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Objective Measures at Different Stages of Cochlear Implantation: A Data Analysis

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ABSTRACT

Objectives: The aim of this literature review was to summarize the results of scientific publications on the use of objective electrophysiological methods at different stages of cochlear implantation. The following aspects were evaluated: usefulness of electrocochleography and auditory evoked brainstem response registration to electrical stimulation for candidates' selection for cochlear implantation; application of neural response telemetry, auditory evoked brainstem response registration and contralateral stapedial muscle reflexes to electrical stimulation as well as intracochlear electrocochleography to acoustic stimulation during implantation; the use of these methods and cortical auditory evoked potentials at the post-surgery stage for monitoring the cochlear implantation outcomes and controlling the speech processor adjustment.

Results: A search was conducted in PubMed and CINAHL databases up to August 2024 to locate articles related to the electrocochleography and auditory brainstem responses measured before, during and after cochlear implantation and cortical auditory evoked potentials – after cochlear implantation. The quality of studies was evaluated using the National Institute of Health (NIH) "Study Quality Assessment Tool for Case Series Studies". A total 186 articles were included for the systematic review including 72 studies devoted to neural response telemetry, 29 – to electrically evoked auditory brainstem response registration, 41 – to intracochlear electrocochleography, 34 – to cortical auditory evoked responses in implanted patients and 10 – to contralateral stapedial muscle reflexes to electrical stimulation during and after cochlear implantation. Based on the analysis of the reviewed publications the optimal sets of objective measurements at different stages of cochlear implantation are recommended.

Conclusions: The battery of the objective audiological methods provides the electrically evoked auditory nerve compound action potential threshold determination at different electrodes of cochlear implant which can be used for the precise speech processor mapping, including investigation of amplitude growth function, excitation summation, spread of excitation and recovery function. The intracochlear electrocochleography to acoustic stimulation provides real-time feedback intraoperatively and has a potential clinical value to monitor the status of hearing preservation. Additional information could be obtained with estimation of auditory evoked brainstem response thresholds to electrical stimulation before, during and after implantation. The invaluable information for the estimation of cochlear implantation effectiveness can be obtained by registration of cortical auditory evoked potentials to acoustic and electrical stimulation which is based on the analysis of the P_1-N_1-P_2 complex.

Keywords: Cochlear Implantation; Electrophysiology; Electrically Evoked Compound Action Potential; Electrically Evoked Brainstem Responses; Cortical Auditory Evoked Potentials; Electrically Evoked Stapedial Reflex Threshold

Introduction

The effectiveness of cochlear implantation (CI) has increased significantly over the past forty years. This is due both to the improvement of technologies for the development and production of implants, to changes in the criteria for CI candidates' selection (age, degree of hearing loss) and significant changes in the procedure for the speech processor adjustment. However, despite this, the results of CI vary significantly among different patients.[1] This variability, of course, depends on the functional integrity of the auditory nerve and structures of central auditory system, the location of the electrode array, and the performance of the implanted electronic device.

An outcome of CI surgery is typically assessed using a battery of tests. The speech perception test investigates the patient's ability to both perceive and discriminate speech information. While widely used, scores are influenced by several factors, including the intelligence quotient, ability to focus, and age. These limitations highlight the need for more objective outcome measures.

With the rising numbers of CI surgeries in recent years, as well as the expansion of candidacy to wider groups of pediatric population, there is a greater need to standardize and optimize the surgical and diagnostic procedures to ensure consistent and favorable outcomes.

Modern methods of computerized tomography and magnetic resonance imaging provide information about the location of electrodes, but they are powerless in determining the functional status of neural elements, the performance of the device, and predicting the results of CI.

Over the past decades, various electrophysiological techniques have been developed and introduced into clinical practice, providing registration of responses from structures at various levels of the auditory pathway to acoustic stimulation The electrophysiological assessment has been shown to be efficient in investigating the functioning of the auditory system and in providing objective data on the benefit of early intervention.

Large number of papers published in the 90s also described approaches for using electrophysiological techniques in implanted patients. The emphasis was mainly on recording of electrically evoked short- and middle-latency potentials.[2-8] However, due to the need to use surface electrodes and special averaging equipment, as well as the importance of the patient's condition during registration, these techniques have not found widespread use in clinical practice. This equally applies to the auditory nerve compound action potential (CAP). And, if the auditory nerve CAP to acoustic stimulation has been widely used in clinical practice for more than 60 years,[9] its registration to electrical stimulation in animals and humans has become possible only since the second half of the eighties.[2,4,5,10-12] This delay was primarily due to the lack of techniques to suppress electrical stimulus artifact. In 1990, Brown et al.[5] developed a recording technique using intracochlear electrodes in patients with cochlear implants, based on the use of a forward masking paradigm.

