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Electrocochleography in the Evaluation of Patients with Ménière's Disease/ Endolymphatic Hydrops

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Abstract

Electrocochleography (ECochG) has evolved as an important tool in the diagnosis/assessment/monitoring of Ménière's disease/endolymphatic hydrops (MD/ELH). This manuscript provides an update on the use of ECochG for these purposes. The material presented includes descriptions of the components of the electrocochleogram; ECochG recording approaches and parameters; how to prepare for an exam, including subject/patient considerations; construction and placement of a tympanic membrane recording electrode; and interpretation the electrocochleogram. Various approaches aimed at improving ECochG's sensitivity and specificity to MD/ELH also are described. These approaches go beyond simple measurement of the now-conventional summating potential (SP)/action potential (AP) magnitude ratio to include the SP magnitude to tonebursts, the SP/AP area ratio, and the AP latency difference to clicks of opposing polarity.

Key Words: Action potential, auditory brainstem response, auditory evoked potentials, broadband click, cochlear microphonic, electrocochleography, extratympanic, Ménière's disease/endolymphatic hydrops, summating potential, toneburst, transtympanic, tympanic membrane, tymptrode

Abbreviations: ABR = auditory brainstem response; AC = alternating current; AP = action potential; AEP = auditory evoked potential; BBC = broadband click; CM = cochlear microphonic; ECochG = electrocochleography; ET = extratympanic; MD/ELH = Ménière's disease/endolymphatic hydrops; SP = summating potential; TM = tympanic membrane; TT = transtympanic

Sumario

La electrococleografía (ECochG) ha evolucionado como una importante herramienta en el diagnóstico, evaluación y monitoreo de la enfermedad de Ménière-hydrops endolinfático (MD/HEL). Este manuscrito aporta una actualización en el uso de la ECochG para estos propósitos. El material presentado incluye descripción de los componentes del electrococleograma; parámetros y enfoques de registro del ECochG; cómo prepararse para un examen, incluyendo consideraciones para el sujeto/paciente; construcción y colocación de un electrodo de registro en la membrana timpánica, e interpretación del electrococleograma. Se describen también varios enfoques orientados a mejorar la sensibilidad y la especificidad de la ECochG en la MD/HEL. Estos enfoques van más allá de la simple medición de la convencional tasa de magnitud del potencia de suma (SP)/potencial de acción (AP), e incluyen la magnitud del SP para bursts tonales, la tasa de área de SP/AP y la diferencia de latencia del AP a clics de polaridad opuesta.

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Palabras Clave: Potencial de acción, respuesta del tallo cerebral, potenciales evocados auditivos, clic de banda ancha, microfónica coclear, electrococleografía, extra-timpánico, enfermedad de Ménière/hydrops endolinfático, potencial de suma, burst tonal, trans-timpánico, membrana timpánica, electrodo para-timpánico

Abreviaturas: ABR = respuesta auditiva del tallo cerebral; AC = corriente alterna; AP = potencial de acción; AEP = potencial evocado auditivo; BBC = clic de banda ancha, CM = microfónica coclear; ECochG = electrococleografía; ET = extra-timpánico; MD/ELH = enfermedad de Ménière/hydrops endolinfático; SP = potencial de suma; TM = membrana timpánica; TT = trans-timpánico

As the term implies, "Electrocochleography" (ECochG) is a technique for recording the electrical events of the cochlea. The clinical application of ECochG, however, is confined to the stimulus-related cochlear potentials and often includes measurement of the whole nerve or compound action potential (AP) of the auditory nerve. As shown in Figure 1, an "electrocochleogram" may comprise the cochlear microphonic (CM), cochlear summating potential (SP), and AP, recorded independently or in various combinations. Although the tracings in this figure were recorded in response to broadband clicks, tonal stimuli also are commonly used to evoke the components of interest.

