2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Electrical Cochlear Response Consistency from different Cochlear Implant Users

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Abstract— **The Electrical Cochlear Response (ECR) is a scalp potential recently described in the literature which offers an alternative approach for objective adaptation of Cochlear Implant (CI) to individual patient requirements. Thus it is necessary to know about the consistency of this response across implanted patients using devices with different design criteria. This work shows that the ECR wave shape morphology is not affected by CI manufacture design differences. For this purpose and to contend with the sensibility to electric stimulation change along the cochlea, six contiguous intracochlear electrodes located at the apical end of the cochlea were studied. According to the CI manufacturer, the population of twelve implanted pediatric patients was divided into three groups. Artifacts due to the CI stimulation pip tone and operation during ECR acquisition were canceled using the Empirical Mode Decomposition method. For wave shape morphology comparison among electrodes, ECR amplitude was normalized, and the average intra- and inter-user group ECR Correlations were calculated. Intra and inter-group Correlation coefficient goes from 0.58 to 0.9 and from 0.63 to 0.85, respectively. For the same patient and group Correlation coefficient between ECR of the electrode located at the apical end of the cochlea and adjacent electrodes decreases from apex to base. These results support the consistency of the ECR waveshape morphology across users of different CI types.**

Clinical Relevance— **ECR offers a new objective methodology for the initial programming and later readjustment of electrical stimulation provided by the cochlear implant. The patient uses the device in daily operation mode; the scenery is quite impossible with the current resources for evaluating CI performance. This methodology is compatible with all current CIs without special hardware or software requirements due to different devices type. It can be applied any time after initial device programming, regardless of patient age or previous training. Therefore, it is important to know that ECR wave shape morphology is not affected by the differences in design and operation of current cochlear stimulation systems.**

I. Introduction

The Electrically Evoked Compound Action Potential (ECAP) is evidence of the patient's auditory nerve response to biphasic electrical stimulation current provided by CI. In this test, the stimulation and the recording electrodes are selected along the electrode array of the device. Stimulus is a single biphasic current pulse of different widths and a lower stimulation rate, ≈ 80 Hz, than those used in the stimulation biphasic current pulse train in the daily use of CI, > 500 Hz [1].

There are different methodologies to obtain the ECAP: Neural Response Image (NRI), Neural Response Telemetry (NRT), and Auditory Nerve Response Telemetry (ART), implemented in cochlear stimulation systems of manufacturers such as Advanced Bionics, Cochlear, and Med-El, respectively. In all these methodologies, the refractory properties of the auditory nerve are considered, and stimulation paradigms or digital signal processing techniques are used to cancel the artifact due to the test pulse.

Applying any of these methodologies results in an ECAP waveform similar to an enlarged "S". It is slightly tilted to the right side with a latency of less than one ms and amplitude, measured between the upper and lower extreme points, is in the range of hundreds of μV, depending on test electrical current level [3], [4]. Current methodologies for obtaining ECAP are not applicable during the daily use of the CI, where the input sound envelope modulates the amplitude of the electrical pulse train stimulation current.

In clinics, every electrode's electric current dynamic range is predicted based on the minimum current level necessary to elicit ECAP [2]. Ideally, minimum and maximum values of the current dynamic range of each intracochlear electrode should coincide with the subject behavioral hearing threshold and maximum comfort levels, respectively. However, this prediction has limited success necessitating later readjustment of the dynamic range with patient cooperation.

Additional to the auditory nerve responsiveness to electrical stimulation variation along the cochlea, active and reference electrodes election influence auditory nerve response. Depending on the input sound's spectral characteristics, one or more intra-cochlear electrodes are activated in the daily use of CI. In comparison, the reference site is one or two extra-cochlear electrodes. In the ECAP recording method, stimulation and reference electrodes are chosen from the intra-cochlear electrode array. Changes in the relative location between active and reference stimulation electrodes modify the electric path current follows, hence changing neural population involved with the stimulation electrode pair, implying changes in the ECAP threshold level used for electrode dynamic range prediction.