The electrically evoked CAP (ECAP) represents a synchronized response generated by a group of electrically activated auditory nerve fibres. Current cochlear implants incorporate a "reverse" telemetry capability that allows near-field recordings of the ECAP (Neural Response Telemetry - NRT - Cochlear; Neural Response Imaging - NRI – Advanced Bionics, Auditory Response Telemetry - ART – Med-EL).[13] Compared with other electrophysiological measures, the ECAP offers several advantages: 1) measuring the ECAP in CI patients does not require extra equipment, special software, or an external recording electrode other than the standard equipment for clinical programming; it can be done through the telemetry function implemented in the CI and the commercial software provided by the manufacturer; 2) it requires minimal patient cooperation and is not affected by patient's arousal status, which is an important advantage for working with pediatric CI users.[13] Clinical application of ECAP recordings include functionality tests during surgery, long-time monitoring of the implant-nerve interface and provide a guidance for fitting when subjective feedback from the CI user is unreliable.[14]

However, it should be noted that despite the above capabilities, NRT provides information only about the functional integrity of the auditory nerve fibres, which certainly limits its ability to assess the state of overlying structures and explain the pronounced intra- and interindividual differences in CI results. This information can be obtained by recording the potentials of the brain stem and auditory cortex to electrical stimulation which can more effectively activate the central auditory pathway, providing auditory perception and enabling development of speech perception skills.[15-17]

The electrically evoked auditory brainstem response (EABR) is an objective method for nerve electrophysiological test based on ABR. This method triggers the auditory nerves and brainstem to generate a series of electrical potential activities through electrical stimulation of spiral ganglion cells/ auditory nerve fibres. EABR can objectively and effectively evaluate the functional status of the auditory conduction pathways and their responsiveness in children with severe and profound sensorineural hearing loss.[18-21] It has an important application value in the selection, intra-operative monitoring, and post-operative evaluation of surgical indications in children receiving CI. Additionally, these responses can be recorded even when excessive stimulus artifacts preclude successful acquisition of the ECAPs.

At the pre-operative stage, a transtympanic EABR (TT-EABR) could be used as an effective clinical procedure which can decrease the likelihood of placing a cochlear implant in a non-stimulable ear and may provide the clinician with a valuable tool for selection of the most appropriate ear for implantation.[22]

It has been shown that the presence of normal TT-EABR may indicate a significantly better outcome after CI surgery than for ears which had abnormal or absent TT-EABR.

Together with TT-EABR the intra-operative implant-evoked EABR with the use of test electrode is recommended to identify the site of lesion in patients with auditory neuropathy spectrum disorders (presynaptic vs. postsynaptic).[23]

Intraoperative testing is used for several purposes during CI surgery: to evaluate device functionality, to verify the position of the implant and electrode array, and to assess the functional status of the patient's auditory pathway.[24,25] These tests include imaging techniques, electrophysiological and biophysical evaluations, such as measurements of the electrode impedance, ECAP, intracochlear ECochG, EABR, and electrically evoked stapedial reflex threshold (ESRT); and other tests like subjective patient responses. Studies have shown that post-operative objective electrophysiological tests correlate well with behavioral levels and these measurements may be used to ascertain an optimal behavioral map for the implanted patient.

The literature reports that ECAP thresholds may be successfully recorded in 80–83% of cases but are not sensitive enough to identify accurate mapping levels. ESRT is known to overpredict the optimal behavioral comfort levels during the initial period of habilitation, and EABR, though reliable, is found to be cumbersome, time-consuming, and impractical to be done for all electrodes to comprehensively program a cochlear implantee.[26-29] Hence, no single electrophysiological test has been found to have high sensitivity and reliability for setting an ideal map [7]. There remains a lack of consensus regarding which tests, if any, should be used before, during and after surgery, and their precise function and utility.

Studies using EABR and later responses have confirmed changes in plasticity of the central auditory system in implanted children,[18,20,31-34] and demonstrated the ability of the central auditory system to adapt the new channel of information provided by the cochlear implant.

