Section II

Background Auditory Evoked Potentials

II

5 Electrocochleography

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Abstract

Electrocochleography (ECochG) is the measurement of stimulus-related cochlear potentials including the cochlear microphonic (CM), summating potential (SP), and the auditory nerve's compound action potential (AP). The generators of the cochlear potentials are inner and outer hair cells, whereas the AP is generated by synchronized type I auditory nerve fibers. ECochG is a valuable tool in the diagnosis, assessment, and monitoring of inner ear disorders and the auditory nerve. For clinical implementation, one must understand the complexity of an ECochG recording. This includes an appreciation of acquisition (i.e., electrode type/montage/impedance, amplification, filter bandwidth, time epoch, sweeps/replications, and transducer) and stimulus (i.e., type, duration, intensity, polarity, rate, and masking) parameters. An analysis of the electrocochleogram first begins with identification of the ECochG response components followed by latency and amplitude measures (e.g., SP amplitude, AP latency, AP amplitude, SP/AP amplitude ratio, and SP/AP area ratio). The ECochG is reliably recorded under standard clinical conditions. With standardization of ECochG recording and measurement protocols and sufficient qualified audiology practitioners graduating from audiology-training programs, the ECochG should remain a valuable diagnostic tool.

Keywords: electrocochleography, electrocochleogram, cochlear microphonic, summating potential, action potential, transtympanic, extratympanic

5.1 Overview

Electrocochleography (ECochG) is the measurement of stimulus-related cochlear potentials including the cochlear microphonic (CM), summating potential (SP), and the auditory nerve's compound action potential (AP). The ECochG components may be recorded separately or in various combinations. The recorded measurement is termed an electrocochleogram. It is a valuable tool in the diagnosis, assessment, and monitoring of inner ear disorders and the diagnosis of retrocochlear disorders of the auditory nerve. The most common applications for ECochG include diagnosis, assessment, and monitoring of the inner ear; enhancement of wave I of the auditory brainstem response (ABR) when hearing loss is present; diagnosis of auditory neuropathy/dyssynchrony; the measurement and monitoring of auditory nerve function during surgery; and assessment of residual hearing in cochlear implant patients.[1] ECochG has also emerged as a tool in the diagnosis, assessment, and monitoring of Ménière's disease. More recently, there has been an increased interest in the use of ECochG for the evaluation of noise over exposure, particularly in attempts to demonstrate noise-induced cochlear synaptopathy.[2,3,4,5]

Popularity of the ECochG has waxed and waned since its clinical application began in the 1970s. It has typically been less applied clinically when compared to the ABR. The low clinical use of ECochG may be attributed to the following: clinicians' deficient background in and familiarity with ECochG; insufficient preparation in performing the technique in their training program; lack of equipment and/or clinical testing facilities providing ECochG; an absence of clinical standards for testing ECochG;[6,7] and/or an absence of support/referrals by physicians who may not be aware of the applications of ECochG or who were not confident in the diagnostic value of the ECochG.[8]

5.2 Historical Aspects

The discovery of the ECochG was reported in 1930 by Wever and Bray.[9] In fact, this study was the first report of an auditory evoked response. While recording from an electrode placed in the auditory nerve of a cat using various sound stimuli applied to its ear, Wever and Bray observed reproduced sounds (i.e., CM) with great fidelity from the recording electrode's output when fed through an amplifier and telephone receiver. Following destruction of the cat's cochlea, the response was eliminated. Others subsequently repeated similar recordings in the 2 years that followed.[10] In 1935, Fromm et al[11] reported the first recordings of ECochGs in humans from two individuals with perforated tympanic membranes (TMs). A faint response was recorded in both individuals using a crude 0.25-mm enameled copper wire, with the end bared and bent round a small piece of cotton wool, placed on the promontory.

In the years that followed Fromm et al's[11] seminal study, improved recording techniques and amplification technology led to enhanced recordings of the CM. Eggermont,[12] in his review of 75 years of ECochG, termed this the period of "early surgical recordings." Recordings were being performed with electrodes placed on the cochlea of animals and humans during surgical interventions. Lempert et al first suggested the placement of an electrode through the TM onto the promontory as a feasible nonsurgical method in 1950.[13] A major advancement was evidenced in 1961 when Ruben et al first recorded the AP from the round window in humans.[14]

A "nonsurgical period" of discovery began in 1967 with the advent of reports of both transtympanic and extratympanic recordings in humans. Research was led by Yoshie and colleagues[14,15,16,17] in Japan and Portman colleagues[18,19,20,21] in France. There was a surge of publication in the 1970s as the clinical application of ECochG became evident with noninvasive recording techniques and the use of signal averaging computers. In the early 1970s, Cullen et al[22] reported recordings with a TM electrode. At the same time, Coats[23] published findings from ECochG recordings with an ear canal electrode. Eggermont[24] published the first report of the application of ECochG with patients with Ménière's disease in 1974. A dramatic increase in publications ensued over the next two decades led by numerous groups of researchers in England (William P.R. Gibson), France (René Dauman), Japan (Nozomu Mori), the Netherlands (Jos J. Eggermont), and the United States (Alfred C. Coats). Eggermont[12] noted that a slump in ECochG publications occurred in the first decade of the 2000s. There has been a

renewed interest in ECochG in the current decade, with an increase in publications owing to the application toward auditory neuropathy, improved diagnostic ability of Ménière's disease, use with intraoperative tests for cochlear implantation, and the application in programming cochlear implants.

5.3 ECochG Components/ Generators

There are three ECochG potentials—two are hair cell potentials and the third is derived from the afferent cochlear nerve fibers. Both the inner hair cells and outer hair cells generate electrical receptor potentials in response to auditory stimulation. Stimulus-related cochlear potentials include the CM and the SP. The AP component of the ECochG represents the synchronous summed response of several thousand auditory nerve fibers that have responded to acoustic stimulation. The actual number of fibers depends on the evoking stimulus. Understanding the generators of the three ECochG potentials is critical for clinical application and interpretation of ECochG results.

