical region.

Other studies demonstrated that slower recovery periods and smaller amplitudes were found at basal electrodes.[23] In our previous study, NRT obtained higher values in the basal region in relation to the apical region, and medial in relation to the apical region. "REC t0" in the medial region was higher than the basal one, "REC A" was lower in the basal region in relation to the apical and medial region. [24] In this study, a significant difference was found for NRT between apical and medial regions, being greater in the medial region. Both REC t0 and REC A were lower in apical and basal regions.

da Silva et al.[19] evaluated in 43 patients electrodes 6,11 and 16. They observed that there was a statistically significant difference in SOE between electrodes 6 and 16, but not 11. Other studies observed an asymmetry of the SOE curve towards the apical region. This asymmetry can be attributed to differences in surviving neuronal populations and the difference in current dispersion along the scala tympani.[18] Results demonstrate wide variations between individual implant users, as well as between electrodes within an individual. In general, the degree of interaction appears to depend on the level of stimulus.[25] For example, in our study the SOE CL was higher in the medial than apical region, as was the SOE mm.

Asymmetry along the electrode array can be explained by wider areas of excitation in the apical part of the cochlea in relation to the basal part.[26,27] The broader responses in the apical region could also be explained by the geometry of the cochlea, which narrows from the base to the apex, reducing the distance to the modiolus and reducing the volume at the apex.[26-29] For Biesheuvel et al.[18] , as we are not able to distinguish cross-turn stimulation, it is also possible that a larger SOE apically may be caused by stimulation of cross turn, which is known to be most likely at the apex, where the cochlea is most tightly coiled.[29] Furthermore, residual hearing could generate larger eCAPs at the apex.[18] But it is understood that electrode to modiolus distance is less important compared to the inter contact spacing for all the SOEs.

One of our possible biases was that we did not perform routine imaging studies on patients. Dimak et al.[30] observed 3 cases of tip foldover in which, due to performance problems, the implants had to be replaced, therefore the use of SOE could help avoid such cases.

In our study, intraoperative NRT measurements were used. The main advantage is that relatively high stimulus levels can be applied under sedation[4,31], often above the tolerability limit in awake individuals. It is known that, during the first months after implantation, physiological changes may occur in the cochlea that lead to certain electrophysiological changes, for example, different impedances or eCAP thresholds.[18] So follow-up measurements would be interesting.

Another bias was that we were unable to perform measurements on all electrodes of all patients. 8 patients in the apical region, 2 in the medial region and 8 in the basal region did not obtain a response in SOE, even with changes in the SOE width level (50%, 75%, 90%).

Also, differences found can be attributed to the sample size, assessment of various etiologies, different periods of auditory deprivation and others. Further studies should better elucidate these differences, possibly comparing objective and subjective measures and evaluating more homogeneous populations.

## V. Conclusion

In our study, a significant difference was found in measurement of SOE in different regions of the cochlea, this difference was more important when comparing the apical with the medial region, also correlating to NRT and REC.

SOE mm correlated with REC t0 and REC A in the apical region, and only with REC t0 in the basal region.

**Acknowledgements**

None.

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## Tables

**Table 1. Demographic data**

| pacient | sex | Age (years) | Cause of hearing loss | Period of hearing loss (years) | Type of electrode |
|---|---|---|---|---|---|
| 1 | F | 7 | Genetic progressive | 6 | CI622 (S) |
| 2 | F | 7 | Genetic progressive | 6 | CI622 (S) |
| 3 | M | 57 | Otosclerosis | 11 | CI24RE (CA) |
| 4 | F | 36 | Genetic progressive | 3 | CI622 (S) |
| 5 | M | 7 | Congenital | 7 | CI24RE (CA) |
| 6 | M | 77 | Idiopathic | 40 | CI24RE (CA) |
| 7 | F | 36 | Gestational Rubella | 30 | CI422 (S) |
| 8 | M | 73 | Idiopathic | 30 | CI24RE(CA) |
| 9 | F | 71 | Otosclerosis | 30 | CI512 (CA) |
| 10 | M | 21 | Genetic | 21 | CI 622 (S) |
| 11 | M | 66 | Ototoxicidade | 42 | CI 622 (S) |
| 12 | F | 1 | Congenital | 1 | CI512 (CA) |
| 13 | F | 1 | Congenital | 1 | CI512 (CA) |
| 14 | F | 2 | Genetic | 2 | CI622 (S) |
| 15 | F | 2 | Genetic | 2 | CI622 (S) |
| 16 | F | 11 | Genetic progressive | 6 | CI422 (S) |
| 17 | M | 22 | Mondini malformation | 18 | CI622 (S) |
| 18 | M | 50 | Measles | 3 | CI24RE (CA) |
| 19 | M | 36 | Meningitis | 1 (and 8 months) | CI24RE (CA) |