In cochlear implant (CI) patients, using the implant electrode, we can measure ECochG signals directly within the cochlea. Intraoperative, intracochlear monitoring of the cochlear response (cochlear microphonic – CM) to acoustic stimulation during CI shows promise as a tool to assist with hearing preservation.[35-37] The cochlear microphonic potential is generated primarily by transduction currents in outer hair cells as soon as mechanically gated ion channels open at the tip of stereocilia when the basilar membrane is displaced.[38] Therefore, the CM is well placed to detect any disturbance of cochlear mechanics, such as fixation of the basilar membrane by the electrode array.[39] When ECochG is recorded from the apical electrode of the array during CI, the signal amplitude tends to rise continuously or plateau for low-frequency stimulation. Observational studies report that even a transient fall in amplitude at any time during implantation results in poorer residual hearing levels postoperatively.[40] Patients with a preserved CM during implantation have been shown to retain more residual hearing for up to 12 months after surgery when compared to patients with an intraoperative CM drop.[41]

Electrocochleography responses can be recorded from an intracochlear electrode at any time after surgery in CI users with preserved acoustic hearing.[42-46] The most widely studied clinical application of postoperative ECochG is for estimating behavioral thresholds based on electrophysiologic thresholds.

Many researchers have demonstrated the possibility of cortical auditory evoked potential (CAEP) recording in CI patients.[7,32,47-62] It is emphasized that the presence of the P_1-N_1-P_2 complex with amplification can serve as an indicator of speech determination at the level of the auditory cortex.[57] In addition, the possibility of using CAEP recording to assess the effectiveness of CI is being considered,[63] and a high degree of correlation between CAEP thresholds and hearing thresholds is noted.[64,65]

The goal of this review is to provide a comprehensive overview of the electrophysiological methods and discuss their recent applications at different stages of cochlear implantation.

Results

A search was conducted in PubMed, CINAHL and Scopus databases up to August 2024 to locate articles related to ECochG and ABR measured before, during and after CI and CAEP – after cochlear implantation. The quality of studies was evaluated using the National Institute of Health (NIH) "Study Quality Assessment Tool for Case Series Studies". Journal articles were also acquired from the reference lists of relevant articles.

A total 186 articles were included for the systematic review: 72 studies devoted to NRT, 29 – to EABR registration, 41 – to intracochlear ECochG, 34 – to CAEP in implanted patients and 10 – to contralateral ESRT during and after CI.

NEURAL RESPONSE TELEMETRY

The electrically evoked compound action potential is a synchronized response that is generated by many cochlear nerve fibres, stimulated by brief electrical pulses delivered to an intracochlear electrode contact of cochlear implant and recorded from the contact of the intracochlear electrode, usually located one or two electrode contacts away (in the apical direction) from the stimulated electrode.

In general, electrically evoked potentials have characteristics like potentials recorded to acoustic stimulation. At the same time, electrical stimulation eliminates processes that are normally present in the cochlea, such as the compressive effects of the basilar membrane and hair cells, as well as processes in synapses. As a result, excitation in the auditory nerve has greater synchrony, shorter latency, and a steeper growth function than similar parameters during acoustic stimulation.[2,5,66]

Electrical stimuli transmitted through electrodes of cochlear implant to the auditory nerve fibres are transmitted to the neural structures. Theoretically, the ability of the auditory nerve to encode and process incoming electrical stimuli should largely determine the results of CI.[13] It has been shown that the physiological activity of the auditory nerve (the number and conditions of spiral ganglion neurons) influences the results.[67-73] Many studies have been aimed at exploring the feasibility of ECAP recording to determine stimulation levels for each CI electrode in a patient.[30,74-78] Over the past 15 years, there has been an increase in the number of studies in which ECAP recording is used to investigate various aspects of auditory nerve fibres functioning and their impact on the results of CI in children and adults.[79-82] Typically, the ECAP from intracochlear electrodes in implanted patients is biphasic and consists of a negative N_1 peak recorded in a time window of 0.2–0.4 msec followed by a positive peak P_2 recorded in a time window of 0.6-0.8 msec.[5,8,83] This ECAP waveform is detected in more than 80% of registrations.[84-86] ECAP with two positive peaks P_1 and P_2 can also be determined,[84,87,88] but no more than in 10-20% registrations.[84,88]

Exceptions in which ECAP cannot be recorded most often include recipients with cochlear nerve deficiency and those with auditory neural dysfunction.

The amplitude of the ECAP response is larger than the amplitude of typical CAP to acoustic stimulation measured with surface electrodes, because the recording electrodes used for the ECAP registration are in close proximity to the neural generator. However, successful recording of the ECAP is challenging because the electrical artifact from the stimulus delivered is much larger than the auditory evoked response. As a result, artifact reduction techniques are required to extract the cochlear nerve response from the competing electrical artifact from cochlear implant.