5.3.1 Cochlear Microphonic

The CM is an alternating current voltage that reflects the instantaneous displacement pattern of the cochlear partition. The CM mirrors the acoustic stimulus waveform. The CM appears with essentially no time delay between arriving stimulus at the cochlea and the CM onset. The latency reflects travel time of the acoustic stimulus through the outer and middle ear. The outer and inner hair cells both contribute to the generation of the CM.[25] The outer hair cells are believed to contribute predominantly by virtue of their greater number.[26] When the CM is recorded outside of the cochlea, outer hair cells from the basal region of the basilar membrane are responsible.[27,28] This latter observation is important in realizing that a CM in response to 500- to 4,000-Hz stimuli is generated from hair cells when basilar membrane displacement is passive. Therefore, a CM may be present with significant outer hair cell loss. Further, an observation of a CM in the absence of otoacoustic emissions cannot be viewed as normal outer hair cell function. Withnell[29] aptly states, "the presence of the microphonic on its own does not mean outer hair cell function is normal; indeed, the absence of an otoacoustic emission in such a case argues for outer hair cell dysfunction as otoacoustic emissions are quite clearly inextricably linked to outer hair cell function and basilar membrane mechanics". In fact, CMs have been detected in ears with profound hearing loss.[30]

Since the CM is an alternating current voltage, it mirrors the evoking stimulus waveform. Considering this, the CM is best observed with a single polarity (i.e., condensation or rarefaction) stimulus. Otherwise, the use of alternating polarity stimulus will cancel out the CM through signal averaging during response acquisition. When the CM is recorded outside of the cochlea, the response can resemble the electrical waveform of the stimulus. Therefore, if recording outside of the cochlea, steps should be taken to confirm that the recorded response is in fact not an "artifactual microphonic" (i.e., transducer artifact).

Pearl

When normal middle ear function is demonstrated and otoacoustic emissions are absent, an observation of the CM does not confirm normal outer hair cell function.

5.3.2 Summating Potential

The SP is a complex response thought to represent nonlinearities associated with the transduction process of the cochlea. It is a direct current potential evoked by an alternating current acoustic stimulus (e.g., a transient stimulus or continuous tone) that persists for the duration of the stimulus. That is, the SP is a reflection of the displacement-time pattern of the cochlear partition.[31] The SP is considered to be a shift in the baseline of the ECochG recording that is related to the stimulus envelopment. The SP does not appear to mimic the stimulus waveform but has a constant polarity—a rectified direct current version that is more representative of the stimulus envelope. The polarity of the SP is dependent on a number of factors including frequency and intensity of the stimulus and site of the recording electrode. The SP is positive in the site of maximum activity and negative elsewhere.[31] In humans, the SP is typically negative occurring with the same polarity of the AP. While holding the intensity constant, the SP may reverse in polarity when the frequency of the evoking tone burst is increased (e.g., 4,000–8,000 Hz).[32,33]

The SP generators have been typically recognized to be both the inner and outer hair cells without any neural contribution.[12] There is some debate as to which hair cells dominate the response. When the SP is recorded at the round window, the response is dominated by the hair cells at the basal turn of the cochlea for at least low to moderate stimulus levels.[34,35] When recorded in the apical turn of the cochlea, outer hair cells are the primary source of the SP.[25,36] Durrant et al[34] noted that "the complexity of SP production, as recorded from the round window, precludes a completely straightforward interpretation of the SP:CAP [compound action potential] in clinical ECochG".

More recently, there is evidence that the auditory nerve contributes to the generation of the SP.[37] Pharmacology study of the gerbil cochlea was undertaken where contributions from normal-hearing animals and those where outer hair cells were isolated with systemic treatment with the ototoxins furosemide and kanamycin. Further recordings were made in the normal-hearing animals and those treated with furosemide and kanamycin after application of neurotoxin kainic acid to the round window. The contribution from inner hair cells was obtained from the post–kainic acid-/furosemide- and kanamycin-treated animals. The neural contribution was obtained from the normal-hearing animals by subtracting the postkainic acid from the prekainic acid responses. The outer hair cells contribution was obtained by subtracting the postkainic acid responses across the hearing conditions. Pappa et al[37] observed that both outer and inner hair cells and the auditory nerve contribute to the generation of the SP. The researchers also noted that when this evidence was applied to data from SPs recorded from the round window in human cochlear implant subjects, a neural input to the SP was evidenced in humans.

5.3.3 Compound Action Potential

The AP is believed to reveal the synchronized type I auditory nerve fiber onset response.[34] The AP is a negative polarity reflecting synchronous discharge from thousands of auditory nerve fibers. The AP amplitude is the largest when evoked with transient stimuli (e.g., clicks and tone bursts) with abrupt onsets. A tone burst excites a limited area along the basilar membrane relative to its nominal frequency. While a click is a broadband stimulus displacing the whole basilar membrane, the AP is dominated by responses from the high-frequency basal region of the cochlear partition.[38]

The AP is an alternating current voltage. The AP waveform is characterized by a series of brief, predominantly negative peaks that are representative of the pattern of resultant neural firings. When evoking stimulus levels are high above threshold, the first negative peak is referred to as N_1. With decreasing stimulus intensity, a second negative peak is evident – N_2. N_1 and N_2 correspond to the same components as waves I and II of the ABR, respectively. Eggermont[33] notes that an increase of stimulus intensity increases N_1 relative to N_2, while lowering the intensity increases N_2 relative to N_1. Both N_1 and N_2 are of approximate amplitude at 65 dB HL. It is believed that two separate pools of auditory afferent fibers contribute to the two individual component peaks.[39]

AP component amplitude and latency reflect different underlying phenomena. AP amplitude reflects the number of auditory nerve fibers with synchronous discharge. Since the preponderance of auditory nerve fibers innervates inner hair cells, AP amplitude also mirrors inner hair cell output. AP latency is the time between stimulus onset and the appearance of the AP components N_1 or N_2. The absolute latency reflects stimulus travel time from the transducer to eventual encoding by the auditory nerve fibers. Reductions of signal intensity are accompanied with a decrease in AP amplitude and an increase in latency with an eventual disappearance of the AP.

5.3.4 Recording ECochG

While ECochG has been used in practice since the 1970s, there is a lack of consensus for recording standards.[8] Ferraro and colleagues[6,7] have maintained that recording, measuring, and interpreting the electrocochleogram varies considerably among users and there is a need for standardization. Ferraro and colleagues have maintained that lack of standardization makes the comparing and sharing of data across clinical sites and between clinicians difficult. The lack of standardization likely contributes to the underutilization of ECochG and confidence among clinicians using ECochG as a clinical tool.[8] What follows is a description of various acquisition and stimulus parameters available to the clinicians based on current published clinical and research literature. It is hoped that some formal standardization of ECochG recording parameters is recognized and adopted in the near future. A summary of the suggested clinical ECochG acquisition parameters is found in ▶ Table 5.1.