In [5], a new methodology is described in which, by using scalp EEG electrodes and the presentation of pip tones in the sound field, ECR is obtained while the patient is asleep and using CI in daily operation mode.

A previous work [6] establishes that ECAP from the apical region of the cochlea has a higher amplitude, lower threshold,

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and a steeper growing slope than the basal region. It is probably because of "closer proximity of the stimulating electrode to neural tissue in the apex and/or to a higher density or survival rate of neural tissue in the apex".

On the other hand, because electrode array length and electrode number are not the same among devices from a different manufacturer, for this work, we studied the intracochlear electrode subset located at the apical end of the cochlea.

II. Theory

Three different artifacts have been visually identified in our laboratory that might contaminate the ECR (see Fig. 1). The first artifact is due to the operation of the IC itself. It is a periodic signal in the hundreds of Hertz range that overlaps the spontaneous EEG. The second one is the sound field pip tone presentation that induces electrical noise upon the EEG electrodes cables. The frequency of this artifact corresponds to the frequency of the stimulation pip tone. The third artifact appears only in the first four apical electrodes called CSS channel type for Med-El devices.

Empirical Mode Decomposition (EMD) was used to remove the artifacts mentioned before. EMD is an adaptive method to decompose nonlinear and non-stationary signals, $x(t)$, into modes (oscillation embedded in the data) called Intrinsic Mode Functions (IMFs) [7]. The IMFs are calculated using an iterative sifting process and ordered in descending order according to their frequency. IMFs must satisfy two conditions: a) the number of extremes (minima and maxima) and the number of crosses by zero must be equal to or differ by at most one. b) the local mean $m(t)$ must always be close to zero. The sifting process can be summarized as follow:1) Local minima and maxima extrema of the original signal $x(t)$ are identified. 2) These local extrema are separately connected with a cubic interpolation to form the lower and upper envelopes. 3) The mean $m\,(t)$ of the two envelopes is calculated and subtracted from $x\,(t)$, $h\,(t) \;=\; x\,(t) \;-m\,(t)$. 4) Verify if $h(t)$ satisfies the conditions to be IMF. 5) If $h(t)$ is not an IMF, steps 1 to 4 are repeated on $h(t)$ as many times as needed till it satisfies the conditions to be IMF. 6) If h(t) is an IMF, $c(t) = h(t)$ and sifting process are repeated on the residue $r(t) = x(t) \;- c(t)$. 7) The iterative process ends when the residue contains no more than one extremum.

In general, each ECR was decomposed into five or six IMFs; it is possible to observe the stimulus artifact in the first IMF. In the second IMF, the artifact generated by the operating characteristics of the implant can be observed (see Figure 2). Since this data analysis method separates the signal into a finite number of components corresponding to different frequencies, it is easy to establish a frequency level to distinguish artefactual IMFs (frequency > 100 Hz) and IMFs related to ECR (frequency < 100Hz). Finally, the Correlation coefficient was used to measure the linear dependency of the ECR between different CI manufacturers.

III. Procedure

Participants were twelve volunteer implanted children within an age range of 2.5 to 5 years old. ECR recordings were made 5-12 months after implant surgery and CI fitting by an audiologist. In all cases during the ECR test patient was accompanied by the responsible adult. Participants were grouped according to manufacturer device: G1) Advanced Bionics: High Resolution 90K Advantage implant, Neptune sound processor and HiFocus Helix electrode array with 16 electrodes and 24.5 mm long; G2) Cochlear: CI24R(ST) implant, sound processor CP810, and Slim straight electrode array with 22 electrodes and 31.5 mm long; and G3) Med-El: Sonata-ti100 implant, OPUS 2 sound processor and Standard electrode array with 16 electrodes and 31.5 mm long. In all cases, electrode array insertion was complete. ECR was obtained for sound field stimulation of pip tones of 20 ms @ 60 dBHL and test frequency equal to the central frequency assigned to each intracochlear electrode as referred to in the patient's MAP. The ECR is obtained by averaging the EEG epochs acquired each time the cochlear implant processes a pip tone of known frequency and intensity. ECR positive peak latency varies from 4 to 8 ms depending on the response time of the cochlear implant; therefore, the 20 ms analysis window used to calculate the correlation shifted in time depending on the device manufacturer.