The electrically evoked compound action potential is a high-amplitude response, which minimizes interference with myogenic activity recordings. Based on ECAP peripheral nature, it is not affected by the maturation of the central auditory system, which is reflected in the absence of differences in the morphological characteristics of ECAP in children and adults[5,30,78] and practically does not change with the duration of implant use.[89] At the same time, the amplitude and latency of ECAP recorded in implanted patients are influenced by external factors, such as the level of stimulation, the position of the stimulating intracochlear electrode, the spacing of the stimulating and recording electrodes, the polarity of stimulation, etc. Thus, with increasing the intensity of stimulation, the amplitude of ECAP increases. The increase in amplitude is characterized quantitatively by the slope of the input/output function. It should be noted that ECAPs recorded from apical electrodes have a larger amplitude than potentials recorded from basal electrodes at the same intensity levels,[88,90-93] which may be due to greater preservation of neurons and a smaller distance between the test electrode and the stimulated neural structure in the apical region. The slopes of the amplitude growth function are also more pronounced at apical electrodes.[14] As the distance between the stimulating and recording electrodes increases, the ECAP latency may decrease, which is associated with a change in the site of potential generation.[94] Biphasic electrical pulses are the typical stimuli used to elicit ECAP They are delivered to one intracochlear electrode contact via monopolar coupling at a rate ranging from 30 to 80 pulses per sec which is much slower rate than that used for most cochlear implant signal coding strategies. In fact, most recipients can tolerate ECAP stimulus levels that are higher than the stimulus levels used for their maps, because the faster stimulus rates used for mapping in modern signal coding strategies elicit a louder auditory percept due to temporal summation. Finally, ECAP evoked by a biphasic anodic-onset pulse has a larger amplitude and shorter latency than that evoked by a biphasic cathodic pulse at the same levels of stimulation intensity.[95-99]

The potential clinical applications of NRT have been actively explored since the development of this method. Most previously published works focused on determining the programming levels of individual electrodes of cochlear implantation systems.[8,30,53,74,75,77,78,83,100-104] There is evidence that auditory nerve health matters for implantation outcomes.[68-70,72,73] In addition, it has been shown that ECAP is sensitive to the location of the electrode and the functional state of the auditory nerve fibres in the area of the recording electrode[86,105,106] and can also be used to monitor the neuronal activity.[49,55] Particular attention has been paid to the study of spectral and temporal encoding of electrical stimuli at the level of the auditory nerve and their relationship to auditory perception in implanted patients.[60,61,80,82,93,107-110]

Based on an analysis of the results of experimental and clinical studies He et al.[13] are mentioning the potential capabilities of ECAP in determining the level of stimulation, spatial selectivity, assessing the temporal characteristics of the response and the functional integrity of the auditory nerve fibres. Pronounced intra- and interindividual variations between stimulating electrodes, as well as between discharge rates, were noted in almost all studies, which was associated with differences in the functional state of the fibre populations that respond to electrical stimulation provided by the cochlear implant. These variations highlight the importance to investigate the extent to which differences in the physiological status of auditory nerve fibres may influence variations in auditory and speech perception between implanted patients and between stimulation sites within an individual patient.

Despite significant progress in our understanding of the ECAP nature, many questions remain to be resolved. This also applies to the possibility of using the spread of excitation (SOE) functions obtained during ECAP recording to determine which electrode should be used for programming maps in a particular patient, and to the significance of the clinical and behavioral manifestation of different temporal characteristics of auditory nerve fibres.[111-113]

The Neural Response Telemetry technique is of particular importance for the speech processor programming in young children. Its widespread introduction into clinical practice has been facilitated by the following factors: there is no need to use external electrodes; intracochlear electrode ensures registration of high-amplitude auditory nerve CAP exceeding in magnitude electrical activity of another origin; the patient's condition during ECAP recording is not so critical, which allows registration to be carried out while the child is awake; given the improvement in the signal-to-noise ratio, a significantly smaller number of averagings are required to obtain a response, which reduces the time of investigation.

However, despite the further development of the method and its wider use in clinical practice, one should remember some important aspects in which the NRT cannot be informative. Since the ECAP of the auditory nerve reflects the activity of the auditory periphery, its information content sharply decreases with changes taking place in the central auditory system.

Electrically Evoked Compound Action Potential Registration for Threshold Determination