Table 5.1 Suggested clinical electrocochleography (ECochG) acquisition parameters

Parameter	Suggestion
Electrode type	Tymptrode
Electrode montage	Horizontal: +/noninverting ($A_{1/2}$); –/inverting ($A_{2/1}$ or $M_{2/1}$), and ground (nasion or F_{PZ})
Electrode impedance	≤ 20,000 Ω
Amplification	50,000–100,000X
Filter bandwidth	5–3,000 Hz
Artifact rejection	±10–25 μV
Time epoch	5 ms or 10–20 ms (for CM/SP recording of long-duration tone bursts)
Sweeps/ replications	1,024 sweeps with a minimum of two replications
Transducer	Insert earphone

5.3.5 Acquisition Parameters

Electrode Type

One primary technical consideration when recording is signal-to-noise ratio. ECochG requires an electrode placed as close to the response generator as possible for the best signal-to-noise ratio. That being said, what electrode type should be employed? Three general electrode options are available for the clinician—transtympanic, extratympanic, or TM placement.

Transtympanic ECochG recording is an invasive procedure that involves passing a long sterile stainless steel needle (e.g., 40–50 mm) electrode through the TM to rest on the cochlear promontory or round window niche.[40] Local anesthesia is required for cooperative adults, while general anesthesia is required for noncooperative adults and children. During surgeries that expose middle ear space, transtympanic recordings can also be made with a "ball" electrode on the promontory.[40] Transtympanic needle electrodes are secured (e.g., by elastic bands to a circular bracket/speculum) and stimulus delivery is achieved with a sound field speaker or a supra-aural earphone is placed over the ear. A subdermal transtympanic electrode, held in place by an insert foam plug, has also been described.[41] The subdermal needle is much shorter (e.g., 12 mm) than the traditional transtympanic needle. Regardless of the transtympanic electrode, an operating microscope and the assistance of a physician is required. The chief advantage of the transtympanic approach is the close proximity of the recording electrode to the response generators. This provides an excellent signal-to-noise ratio. Transtympanic ECochG recordings yield amplitude responses that are 10 times larger than extratympanic electrode recordings.[42] The obvious major limitation of transtympanic ECochG recording is its invasiveness. For this reason, most clinics use an extratympanic electrode approach for recording the ECochG.[1]

Pearl

Patient discomfort may be reduced prior to the insertion of a tymptrode electrode by the application of a 10% lidocaine solution wash.[7,43]

With the introduction of commercially available extratympanic electrodes in the late 1980s and early 1990s, clinical investigation of ECochG became increasingly more feasible to clinical audiologists.[40] One example is a gold foil electrode wrapped

around a foam insert (e.g., TIPtrode) that is placed in the ear canal. An insert earphone attached to the foam insert delivers the ECochG stimuli. While this is more comfortable for the patient, it results in a significantly smaller magnitude (i.e., approximately 80-fold reduction) of the response relative to transtympanic electrodes.[40]

A compromise in increased magnitude and decreased signal averaging without significant patient discomfort is the use of a TM (or "tymptrode") electrode placed on the lateral surface of the TM.[42] Commercially available tymptrode electrodes are now available (e.g., Bio-logic TM-ECochGtrode, Natus Medical Incorporated; Lilly TM-Wick Electrode, Intelligent Hearing Systems; and Sanibel, Sanibel Supply). These electrodes are typically constructed with a small silver wire, enclosed in a flexible tube, attached to conductive hydrogel, a small sponge, or a cotton tip. Sponge and cotton tips are usually infused with gel or saline, respectively. The electrode is placed in the ear canal such that the tip makes contact with the TM. Contact can be verified by having the patient report when they heard the electrode bump against the TM or otoscopic/otomicroscope visualization of the tymptrode electrode placement against the TM. Once the electrode is in place, it is typically secured with tape anteroinferior to the intertragal notch. Following this, an insert earphone is inserted for stimulus delivery. Relative to the extratympanic TIPtrode, closer proximity to the ECochG generators yields significantly larger response amplitudes and a greater expression of SP and AP responses during ECochG recording.[40,44] An example of an ECochG recording with a tymptrode and TIPtrode is shown in ▶ Fig. 5.1.

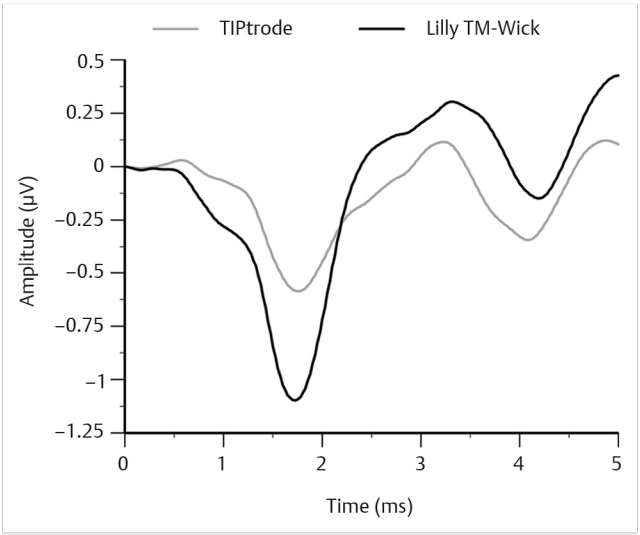

Fig. 5.1 Representative electrocochleogram (ECochG) recordings from a listener as a function of the electrode. ECochG responses were evoked with 90 dB nHL 100-microsecond click stimuli of alternating polarity. A horizontal recording montage was utilized (i.e., the noninverting electrode on the lateral surface of the tympanic membrane for recording with a Lilly TM-Wick electrode and the lateral external auditory canal for TIPtrode recording, the inverting electrode on the contralateral mastoid, and the ground electrode on the high forehead [F_{PZ}]).

Pitfall

Clinicians may be attracted to the use of extratympanic gold-foiled foam electrodes because of ease of application. However, significant reduction in ECochG response amplitude may ensue. The use of commercially available tymptrode electrodes is strongly encouraged.

Electrode Montage

The typical ECochG recording involves a single-channel "horizontal" electrode montage. The electrode on the stimulus side (i.e., transtympanic, TM, or extratympanic ear canal; $A_{1/2}$) is connected to the + /noninverting input of the differential amplifier. The –/inverting input is received from the contralateral electrode. Contralateral placements include extratympanic ear canal, earlobe, or mastoid ($A_{2/1}$ or $M_{2/1}$). The ground electrode is commonly placed on the nasion or high forehead (F_{PZ}). This recording montage yields a negative polarity AP.