F= female, M=male, S= Straight, CA= contour advanced

**Table 2 – Analysis of correlation, by region**

| Varibles | APICAL | | | MEDIAL | | | BASAL | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | r | p | n | r | p | n | r | p |
| NRT x SOE (mm) | 11 | 0,54 | 0,089 | 17 | 0,11 | 0,666 | 11 | 0,65 | 0,030 |
| NRT x SOE CL (cu) | 18 | 0,99 | <0,001 | 19 | 0,98 | <0,001 | 18 | 1,00 | <0,001 |
| NRT x REC CL (cu) | 16 | 1,00 | <0,001 | 17 | 0,98 | <0,001 | 14 | 0,98 | <0,001 |
| NRT x REC t0 (us) | 16 | 0,37 | 0,157 | 17 | 0,35 | 0,173 | 14 | -0,20 | 0,491 |
| NRT x REC tau (us) | 16 | 0,00 | 0,996 | 17 | -0,12 | 0,652 | 14 | 0,06 | 0,851 |
| NRT x REC A (uV) | 16 | 0,46 | 0,070 | 17 | -0,35 | 0,173 | 14 | 0,32 | 0,265 |
| SOE (mm) x SOE CL (cu) | 11 | 0,60 | 0,051 | 17 | 0,12 | 0,635 | 11 | 0,63 | 0,040 |
| SOE (mm) x REC CL (cu) | 10 | 0,49 | 0,148 | 16 | 0,10 | 0,712 | 8 | 0,33 | 0,420 |
| SOE (mm) x REC t0 (us) | 10 | 0,65 | 0,043 | 16 | 0,16 | 0,557 | 8 | -0,83 | 0,010 |
| SOE (mm) x REC tau (us) | 10 | 0,14 | 0,701 | 16 | -0,04 | 0,888 | 8 | -0,05 | 0,911 |
| SOE (mm) x REC A (uV) | 10 | 0,90 | <0,001 | 16 | 0,48 | 0,062 | 8 | 0,21 | 0,610 |
| SOE CL (cu) x REC CL (cu) | 15 | 0,99 | <0,001 | 16 | 0,34 | 0,192 | 13 | 0,98 | <0,001 |
| SOE CL (cu) x REC t0 (us) | 15 | 0,40 | 0,141 | 16 | 0,63 | 0,009 | 13 | -0,16 | 0,608 |
| SOE CL (cu) x REC tau (us) | 15 | -0,04 | 0,899 | 16 | -0,04 | 0,897 | 13 | 0,16 | 0,602 |
| SOE CL (cu) x REC A (uV) | 15 | 0,50 | 0,060 | 16 | -0,47 | 0,064 | 13 | 0,42 | 0,157 |
| REC CL (cu) x REC t0 (us) | 16 | 0,37 | 0,155 | 17 | 0,29 | 0,268 | 14 | -0,21 | 0,469 |
| REC CL (cu) x REC tau (us) | 16 | 0,02 | 0,931 | 17 | -0,17 | 0,515 | 14 | 0,06 | 0,828 |
| REC CL (cu) x REC A (uV) | 16 | 0,47 | 0,067 | 17 | -0,22 | 0,405 | 14 | 0,38 | 0,177 |
| REC t0 (us) x REC tau (us) | 16 | 0,03 | 0,914 | 17 | 0,33 | 0,202 | 14 | -0,10 | 0,737 |
| REC t0 (us) x REC A (uV) | 16 | 0,16 | 0,564 | 17 | -0,41 | 0,098 | 14 | -0,08 | 0,782 |
| REC tau (us) x REC A (uV) | 16 | -0,07 | 0,803 | 17 | -0,03 | 0,918 | 14 | 0,63 | 0,016 |