Implantation of children aged 12 months and younger previously presented a problem not only in terms of candidate selection, but also in terms of the speech processor postoperative programming. Considering that during ECAP registration there is no need to obtain behavioral responses, electrophysiological techniques have found widespread use before and after CI in young children. As a rule, the stimuli used in electrophysiological and behavioral studies do not differ from each other, and therefore the thresholds determined in these measurements also correlate well. However, the stimuli used for ECAP registration differ significantly from the stimuli used to program the speech processor. In the first case, a sequence of stimuli with a frequency of 30-80 Hz is used, while in the second - with a frequency of 250 Hz and higher. Considering that behavioral thresholds and maximum comfort levels (MCL) reflect temporal integration, but ECAP and EABR thresholds do not, it is logical that there is only a subtle relationship between electrophysiological thresholds and behavioral levels of programming, as well as significant intersubject variability. In this regard, many authors have proposed combining the results of NRT with a limited amount of behavioral data to predict levels of speech processor programming. Even though the methods proposed by different authors were somewhat different from each other, they led to an increase in the correlation between ECAP thresholds and threshold and comfort levels of processor programming, both by adjusting the threshold level when using behavioral threshold values on a specific electrode, and when determining the speech perception threshold of the stimulus presented through the processor. However, despite the unexpressed correlation of the registered ECAP thresholds with threshold and comfortable levels of stimulation, it is necessary to note the high correlation between the ECAP thresholds profiles and the profiles of individual stimulation maps of the speech processor, which makes it possible to objectify the adjustment process as much as possible, while creating maps of stimulation, that correspond to the profile of the registered ECAP thresholds. [87,113-115]

Brown, Abbas, Gantz (1990)[5] recorded ECAPs in implanted patients. They obtained data indicating a high degree of correlation between the electrophysiological response and the results of implantation.

With multichannel cochlear implants, each electrode is expected to stimulate different populations of neurons. Based on histological data obtained in animals with experimental deafness and on human temporal bones, it was concluded that the degeneration of spiral ganglion cells and their peripheral processes significantly differs along the cochlea.[116-119] If we assume that changes in ECAP parameters reflect the properties of the stimulated populations of neurons, then we can expect that these responses will vary not only between subjects, but also depending on the site of stimulation in each subject.

The electrically evoked compound action potential thresholds can be determined visually or by amplitude growth function determination. It typically includes measures completed at a stimulation level that is below the ECAP threshold and several ECAP measures at suprathreshold stimulation levels.

When determining the ECAP amplitude growth function various maskers and stimuli corresponding to the upper limit of the dynamic range are used. As the stimulation intensity decreases, the masker level decreases by the same amount (10 CL). It is possible to extrapolate the obtained data to determine the ECAP threshold value. As a rule, ECAP threshold is located below the MCL and above the level of threshold perception (closer to the MCL).

Advanced variations in ECAP measurements may be completed to gather additional information about the auditory system's responsiveness to electrical stimulation. These advanced measurements include the recovery function and SOE measures. However, although these measurements are of scientific interest, they are rarely conducted as part of the clinical management of cochlear implant recipients.

The spread of excitation measurement may be completed by manipulating the conventional ECAP registration parameters and may refer to the amount of electrical current spread from a stimulated to surrounding electrode contacts.

Although SOE measurement can provide an indication of channel interaction, research has generally failed to establish SOE as a tool to effectively predict a recipient's performance or to determine the need to disable certain electrode contacts to avoid channel interactions. However, several researchers have shown the SOE to be useful for detecting electrode array tip fold-over based on the change in the shape of SOE in atypical manner when the electrode contacts involved with the foldover are used as a masker.[120-122]

Another advanced ECAP measurement is the investigation of recovery function in CI users. The rate of recovery ECAP measurement is a variation of the forward-masking subtraction technique – multiple ECAP measurements are made with varying masker-probe intervals (MPIs).

When using short MPIs, neurons, having responded to the presentation of a masker, are in a refractory pause at the moment of stimulus presentation. As the MPI lengthens, the number of neurons responding to the stimulus increases. The functions describing the relationship between the ECAP amplitude, and the MPI reflect the time required for the recovery of the nerve from a refractory state.

The results of ECAP registration in patients with cochlear implants (thresholds, growth functions and refractory properties) using short stimuli (40 µs/phase), providing a high degree of synchrony of nerve discharges, allow us to consider the amplitude of ECAP as an indicator of the sum of action potentials caused by a certain stimulus. The findings of differences in growth and recovery functions both between patients and between locations of stimulated electrode pairs may indicate differences in the size and characteristics of the stimulated neuronal population response. Previous experimental studies have shown that ECAP is sensitive to degenerative changes in the auditory system of animals with experimental hearing loss[123,124] and that these findings may also apply to speech perception in implanted patients.[5] Given the noted variability in physiological studies and the high correlation between them and psychophysically determined data,[125] it can be assumed that electrophysiological measurements and especially thresholds, amplitude growth functions and temporal characteristics of the response, can be used for description of the stimulated neuronal population properties. Threshold measurements are typically used to select speech processor stimulation parameters and to select the range of electrical stimulation, in particular.