Occasionally, clinicians may prefer to record both the ECochG and ABR simultaneously using a multichannel evoked potential system. This can be achieved with as little as four electrodes. In addition to using the three electrode sites described above, a fourth vertex (C_Z) electrode is required. If a three-channel evoked potential system is employed, an ipsilateral ($C_Z - A_{1/2}$) and contralateral ($C_Z - A_{2/1}$) montage ABR may be recorded along with a horizontal montage ECochG ($A_{1/2} - A_{2/1}$). "Jumper cables" are required to share electrode inputs between channels (i.e., C_Z, A_1, and A_2). If only two channels are available with the evoked potential system, ABR recordings can be made with the ipsilateral and contralateral electrode montages. A postrecording horizontal ECochG montage can be derived by the subtraction of the ipsilateral montage waveform from the contralateral montage recorded waveform. This subtraction process eliminates the contribution from the shared electrode (i.e., C_Z) yielding the ipsilateral and contralateral electrode recording from each montage. Mathematically, the subtraction process is as follows: $(C_Z + A_I) - (C_Z + A_C) = A_C - A_I$, where A_C and A_I represent the contralateral and ipsilateral electrodes, respectively. With the A_I for the ABR recording placed in the inverting input, one must be cognizant that the resultant subtraction renders a positive AP.

Electrode Impedance

Low electrode impedances are a prerequisite for quality ECochG recording. Electrode impedances should be tested prior to recording and during the testing if one suspects movement of an electrode and/or impedance change. Balanced interelectrode impedance is also desired. Conventional guidelines suggest interelectrode impedances < 2,000 Ω. Electrode impedances vary according to electrode type. Impedances tend to be the highest with transtympanic electrodes and the lowest with extratympanic electrodes. TM electrode impedance falls between the two. Ruth and Lambert[45] reported mean electrode impedances of 75,000 and 25,000 Ω for transtympanic electrodes and TM electrodes, respectively. Commercially available Lilly TM-Wick electrodes can be maintained at or below 20,000 Ω. Tymptrode electrode impedances, however, can

range substantially (e.g., 10–100,000 Ω).[7] TIPtrode electrodes can easily be applied with impedances < 5,000 Ω.

Amplification

Amplification of ECochG responses depends on the size of the response—typically dictated by the recording electrode/site. That is, more gain is required for low-amplitude responses and vice versa less gain is required for high-amplitude responses. Amplification of 50,000 to 100,000 times is generally required for extratympanic recordings owing to the small amplitude of the response (~0.5 µV for the TIPtrode electrode).[40,44] Similar amplification is suitable for TM recordings even with amplitudes of the ECochG response an order of magnitude larger (≤ 5 µV).[40,44,45] With transtympanic recording, ECochG amplitudes exceed 20 µV.[40,45] Amplifier gain for these recordings can be significantly reduced in the order of 5,000 to 25,000 times.

Filtering Bandwidth and Artifact Rejection

Bandpass filtering is essential for all auditory evoked recordings and the ECochG is no exception. Adequate high- and low-pass knee points are critical for recording the ECochG response and eliminating extraneous noise. As noted above, the SP is a direct current potential and as such is best recorded with minimal or no high-pass filtering. In fact, even a high-pass knee point of 1 Hz may distort the SP.[40] For clinical recording of ECochG, a high-pass knee point of 5 to 20 Hz is recommended.[6,7] The CM will contain the spectra of the evoking stimulus. Low-pass filtering should therefore be wide enough to include these spectra. The predominant spectral ECochG energy is below 2,000 Hz in both normal and abnormal ears.[43] A low-pass filter knee point of 3,000 Hz is sufficient to record the ECochG spectra.

Employing automatic artifact rejection also eliminates extraneous noise from ECochG recording.[46] Electrical signals recorded by the electrodes exceeding a chosen predetermined voltage are rejected and not included in the signal averaging. This process effectively removes high-voltage extraneous electrical signals from the averaging process, thus improving signal-to-noise ratio. While there is no consensus in the literature, artifact rejection levels are similar to those utilized in ABR recording. Electroencephalogram samples exceeding ±10 to 25 µV are commonly employed.

Time Epoch

The ECochG time epoch for recording must be sufficiently long enough to capture the response. A recording window of 5 milliseconds is adequate for ECochG evoked with transient stimuli. If one is interested in simultaneously recording the ABR, the analysis time epoch can be increased to 10 milliseconds. Most commercial evoked potential systems sample at 256 or 512 points giving adequate temporal resolution to express the ECochG waveform. If one is interested in examining the cochlear potentials with longer-duration stimuli (e.g., tone bursts), the analysis window needs to be of sufficient duration to capture the entire response. Consider evoking a response with a 10-millisecond 1,000-Hz tone burst (i.e., 2-millisecond rise/fall with a 6-millisecond plateau)—a 15-millisecond time epoch would be adequate.

Replications/Sweeps

A number of factors come into consideration when selecting the number of stimulus presentations including the type of recording electrode and the patient's degree of hearing impairment. The goal is to obtain an adequate signal-to-noise ratio during averaging to observe the ECochG response. With hearing-impaired listeners, a greater number of stimulus presentations may be necessary to observe a response. Fewer stimulus presentations are needed for the more robust response recorded with a transtympanic electrode. More presentations are needed for the small extratympanic electrode recordings (i.e., TM and TIPtrode electrodes). For transtympanic electrode recordings, 100 to 200 repetitions are recommended.[40] For extratympanic tymptrode recordings, 1,000 to 2,000 repetitions are recommended.[40] If one is simultaneously recording an ABR, objective measures of response detection (i.e., residual noise floor calculation and/or F_{sp} statistical response presence calculation) may be employed and recordings may be halted with a fewer number of sweeps. All ECochG responses should be replicated at least twice.

Transducer

Unless contraindicated, an insert earphone is the transducer of choice. The insert earphone offers numerous advantages over the traditional supra-aural earphone for all evoked potential recordings, including the ECochG. Advantages for ECochG include increased patient comfort, aural hygiene, coupling with the TIPtrode electrode, reduced stimulus artifact, and reduced transducer ringing with transient stimuli.[46] Supra-aural earphones,[47] insert earphones,[41,42] and sound field speakers[17,30] have been used with transtympanic electrode recordings.

5.3.6 Stimulus Parameters

Many combinations and permutations of stimulus parameters are possible. The choice of stimulus type and stimulus characteristics depends on the purpose of the ECochG recording. As noted above, common applications for ECochG include diagnosing, assessment, and monitoring of inner ear disease including Ménière's disease, enhancement of wave I of the ABR, monitoring of auditory nerve function during surgery, diagnosis of auditory neuropathy/dyssynchrony, and evaluation of noise overexposure. Different stimuli and specific parameters are more appropriate for each specific application of the ECochG recording. A summary of the suggested clinical ECochG stimulus parameters is found in ▶ Table 5.2.