IV. Results

A typical ECR waveshape is shown in Fig. 1A; morphology resembles the positive phase envelope of the input pip tone. ECR amplitude, peak to peak (a-a'), is in the range of tens of μV, which increases as stimulation current does. The ECR duration is the same as stimulation pip tone and latency, 20 ms in Fig. 1A, depends on CI response time and microphone sound processor distance to sound source.

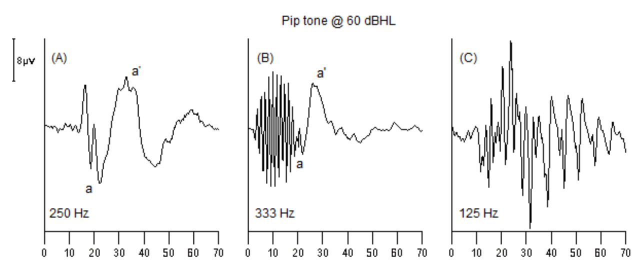

Figure 1. The waveforms illustrate the ECRs of apical electrodes with different noise levels from distinct CI manufacturers. (A) For Cochlear devices, ECR positive peak appears in the range of 20 to 35 ms after the onset of pip tone; amplitude is measured between a-a' peaks. (B) Artifact observed in Advanced Bionics devices due to stimulation pip tone that precedes the ECR positive peak. (C) Artifact observed in Med-El devices extends along the entire epoch due to the current stimulation rate (2.4 to 10 kHz) typically used in the first four apical electrodes.

As mentioned above, Empirical Mode Decomposition was used to decompose ECR and identify IMFs related to artifacts and response. Fig. 2 shows an example of determining the IMFs related to artifacts. Fig. 2A shows the original ECR register obtained from the most apical electrode, e1, of an *Advanced Bionics* CI. Fig 2B shows the corresponding decomposition in six IMFs and one residue, and Fig. 2C shows the FFT of the first IMF whose spectral content coincides with the stimulation pip tone frequency. Fig. 2D original ECR (blue trace) is shown along with the resulting ECR after removing the IMFs associated with the pip tone artifact (red trace).

Fig. 3 depicts the artifact remotion procedure followed in three implanted patient users of devices from a different manufacturer. AB1: *Advanced Bionics* user #1; MD1: *Med-El* user #1; and CO3: *Cochlear* user #3. EMD identified two main artifacts: stimulation pip tone and another related to the CI's operation, which extends throughout the entire recording. After removing those artifacts, it is possible to recognize the typical ECR waveform; notice that the ECR amplitude was normalized for comparison purposes. There are ECR positive peak latency differences among devices.

Finally, Fig. 4 shows the average ECR for the six apical electrodes (e1-e6) from the three different cochlear implant manufacturers included in this work; AB: Advanced Bionics; MD: Med-El; and CO: Cochlear. ECR amplitudes were normalized for comparing purposes. As mentioned before, the Correlation coefficient was used to measure the linear dependency intra-patient, intra-, and inter-groups; results are included in Table I, Table II, and Table III, respectively.