INTRACOCHLEAR ELECTROCOCHLEOGRAPHY

A new step that opens great prospects for preserving residual hearing during cochlear implantation has been the introduction into clinical practice of intraoperative intracochlear ECochG to acoustic stimulation. When the electrode array of the cochlear implant is inserted, the CM is recorded and the function of intact outer hair cells is monitored.[35,42,44,46,126-139] The cochlear microphonic portion of the ECochG reflects hair cell function, while the auditory nerve neurophonic represents sustained phase-locked neural activity.[140]

Intracochlear ECochG via the reverse telemetry system offers real-time feedback about cochlear responses during electrode insertion.[35,43,137,138,141-143] The prognostic value of intracochlear ECochG recordings during CI surgery was investigated to determine whether this technique can be used to assess insertion trauma and predict early postoperative hearing preservation.[144-147] Mixed results were reported on the relationship between changes in the ECochG response and hearing preservation. It was shown that CM amplitude alone is not sufficient to detect damage or insertion trauma. Considering both the phase and amplitude might identify ECochG amplitude drops caused by touching or damaging the basilar membrane better than simple amplitude because the recording electrode has just passed the generator.[148]

The electrocochleographic responses can be recorded from intracochlear electrode at any time after CI surgery in patients with preserved acoustic hearing.[42-46] Postoperative intracochlear ECochG has been used to determine the lowest stimulus presentation level that generates CMs in CI patients with residual hearing. The results show a significant correlation between CM thresholds and behavioral thresholds in CI patients.[43-46,142,149-151] It was shown that both the CM and auditory nerve neurophonic responses could be identified from most patients with preserved low-frequency hearing using acoustic stimulation. Cochlear microphonic and neurophonic thresholds measured with 500 Hz tone burst significantly correlated with postoperative behavioral thresholds at 500 Hz.[42]

It is also important to consider the location of the CI electrodes which determines the place-pitch sensation produced by electrical stimulation of each individual electrode.[127,152]

ELECTRICALLY EVOKED BRAINSTEM RESPONSE REGISTRATION TO ELECTRICAL STIMULATION

Auditory nerve fibres are more steeply tuned to acoustic stimuli than to electrical stimuli. In addition, phase synchronization occurs to the positive phase of the acoustic sinusoidal stimulus, while with electrical stimulation, phase synchronization occurs to the negative phase of the stimulus and is more pronounced.[80] The normal functioning of the auditory nerve fibres involves excitation of the inner hair cells, which results in a greater dynamic range. With electrical stimulation, auditory nerve fibres are stimulated bypassing the inner hair cells and have a smaller dynamic range.[153] It should also be noted that the maximum discharge rate and SOE in the auditory nerve are more pronounced with electrical stimulation.[153] It is known that synchrony in recording electrically evoked potentials in implanted patients is more pronounced than acoustically evoked potentials in individuals with normal hearing, which is due to direct stimulation of auditory nerve fibres by electrical stimuli with a rapid onset.[30] Due to the absence of delays mediated by mechanical propagation of the traveling wave, transduction in sensory cells and synaptic excitation in primary afferent neurons, the absolute values of the latencies of EABR waves are shorter than the latencies of ABR waves during acoustic stimulation by 1-2 msec. Moreover, the P_{III}-P_V intervals were the same for both types of stimulation.[34] The slope of latency/intensity function is steeper with electrical stimulation. With acoustic stimulation, the latency decreases to 2 msec between threshold and saturation of potential, while with electrical stimulation, the latency changes only slightly.[33]

With electrical stimulation, a greater amplitude of the ABR waves is determined than with acoustic stimulation. The auditory nerve fibres that respond with synchronous discharges to click stimulation originate mainly from the basal regions of the cochlea,[154] while with electrical stimulation all fibres respond synchronously.[2]

Previous studies have noted intra- and intersubject differences in amplitude, thresholds, and wave morphology when recording EABR from different electrodes.[53,155] It was noted that the latency of wave V had larger values when recorded from more basal electrodes than when recorded from apical electrodes.[156] In patients with cochlear implants, better responses were recorded (relative to latency, amplitude and wave morphology) from apical electrodes.[54,157] The closer the electrode array is to the stimulated spiral ganglion neurons, the greater is the effect of stimulation on thresholds.[106,158]

The electrically evoked auditory brainstem response parameters (thresholds, amplitude growth function, slope) are influenced by intact neurons of the spiral ganglion. Some studies have noted a low degree of ability to predict a functional integrity of spiral ganglion neurons using EABR,[105,159] while others have obtained good predictive results.[125,160-162] A greater correlation between the number of intact spiral ganglion neurons and the effectiveness of CI can be expected if a more adequate method for assessing the integrative function of the auditory nerve is used. Hall (1990) demonstrated that in rats with experimental deafness there was a high degree of correlation between the amplitude and/or growth function of EABR wave I and the number of intact spiral ganglion cells.[124] However, this correlation significantly decreased for later waves. It should be borne in mind that EABR wave I recording in humans is extremely difficult because it has a low amplitude and is practically masked by an artifact of the electrical stimulus or artifacts of a different nature. The way out of this situation is to record the ECAP of the auditory nerve. Being the response to electrical stimulation of the corresponding groups of fibres, ECAP can be considered as an analogue of the EABR wave I. In doubtful cases of CI candidates' selection, the useful method to evaluate the integrity of the auditory pathway is the EABR registration.