Type

The most common stimulus used to elicit the ECochG is the click. The click is a broadband stimulus generated by applying a transient rectangular voltage pulse to a transducer. The onset of a click is instantaneous promoting broad cochlear excitation and synchronous auditory nerve discharge, which are critical for robust AP recording. However, the brevity of a click stimulus may be problematic, for examining cochlear potentials. Tone bursts are also effective if frequency specificity is desired. Tone bursts with abrupt onsets and short durations are effective in evoking clear APs. Longer-duration tone bursts can be

Table 5.2 Suggested clinical electrocochleography (ECochG) stimulus parameters

Parameter	Suggestion
Type	Click and tone burst (1,000 Hz)
Duration	Click: 100 microseconds Short tone burst (5 cycles): 2 cycle rise (2 ms)/fall and 1 cycle (1 ms) plateau Long tone burst (10–15 cycles): 2 cycle rise (2 ms)/fall and 6–11 cycle (6–11 ms) plateau
Intensity	75–90 dB nHL
Polarity	Alternating, condensation, and rarefaction
Rate	< 10/s
Masking	None

effective in examining the CM and SP. There is also evidence that 1,000-Hz tone bursts have higher diagnostic sensitivity and specificity in identifying Ménière's disease when compared to the click stimulus.[48,49]

Duration

The typical ECochG duration configurations for stimulus include transient clicks, "short" tone bursts, and "long" tone bursts. The most common duration of a click stimulus is 100 microseconds. The first spectral zero for a click of this duration occurs at 10,000 Hz (i.e., the inverse of its duration). The spectra of a click transduced by an insert earphone are essentially flat across the frequency response output. Short tone bursts are typically 4 to 5 cycles in duration, while long tone bursts are typically 10 to 15 cycles in duration. Both long and short tone bursts normally have two cycle rise/fall characteristics. The abrupt onsets of the stimuli are desired to evoke the AP. Higher-frequency tone bursts are more effective in evoking APs, since the duration of their two cycle rise is shorter in duration than lower-frequency tone bursts. Longer-duration tone bursts are more desirable for recording cochlear potentials. Recall that the CM and SP approximately follow the acoustic stimulus waveform. The brevity of the clicks and short tone bursts makes it more difficult to see CMs in some listeners.[44] A longer-duration tone burst with a stable plateau facilitates a more accurate visualization of the CM and SP.[50,51,52]

Intensity

The effect of intensity on ECochG components has been known for decades. Both the CM and SP display a saturating nonlinearity in their input–output functions with increasing stimulus intensity.[53,54,55] That is, CM and SP amplitudes increase linearly from low to moderate intensities and then saturate at higher stimulus intensities with little or no further growth in amplitude. Few studies have examined the effect of stimulus intensity on the CM and SP in humans. Zhang[52] examined the effect of low-frequency tone burst stimulus intensity on the CM in normal-hearing adults. A 500-Hz tone burst with a duration of 14 milliseconds (2-millisecond rise/fall time with a 10-milliseconds plateau) was the evoking stimulus. The tone burst was presented at intensity levels of 10, 20, 30, 40, 60, and 80 dB nHL. As expected, the growth function evidenced a saturating nonlinearity—with saturation occurring above 40 dB nHL. When the stimulus intensity is held constant (e.g., 75 dB nHL), the amplitude of CM decreases with an increasing stimulus frequency (i.e., 500, 1,000, 2,000, and 6,000 Hz) of long-duration tone bursts.[51] Ferraro et al[50] similarly observed the decrease of SP amplitudes with increasing long-duration tone burst stimulus frequency (i.e., 500, 1,000, 2,000, and 4,000 Hz), when the evoking intensity level remained constant (i.e., 90 dB nHL). The click evoked SP is first detected at approximately 95 dB peSPL (65 dB nHL).[33,56]

The effect of stimulus intensity on N_1 of the AP is also well documented. Decreasing stimulus (i.e., click or tone burst) intensity decreases N_1 amplitude and increases N_1 latency.[12,33,56] Eventually the AP disappears at low intensity levels. The AP can be detected as low as 10 to 20 dB nHL when recorded transtympanically.[57,58] The intensity input/amplitude output function has two components.[57] At low intensities, growth is shallow up until 50 dB nHL. At higher intensity levels, the function becomes much steeper. The amplitude growth slope is approximately 0.05/10 to 40 dB SL. Above 50 dB nHL, the amplitude growth slope is approximately 0.20/10 dB. AP latency shifts are greater at lower intensity levels (i.e., < 50 dB nHL). As intensities increase, latency shifts become much smaller with higher intensities.

ECochG is typically recorded at high stimulus levels (i.e., ≥ 75 dB nHL), unless one is interested in establishing thresholds. At high intensities, CM and SP compounds are saturated and at maximum amplitudes. Likewise, the AP is robust and easily observed. The suggested starting level for ECochG is 90 dB nHL.[6,7]

Polarity

Polarity is of major importance for evoking the ECochG. Since the CM is an alternating current voltage, it must be recorded with a single polarity stimulus (condensation or rarefaction). Reversing the polarity of the stimulus results in an approximately 180-degree shift in phase of the response. Alternating the stimulus polarity cancels out the CM. This is desired when the CM needs to be eliminated, such as in the case that its persistence is obscuring the AP, or when the SP response is wanted. Alternating polarity stimulus is therefore required when SP and AP measures are warranted. Subtracting ECochG responses acquired with condensation and rarefaction enhances the CM.[59] An example of an ECochG recording to a long tone burst with condensation and rarefaction polarity is shown in ▶ Fig. 5.2.

Several researchers have demonstrated the increased diagnostic sensitivity of using condensation and rarefaction clicks in the identification of Ménière's disease.[60,61,62,63] In normal ears, the AP latency is approximately 0.1 milliseconds shorter for moderate to high intensity level rarefaction polarity stimuli compared to the AP evoked with condensation polarity stimuli. In patients with Ménière's disease, this latency difference is amplified. The comparison of AP latency differences evoked by stimuli with two polarities, in addition to an examination of SP and AP components, increases the sensitivity and specificity of ECochG in detecting Ménière's disease. Clinical strategy should employ an examination of ECochG responses to condensation and rarefaction stimuli.