( r ): Spearman coefficient

n= number of patients, cu= current units, us= micro seconds, uV= micro volts, cl= current level, mm= millimetres

**Table 3. Comparison of measures related to regions**

| Variable | Region | n | Average | SD | Median | Min | Max | p* |
|---|---|---|---|---|---|---|---|---|
| NRT | Apical | 19 | 179,9 | 21,9 | 181 | 150 | 240 | |
| | Medial | 19 | 187,9 | 12,1 | 185 | 165 | 205 | |
| | Basal | 19 | 186,7 | 22,2 | 185 | 162 | 238 | 0,016 |
| SOE (mm) | Apical | 8 | 2,45 | 2,00 | 2,32 | 0,19 | 4,99 | |
| | Medial | 8 | 4,58 | 2,20 | 4,39 | 0,94 | 8,44 | |
| | Basal | 8 | 2,47 | 3,41 | 1,13 | 0,52 | 10,70 | 0,010 |
| SOE CL (cu) | Apical | 18 | 191,6 | 22,0 | 191,5 | 161 | 250 | |
| | Medial | 18 | 200,3 | 11,7 | 196,5 | 183 | 225 | |
| | Basal | 18 | 196,8 | 22,7 | 194,5 | 172 | 251 | 0,027 |
| REC CL (cu) | Apical | 14 | 192,1 | 12,9 | 195,5 | 170 | 209 | |
| | Medial | 14 | 203,9 | 11,0 | 205 | 185 | 225 | |
| | Basal | 14 | 201,1 | 15,9 | 204,5 | 175 | 225 | 0,011 |
| REC t0 (µs) | Apical | 14 | 444,7 | 228,8 | 406,5 | 157,8 | 972,7 | |
| | Medial | 14 | 644,7 | 294,2 | 573,2 | 327,3 | 1420 | |
| | Basal | 14 | 425,6 | 175,4 | 483,2 | 127,6 | 616,3 | 0,032 |
| REC tau (µs) | Apical | 14 | 1448,9 | 279,8 | 1357,1 | 1133,8 | 1965,9 | |
| | Medial | 14 | 1388,0 | 349,4 | 1384,6 | 806,0 | 1964,6 | |
| | Basal | 14 | 1112,5 | 577,5 | 1198,8 | 61,9 | 1824,3 | 0,395 |
| REC A (µV) | Apical | 14 | 134,2 | 50,2 | 124,4 | 60,6 | 262,7 | |
| | Medial | 14 | 180,9 | 96,7 | 140,9 | 62,5 | 390,2 | |
| | Basal | 14 | 103,3 | 64,6 | 97,1 | 19,8 | 246,1 | 0,003 |

*Friedman's non-parametric test, p<0.05

n= number of patients, Min= minimum, Max=maximum, SD= standard deviation, cu= current units, µs= micro seconds, µV= micro volts, cl= current level, mm= millimetres

**Table 4. Comparison of regions two by two.**

| Compared regions | p* | | | | | |
|---|---|---|---|---|---|---|
| | NRT | SOE (mm) | SOE CL (cu) | REC CL (cu) | REC t0 (µs) | rec A (µV) |
| Apical x medial | 0,028 | 0,018 | 0,037 | 0,024 | 0,070 | 0,267 |
| Apical x basal | 0,069 | 1 | 0,137 | 0,042 | 1 | 0,267 |
| Medial x basal | 1 | 0,037 | 1 | 1 | 0,070 | 0,002 |

*Friedman's non-parametric test, p<0.05 (Bonferroni-corrected p-values)