Polterauer et al. (2018, 2022)[163,164] used the trans-tympanic approach for the EABR registration before the CI. However, because such tests fail to judge auditory nerve excitability in many cases and based on the results of Lassaletta et al. (2017)[165] the intra-operative EABR registration before the CI with the use of test electrode was recommended.[166,167]

CORTICAL AUDITORY EVOKED POTENTIALS

The P_1-N_1-P_2 complex can be recorded in implanted patients in response to sounds presented either electrically (directly to the speech processor of the cochlear implant) or acoustically (via a loudspeaker to the microphone of the speech processor). However, the response is often superimposed by stimulus artifact. Often, the artifact caused by radiofrequency pulses occurs in the electrodes located in the region of the implant magnet, but it can be eliminated by moving the electrode away from the magnet. In some studies, the problem was solved by using relatively short stimuli, which resulted in the stimulus artifact ending before the onset of the potential peak.[50,51,168]

Quite encouraging results when recording the P_1-N_1-P_2 complex from intracochlear electrodes in implanted patients were noted in studies by Attias et al. (2022)[169] and Callejón-Leblic et al. (2022).[170]

It is emphasized that the greatest amplitude of the complex is recorded during stimulation of the apical electrodes, and the most stable is the N_1 peak. In patients with lower levels of comfortable loudness, shorter N_1 latencies were determined.[170]

The P_1 peak recorded in implanted children does not differ in shape from that recorded in children with normal hearing but has an extended latency. In the studies of Ponton et al. (1996)[50], it was noted that the latency of the P_1 peak depends on the duration of use of the cochlear implant. The curve of the P_1 peak development in an implanted child is shifted by the time during which the child remained without activation of the central auditory system.

It should be remembered that a cochlear implant, like a hearing aid, distorts the morphology of the recorded response, which depends on the number of electrodes, the volume control setting, etc.

Of note is the work of Eggermont et al. (1997)[171] examining the maturation of the auditory system in children using cochlear implants. According to P_1 registration data (latency changes), it was shown that in the group of children with normal hearing, P_1 maturation occurred by the age of 15 years, while in children with cochlear implants there was a delay in P_1 maturation equal to the duration of deafness.

It has been shown that the developmental regression line constructed according to P_1 is interrupted in deaf children, but continues again after CI and reaches maturation, depending on the age at which the implantation took place.[50] Most changes in peak P_1 occur in the first 6 months after CI. Moreover, the earlier the operation is performed, the faster the peak latency decreases.

Based on this, it can be concluded that peak P_1 and its latency can serve as a "biological marker" of development and plasticity of the central auditory system.[172,173]

ELECTRICALLY EVOKED STAPEDIAL MUSCLE REFLEX

A special niche among the objective methods takes the stapedial muscle reflex threshold registration to electrical stimulation (ESRT). These reflexes can be visualized by the surgeon during surgery (muscle contraction when stimulating the corresponding pairs of electrodes after the electrode array insertion) or registered on the contralateral ear using an acoustic immittance meter (possible both during surgery and during the speech processor fitting after implantation). During surgery the ESRT presence can be verified visually based on muscle contraction or the stapes footplate movements. In most studies devoted to ESRT a pronounced correlation of contralateral ESRT with MCLs of electrical stimulation was noted.[174-180] As for the dependence of visually determined ipsilateral ESRT and the levels of speech processor adjustment, there are still many unsolved issues.

The contralateral ESRT registered from different CI electrode array channels in the same patient, has a flatter leading edge at near-threshold stimulation levels. The ESRT recorded from high-frequency electrodes, has a triangular shape that persists up to stimulation levels bordering on uncomfortable levels.

With presentation of two short stimuli (0.5 sec) following one another with the interval between them less than 1 sec, the effect of reflex amplitude summation is observed.

Usually, the ESRT is lower than the uncomfortable loudness level and is closer to MCL. It is necessary to mention that sometimes contralateral ESRT is not registered even in patients in whom it was visualized during surgery.