Most commercially available clinical evoked potential systems permit the presentation of alternating polarity signals,

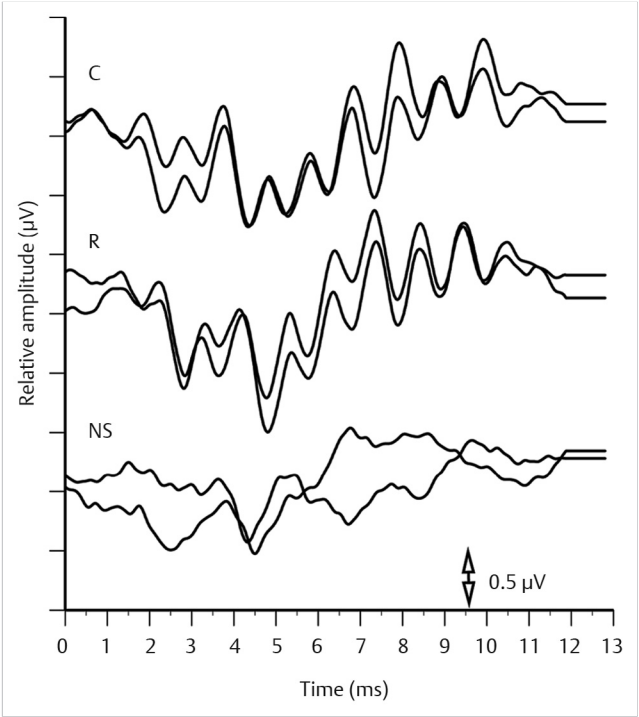

Fig. 5.2 Electrocochleograms (ECochGs) were evoked with condensation (C) and rarefaction (R) 1,000-Hz tonal stimuli presented at 90 dB nHL at a rate of 7.7/s. The tonal stimuli had a linear rise/fall time of 2 milliseconds with a plateau of 5 milliseconds. Extratympanic ear canal electrodes (TIPtrode) were utilized with an ipsilateral/noninverting–contralateral/inverting montage with the ground electrode on the high forehead (F_{PZ}). Confirmation that the recording was cochlear in origin is seen in the bottom tracing where the insert tubing was disconnected from the transducer, which remained in place, and no acoustic stimuli (NS) were delivered to the ears. Reversal of the cochlear microphonic is evidenced with stimulus polarity reversal.

with ongoing subaveraging of condensation and rarefaction responses during ECochG acquisition. This permits separate storage and allows posttesting retrieval of the responses generated by each stimulus polarity. It is therefore possible to analyze the CM and AP ECochG components for the rarefaction and condensation polarity stimuli. In addition, the SP and AP ECochG components can be analyzed with an alternating polarity stimulus. An increase in the number of alternating stimulus presentations may be advised to ensure adequate subaverages of condensation and rarefaction responses.

Rate

Stimulus rate is another parameter of interest in ECochG recording. Ferraro and colleagues[1,6,7,64] and others[60] have recommended a slow rate of stimulation (i.e., 8.7–11.3/s). Some[59,65,66,67,68] have suggested recording with a fast rate of stimulation (i.e., ≥ 90/s) in addition to a slow rate. Those that have argued for a fast stimulus rate offer the rationale that a faster stimulus rate fatigues the AP allowing for better visualization of the SP. Ferraro and Durrant[64] noted:

…unfortunately, the use of such fast rates has not proven to be very successful in the clinic, in part because the AP contribution is not completely eliminated and the SP may also be reduced under extreme conditions (e.g., click rates greater than 90/sec)…. [and] rapid clicks presented at loud levels tend to be very annoying for patients.

In a recent study, Lake and Stuart[44] evaluated both fast and slow (i.e., 7.7 and 77.7/s) presentation rates with a click stimulus. While the fast rate resulted in an increase in SP amplitude, it reduced the expression of AP and SP components in some listeners. Approximately 10% of AP and SP responses were lost using a tympanic electrode recording. Extratympanic ECochG recording evidenced a 40 to 50% loss of SP and AP responses.

The choice of stimulus rate depends on the ECochG test strategy. The CM and SP ECochG components are comparatively steady over a broad range of stimulus rates.[68] On the other hand, the AP component evidences reduced amplitude and increased latency with increasing rates. In contrast, latency of the AP component increases and amplitude decreases as stimulus rate increases.[69] When stimulus rates approach 100/s, the AP is minimal and detection of the SP is enhanced as amplitude increases, albeit some listeners' responses are unable to be detected.[44] Therefore, if one is interested in recording the AP, a slow rate of stimulus presentation is advised. If only the cochlear potentials (CM and SP) are of interest, fast stimulus rates can be tolerated and test time can be reduced.

Masking

Contralateral masking of the nontest ear is not warranted in a typical ECochG recording for several reasons. While stimulus intensity may be high (e.g., 90 dB nHL), the use of insert earphones offers good interaural attenuation. Any stimulus that may crossover would not be of sufficient intensity to generate an electrophysiological response of any magnitude from the nontest ear. Further, the ECochG is generated by the test ear and before any contralateral crossover in the ascending auditory pathway.

Special Consideration

The referral source and/or suspected pathology of the patient will drive the choice of stimulus and acquisition parameters. For example, a patient suspected with Ménière's disease is best assessed with click and short-duration tone bursts with both condensation and rarefaction stimuli to examine the SP and AP components. On the other hand, a patient suspected with auditory neuropathy/dyssynchrony could be assessed with long-duration tone bursts of singular polarity to examine the CM.

5.4 Electrocochleogram Analyses

An analysis of the electrocochleogram first begins with identification of the ECochG response components of interest. As noted above, acquisition and stimulus parameters will dictate the best expression of ECochG components that the tester is interested in obtaining. ECochG response morphology is decidedly dependent on a variety of acquisition and stimulus parameters discussed above. For example, the CM is generated with a single

polarity stimulus. The SP is expressed with an alternating polarity stimulus, since the CM is cancelled during averaging. The time period for the expression of the ECochG depends on the duration of the stimulus. For example, the CM, SP, and AP components will be seen in the first several milliseconds from poststimulus onset for transient stimuli with a rapid onset (i.e., clicks and tone bursts). For longer-duration stimuli (e.g., a 10- to 15-millisecond tone burst), the CM and SP will be seen during the entirety of the duration of the acoustic signal. The AP, as an onset response, will always be seen within the first few milliseconds shortly after stimulus onset.

Pitfall

One must confirm that a CM recording is cochlear in origin. Failure to do so may lead to a diagnostic error. Confirmation is demonstrated by removing the acoustic stimulus (i.e., by clamping the insert earphone tube or disconnecting it) while leaving the insert transducer in place. Recording under these conditions should eliminate the CM and thereby differentiate a cochlear response from transducer artifact.