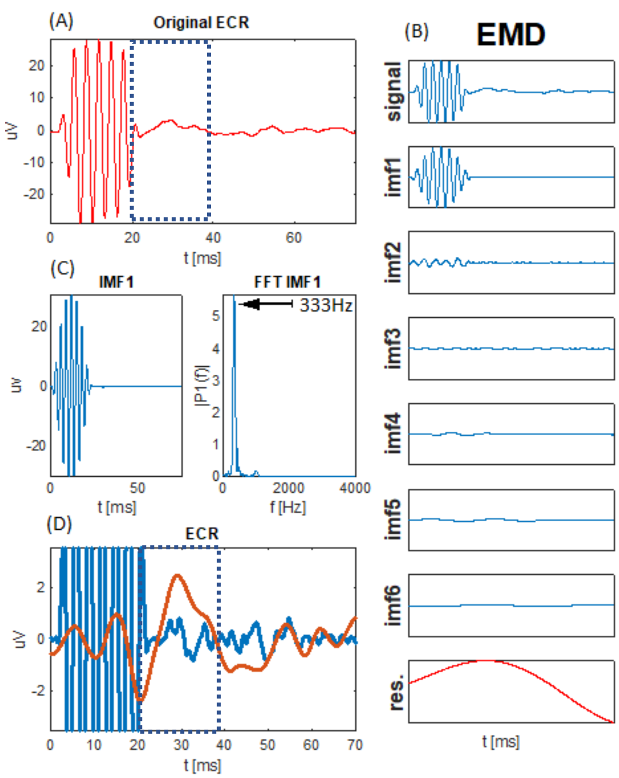

Figure 2. (A) Original ECR signal, (B) Empirical Mode Decomposition in six Intrinsic Mode Functions (imf) and a residue (res.), (C) First IMF and its FFT and (D) zoom to the comparison between original ECR (blue trace) and final ECR (red trace) after pip tone artifact removing. Dotted box in (A) and (B) marks where ECR is expected.

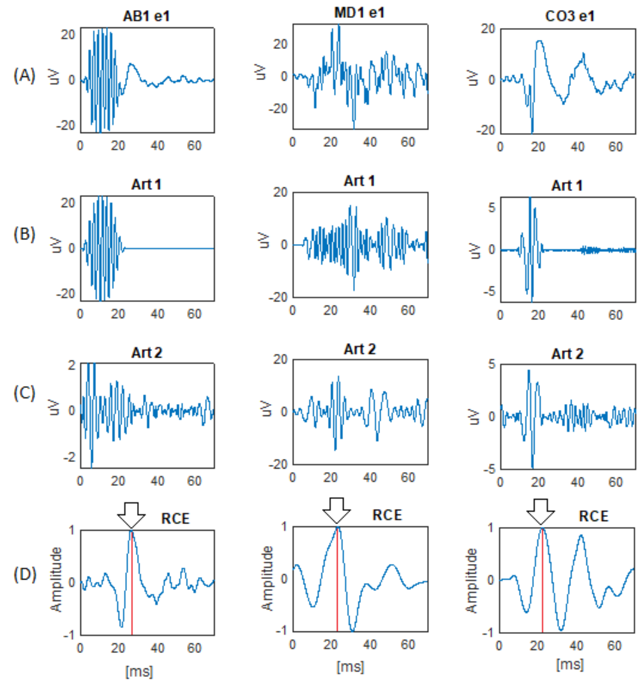

Figure 3. Row (A): Original electrode No.1 ECR from three different CIs. Row (B): Pip tone artifact identification. Row (C): Artifact due to CI functioning identification. Row (D): Normalized ECRs after artifacts remotion; arrow indicates ECR positive peak latency. ECR positive peak latency variations are due to differences in the CI time response, pip sound intensity level, and patient distance to sound source.