The characteristic features of the ESRT waveform can be explained by differences in the loudness temporal summation in patients using cochlear implants from the loudness temporal summation in individuals with normal hearing: in patients the loudness temporal summation is extended to 1 sec. The results of studies indicate a deterioration in the perception of the temporal structure of the signal by patients with cochlear implants.[181]

The high level of correlation of the ESRT with MCL can be considered as a basis for using the registration of contralateral ESRT to determine the MCL when setting up a speech processor. However, the clinical utility of ESRT is limited because it is not observed in all CI users.[182] While the registration of ESRT is widely used to assist with CI programming, underlying factors are not well understood. The significant factors of aging and sex could be due to middle ear mechanics or neural health differences. However, further data are needed to better understand these associations.[183]

RECOMMENDATIONS FOR DIFFERENT OBJECTIVE METHODS APPLICATION

Candidates' selection

Promontorial Test, Pre-Surgery Testing

The trans-tympanic approach for the EABR registration as well as the registration of contralateral ESRT to electrical stimulation are recommended. However, because such tests fail to judge auditory nerve excitability in many cases and based on the results of Lassaletta et al. (2017)[165] the intra-operative EABR registration before the CI with the use of test electrode can be considered as a method of choice.[166,167]

Surgical stage

Recently the widely used technique during the implantation is NRT, registration of EABR using the inserted CI electrodes as well as recording of the contralateral ESRT.

A significant reduction in the time of intraoperative testing, including AutoNRT, the electrode resistance measurement, determination of ECAP thresholds and threshold profiles, became possible after the introduction into clinical practice of wireless CR120/220 device and later SmartNav solution developed by Cochlear (Australia). The use of CR120/220 ensured a reduction in the time required to register ECAP by 22%, compared to the time spent using CustomSound. At the same time, a high degree of correlation was revealed between the thresholds of ECAP and NRT data recorded using CustomSound.[184] It should also be noted that intraoperative testing using the CR120/220 device can be performed by less qualified personnel. This allows more experienced specialists to devote more time to patients after CI at the rehabilitation stage.

The Nucleus SmartNav provides the diagnostic measurements to confirm the device integrity, auditory system response and supports post-operating fittings. It also provides useful information about the angular insertion depth, speed of insertion and placement check functions, so that a possible electrode displacement or a tip fold-over can still be detected intraoperatively without radiation exposure from x-rays.[185]

Advanced Bionics (Switzerland) recently introduced the AIM system which can use the implant to measure potentials generated by the inner ear and the auditory nerve in response to acoustic stimuli. The ECAP can also be measured with this hand-held device.[186] This continuous and real-time measurement during electrode insertion can provide invaluable feedback to the surgeon.

As noted above, in recent years intracochlear CM registration to acoustic stimulation during the CI electrode insertion into the cochlea has become increasingly relevant, which helps prevent traumatic injuries to the preserved cochlear fine structures. This technique can also be successfully used after surgery to construct audiograms based on CM recording.

Speech Processor Adjustment

During the speech processor mapping the registration of ECAP, EABR and stapedial muscle reflexes to electrical stimulation can be successfully used.

It is recommended to begin the study with ECAP registration to create an initial individual map of stimulation. To determine the level of stimulation of acceptable intensity, it is recommended to begin with ECAP and EABR registration. This level should be used to develop behavioral reflexes to sounds with subsequent adjustment of speech processor based on these reflexes. Additional information on the MCL of stimulation can be provided by results of ESRT registration.

Recently, to assess the adequacy of speech processor settings and the effectiveness of CI in general, increasing attention has been paid to recording of CAEP to both acoustic and electrical stimulation.

Conclusions

The electrophysiological methods have been widely applied as a clinical tool providing the valuable information about the auditory pathway including cochlear hair cells, auditory nerve, brainstem and auditory cortex. Using different objective measures at different stages of CI we can identify the site of lesion (presynaptic vs. postsynaptic) (ECochG), the auditory nerve functional integrity (EABR) and understand considerable variance in postoperative performance of CI users (CAEP).

The Neural Response Telemetry provides the ECAP threshold determination at different electrodes of cochlear implant which can be used for the precise speech processor mapping, including investigation of amplitude growth function, excitation summation, spread of excitation and recovery function. The intracochlear ECochG to acoustic stimulation supports the real-time feedback intraoperatively and has a potential clinical value to monitor the status of hearing preservation. Additional information could be obtained with estimation of EABR thresholds to electrical stimulation before, during and after implantation. The invaluable information for the estimation of cochlear implantation effectiveness can be obtained by registration of cortical auditory evoked potentials to acoustic and electrical stimulation which is based on the analysis of the P_1-N_1-P_2 complex.

A differentiated approach to the selection of diagnostic methods at different stages of CI will help to improve the diagnostic accuracy, individualize speech processor settings and evaluate the effectiveness of implantation.

Disclosure

Authors declare no conflict of interest.

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