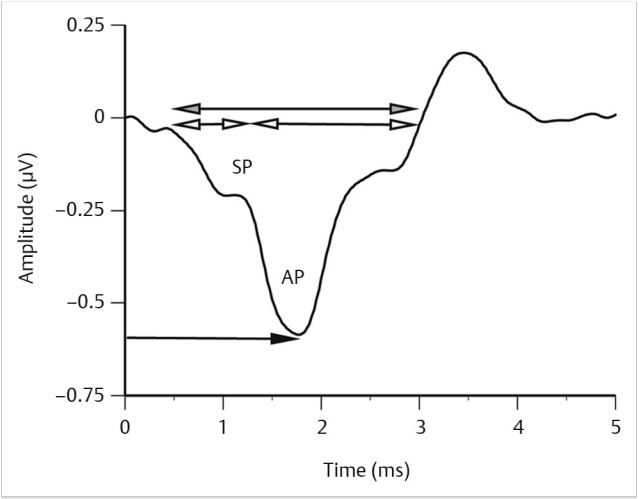

Fig. 5.3 Electrocochleogram latency analyses: action potential (AP) absolute latency is calculated from the stimulus onset to the AP peak (*solid arrow*). Summating potential (SP) and AP durations are illustrated with a *double-sided white arrow*. Total SP/AP duration is illustrated with a *double-sided gray arrow*.

The bases of ECochG analyses are examinations of response component latency and amplitude—as is common to all auditory evoked potentials. It is extremely important to have operational definitions for all ECochG latency and amplitude components for the particular recorded stimulus and acquisition parameters. This is specifically important when comparing acquired responses to normative data within and across clinics/laboratories. Commercially available evoked potential systems allow for ECochG component labeling and the calculation of latency and amplitude values for identified components. Some system's software also allows for more advanced calculations (e.g., area under the curve and spectral analysis). The astute clinicians and students are advised to thoroughly read their evoked potential system manual to completely understand and take advantage of the capabilities of their system.

Once ECochG indices are extracted from the electrocochleogram, they can be compared to normative data generated by one's individual clinic normative data, or compared to values in published reports of normative data.[44,70] In the case of the later, it is important only to compare data that have been gathered under the same acquisition and stimulus parameters. In the cases where pathology is suspected in one ear, comparison of ECochG indices between ears can be invaluable for final diagnosis.[71] ECochG test results should also be cross-checked with other diagnostic results.[72]

5.4.1 Latency

Calculation of the absolute response latency of an auditory evoked response is a fundamental first step following response identification. Absolute latency is calculated from the stimulus onset. When the ECochG is obtained with an insert earphone, the nominal traveling time from the transducer through the insert tube (e.g., 0.8–0.9 milliseconds) is subtracted from the response latency. When stimuli are presented in sound field, absolute latency is defined from the relative onset of the CM.[30,58] The most common ECochG latency measure is AP/N_1 absolute latency. Calculation of the AP latency is illustrated in ▶ Fig. 5.3. The AP is typically identified as the first negative going peak after 1 millisecond.[73] The AP absolute latency with a high presentation level and slow rate is typically in the range of 1.5 to 1.75 milliseconds.

Less common are measures of ECochG duration or width of response. SP and AP durations in isolation or combination have been reported.[30,58,73,74] SP duration has been defined from the onset of the initial negative deflection of the SP to the leading edge of the AP, as illustrated in ▶ Fig. 5.3. The SP/AP duration is defined from the onset of the initial negative deflection of the SP to when the AP returns to baseline, as illustrated in ▶ Fig. 5.3. A straight line is projected from the preceding response baseline past the AP response for this calculation.

5.4.2 Amplitude

Absolute amplitude measures may be calculated in two ways: peak-to-peak or using baseline-to-peak as illustrated in ▶ Fig. 5.4. Baseline-to-peak amplitude measures render larger values. Peak-to-peak absolute values are typically preferred, as it is often difficult to determine the point preceding the response to label as the baseline value. SP and AP absolute amplitudes are first determined. In the cases where long-duration tone bursts are used to examine the SP, the amplitude of the response is measured at the midpoint of the response. This practice minimizes the influence of the AP relative to baseline amplitude.

Once response identification and absolute amplitude are determined, additional calculations can be undertaken. These indices are of diagnostic value particularly with Ménière's disease. The first is the SP/AP amplitude ratio. The SP/AP amplitude ratios to click stimuli occur within a relatively small range (i.e., 0.16–0.31) despite the use of different recording approaches.[75] Area under the curve or more commonly called "area" calculations are also utilized. This measurement involves

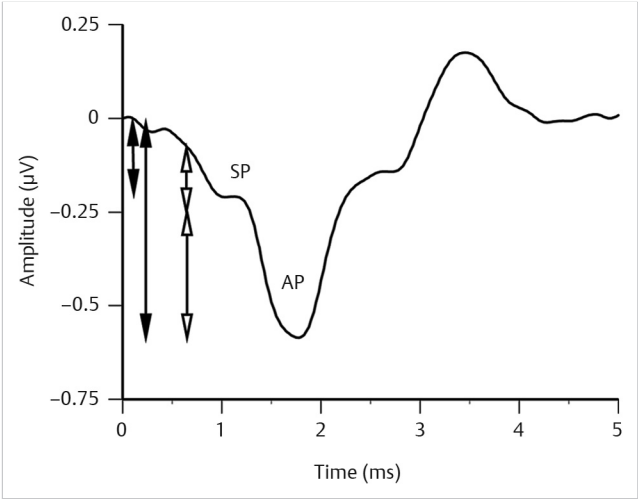

Fig. 5.4 Electrocochleogram amplitude analyses: *double-sided black and white arrows* illustrate baseline-to-peak and peak-to-peak amplitude measures, respectively. *Short and long arrows* illustrate summating potential (SP) and action potential (AP) responses, respectively.