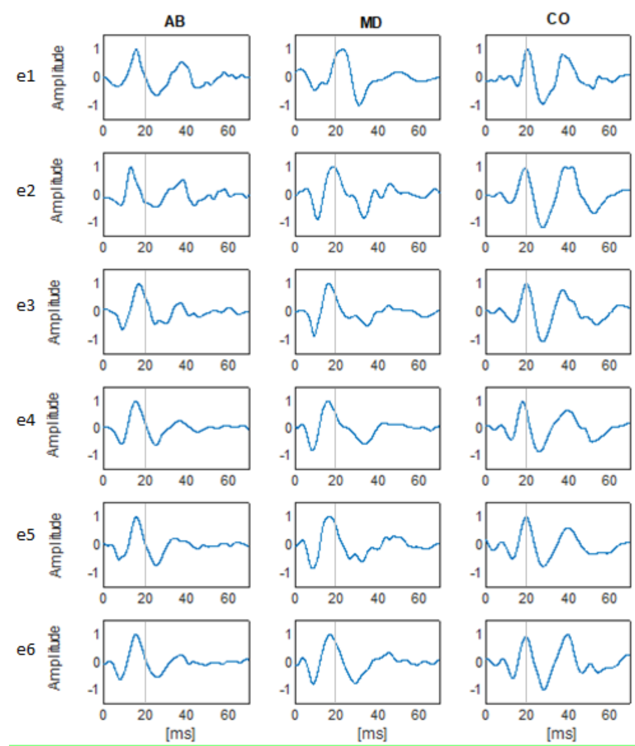

Figure 4. Average group ECR waveforms from apical electrodes (e1-e6) after artifacts removing. AB: Advanced Bionics, MD: Med-El, and CO: Cochlear. ECR positive peaks latency variations depending on device manufacturer are apparent respect 20 ms gray vertical line.

In Table I, it is possible to observe that the Correlation coefficient between electrodes in each patient is similar; there is no clear tendency. The average Correlation coefficient in AB3 was 0.86, followed by CO2 whit 0.83 and finally MD4 with a value equal to 0.63. The intra-group Correlation coefficients are included in Table II; those values show an apparent reduction as electrodes are further apart. Again, AB has the highest average value (0.90), followed by CO (0.82) and at the end MD (0.58). On the other hand, inter-group Correlation coefficients go from 0.63 to 0.85 (Table III).

TABLE I. INTRA-PATIENT CORRELATION COEFICIENTS

Patient	e1-e2	e1-e3	e1-e4	e1-e5	e1-e6	Average
AB3	0.87	0.90	0.84	0.83	0.86	0.86
CO2	0.83	0.93	0.86	0.78	0.76	0.83
MD4	0.74	0.73	0.54	0.50	0.63	0.63

AB: *Advanced Bionics*, MD: *Med-El*, and CO: *Cochlear*, e#: electrode number.

TABLE II. INTRA-GROUP CORRELATION COEFICIENTS

Group	e1-e2	e1-e3	e1-e4	e1-e5	e1-e6	Average
AB	0.92	0.94	0.90	0.88	0.87	0.90
CO	0.92	0.89	0.83	0.80	0.71	0.83
MD	0.73	0.58	0.54	0.48	0.57	0.58

AB: *Advanced Bionics*, MD: *Med-El*, and CO: *Cochlear*, e#: electrode number.

TABLE III. INTER-GROUP CORRELATION COEFFICIENTS

Electrode	*AB-CO*	*AB-MD*	*CO-MD*	Average
e1	0.90	0.96	0.90	0.92
e2	0.92	0.84	0.80	0.85
e3	0.95	0.85	0.84	0.88
e4	0.87	0.74	0.44	0.68
e5	0.73	0.53	0.33	0.52
e6	0.71	0.55	0.53	0.59
Average	0.85	0.74	0.63	

AB: *Advanced Bionics*, MD: *Med-El*, and CO: *Cochlea*r, e#: electrode number.

V. CONCLUSION

One first conclusion of this work is that the frequency criterion for ECR artifacts remotion using an EMD method is good enough for the three devices included in this work. Additionally, it should be noted that artifacts accompanying ECR acquisition differ from the well-known artifact that affects the ECAP obtention.

Generally, ECR morphology from apical electrodes follows the positive envelope of the incoming pip tone with a positive peak coincident in time with the pip tone peak. See Fig. 1, in contrast to cochlear base electrodes, not shown.

Although this work refers to a noisy electrode subset, where a robust ECR is obtained, the EMD method to remove artifacts can be applied to the rest of the electrode array where ECR amplitude might be minor, and waveshape is not well defined. This is generally observed in our laboratory, especially for devices having many electrodes, probably due to electric current sensibility variation along the cochlea and an increase in the distance from the electrode guide to modiolus.

The ECR is a novel objective alternative designed for patient-cochlear implant performance evaluation in natural use conditions. This work suggests consistency of this response from patient users of different cochlear implant types, hence increasing ECR use expectations.

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