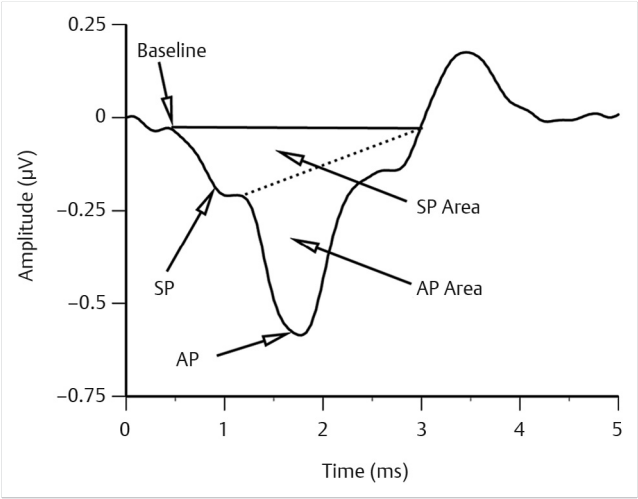

Fig. 5.5 Electrocochleogram (ECochG) area analyses: illustrated ECochG area calculations as performed by the Intelligent Hearing Systems SmartEP (Version 3.98) evoked potential system. Identified components of interest include baseline, summating potential (SP), action potential (AP), SP area, and AP area.

the calculation of the amplitude voltage across the duration of the response. This function is becoming more available for clinicians through commercially available evoked potential system software. Area calculations are illustrated in ▶ Fig. 5.5. The calculation involves determining the total area of the SP and AP and dividing it by the area of the AP to derive the SP/AP area ratio. The SP/AP area index is of diagnostic value in the evaluation of Ménière's disease.[73,76]

5.4.3 Spectra

Power spectrum analysis determines the spectral energy in the ECochG. That is, a picture of the magnitude of the frequency components of the ECochG. Power spectra are generally generated through fast Fourier transform analysis of the ECochG amplitude/time waveform. Spectral analysis of the ECochG has received little attention in the literature. This is surprising considering it may be of diagnostic value in Ménière's disease. The peak power spectrum in patients with Ménière's disease has been reported to be significantly lower than that found in asymptomatic normal-hearing individuals.[43,77] Power spectrum analysis is available with several commercially available evoked potential systems (e.g., Intelligent Hearing Systems SmartEP and Interacoustics Eclipse).

Electrocochleogram Reliability

One important question for clinicians is: "Are ECochG measures reliable?" Several studies have reported the test–retest variability of ECochG. Bergholtz et al[78] examined the test–retest reliability using a transtympanic electrode placement. Eighty-four test comparisons were made between ECochG tests acquired from 40 patients with varying degrees of hearing loss. They reported statistically significant correlations for test–retest AP latencies ($r = 0.98$; $p < 0.001$) and amplitudes ($r = 0.78$; $p < 0.001$). Densert et al[66] also examined the reproducibility of transtympanic recorded SP and AP indices in 17 normal-hearing subjects and 26 patients with Ménière's disease. Responses were evoked to clicks and long tone bursts. Intratest (i.e., recorded repeated measures within the same test) and intertest reliability (i.e., retest after replacement of all electrodes) were examined. Intratest reproducibility was good for all parameters. Intertest indices exhibited larger variability and more so with long tone bursts.

Mori et al[79] investigated four normal-hearing and seven hearing-impaired listeners utilizing an extratympanic silver ball electrode placed on the posterosuperior auditory canal wall within 3 mm of the TM. The test and retest interval ranged from 10 days to 2 years and 5 months. They reported excellent correlations between test and retest: AP latency ($r = 0.99$; $p < -0.001$), AP amplitude ($r = 0.93$; $p < 0.001$), SP amplitude ($r = 0.96$; $p < 0.001$), and SP/AP amplitude ratio ($r = 0.94$; $p < 0.001$).

Park and Ferraro[80] examined the test–retest reliability with a tymptrode electrode. They examined the SP/AP amplitude ratio over six sessions with 2- to 14-day intervals from the same subjects. Their calculated measures of variability were overall range, overall average standard deviation, and mean average difference. They found no significant differences in examiner measures between the first three and last three recording sessions. McClaskey et al[81] examined the reliability of the AP recorded with a TM electrode placement. They recorded click evoked APs in 24 younger and 20 older adults. Peak amplitudes were estimated from peak-to-peak measurements and baseline-corrected measurements. They found both peak-to-peak and baseline-corrected measurements of AP amplitude had "good to excellent reliability" evidenced by intraclass correlation coefficient values > 0.60.

Roland et al[82] evaluated the reliability of ECochG recordings with the TIPtrode electrode. They examined 17 normal-hearing adults repeatedly over 1-week periods averaging 5.3 weeks. Click stimuli were presented at 95 dB nHL at a rate of 9.7/s. Averages and standard deviations of the SP and AP amplitudes were measured and the SP/AP amplitude ratios were calculated.

Roland et al[82] reported an average SP/AP amplitude ratio of 0.22 with a standard deviation of 0.06. Recently, Lake and Stuart[44] examined the test–retest reliability of both extratympanic (TIPtrode) and tympanic (Lilly TM-Wick) electrode on five ECochG indices (i.e., SP amplitude, AP latency, AP amplitude, SP/AP amplitude ratio, and SP/AP area ratio) with 18 normal-hearing young adults. Statistically significant correlations ($p < 0.05$) were found between initial tests and retests with all ECochG indices for both electrodes, with the exception of SP amplitude using TIPtrode electrode. There were also no significant main effects of test (i.e., initial vs. retest) or interactions of test and electrode or rate for any of the ECochG indices ($p > 0.05$). As expected, recordings with the Lilly TM-Wick electrode produced larger SP amplitudes, AP amplitudes, and SP/AP area ratios when compared to the TIPtrode electrodes. In addition, SP and AP responses were more likely to be present with the tympanic electrode. Lake and Stuart[44] concluded that there was no difference between electrodes in regard to test–retest measures. However, considering the higher likelihood of ECochG SP and AP responses and larger SP amplitude, SP/AP amplitude ratio, and SP/AP area ratio indices, the tympanic electrode placement is recommended for clinical practice.

5.5 Conclusion

Although the ECochG is the oldest auditory evoked potential, being first reported in 1930, its popularity remains today. It is a valuable tool in the diagnosis, assessment, and monitoring of inner ear disorders and the auditory nerve. The most common clinical applications for ECochG include assessing Ménière's disease, auditory neuropathy/dyssynchrony, measurement and monitoring of auditory nerve function during surgery, and the evaluation of noise overexposure cochlear synaptopathy. For wider clinical acceptance and adoption of ECochG, Ferraro and colleagues'[6,7] call for the standardization of ECochG recording and measurement protocols is strongly endorsed. It is also suggested that audiology training programs adopt such standards and train their students accordingly. Training should include instruction and clinical practice with the use of otoscopic/otomicroscopes for visualization of the external auditory canal and TM, and for confirmation of tympanic electrode placement against the TM. Ultimately, patient comfort, as well as consistent and reliable clinical ECochG recordings, will be assured with proper instruction and clinical training of students.

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