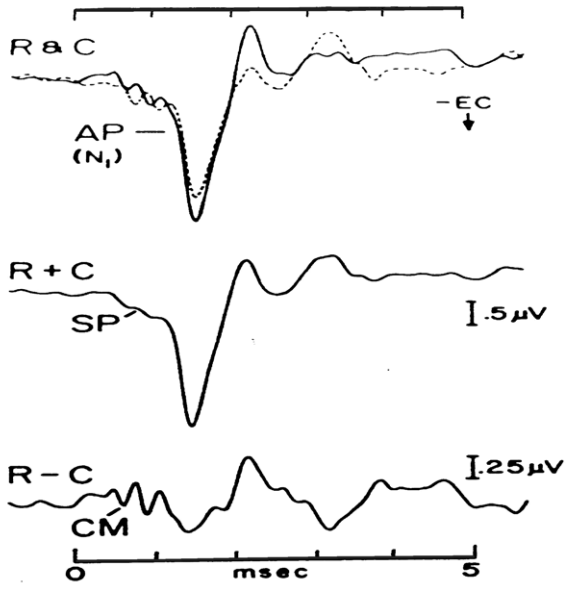

Figure 1. Electrocochleograms evoked by broad-band click stimuli. Top tracings show responses to rar-efaction (R) and condensation (C) polarity clicks. Adding R and C responses (middle tracing) enhances the Summating Potential (SP) and auditory nerve Action Potential (AP), which are not phase-locked to the stimulus. Subtracting R and C responses (bottom tracing) enhances the Cochlear Microphonic (CM) (from American Speech-Language-Hearing Association, 1988, p. 9, based on data from Coats, 1981).

ECochG emerged as a clinical tool in the 1970s, even though attempts to record the CM from humans date back almost to the time of its discovery in the cat by Wever and Bray (1930) (e.g., Fromm et al, 1935; Andreev et al, 1939; Perlman and Case, 1941; Lempert et al, 1947; Lempert et al, 1950). The SP was described in animals in 1950 (Davis et al, 1950; von Bekesy, 1950) but received little to no attention in humans until much later (e.g., Eggermont, 1976; Gibson et al, 1977; Gibson, 1978). The first recordings of human auditory nerve APs are credited to Ruben and his colleagues (1960), who performed their measurements on patients undergoing otologic surgery.

Increased attention to all auditory evoked potentials (AEPs) began to occur in the early 1970s, following the discovery and clinical application of the auditory brainstem response (ABR). The development and refinement of noninvasive recording techniques also facilitated the clinical application of AEPs, including ECochG.

The technical capability to record cochlear and auditory nerve potentials in humans has led to a variety of clinical applications for ECochG, chief among them being a tool in the diagnosis/assessment/ monitoring of Ménière's disease/ endolymphatic hydrops

(MD/ELH) and the assessment/monitoring of treatment strategies for these disorders. The material for this article has been organized to include brief descriptions of the salient features of the components of an electrocochleogram, and how ECochG is recorded, interpreted and used clinically, especially with reference to the above application. Much of this information is derived from recent chapters by the authors on ECochG (Ferraro, 2000; Ferraro and Durrant, 2002), and the reader is referred to these chapters for supplemental reading in this area.

ECochG COMPONENTS

Detailed descriptions of the CM, SP, and AP are abundant in the hearing science literature and beyond the scope of this article. However, be assured that the practice of performing ECochG should not be attempted without a thorough and working knowledge of auditory electrophysiology. The following section summarizes the salient features of the CM, SP, and AP, especially as related to clinical ECochG.

CM

The CM is an alternating current (AC) voltage that reflects the instantaneous displacement of the basilar membrane along some distance within the cochlea (Ferraro and Durrant, 2002). This distance is defined by the effective site and method of the recording, and the conditions of the stimulus. As reflected by the CM, the organ of Corti acts (in a limited way) as a microphone, but here the tranducers are numerous as each hair cell produces a receptor potential that is substantially AC (but not exclusively; see section on SP below). In animals, the CM is perhaps the most thoroughly investigated electrical potential of the inner ear, but it certainly remains to be fully understood. The historical popularity of the CM in the laboratory derives from its link to cochlear transduction, from well-demonstrated sensitivity to the health of the cochlear partition, and, certainly, because it can be recorded from within or near the cochlea. This latter factor is facilitated by the CM's considerable magnitude compared to other electrical phenomena associated with the auditory periphery. One would think that such features would render the CM an ideal tool for human clinical applications. In reality, however, the utility of the CM in differential diagnosis of inner ear versus auditory nerve disorders has yet to be established. Although reductions in CM magnitude have been reported for various disorders such as MD/ELH (Gibson and Beagley, 1976), these features tend to reflect general rather than specific cochlear pathology. Furthermore, examination of the CM with confidence that the recording represents the true potential remains challenging in the clinical setting. Since the CM mimics the waveform of the evoking signal (just as the voltage output of a microphone), it is difficult to separate from stimulus artifact.

SP

The SP is a complex response comprising several components. Like the CM, the SP is stimulus related, generated by the hair cells of the organ of Corti, and a reflection of the displacement-time pattern of the cochlear partition. However, whereas the CM mirrors the stimulus waveform (i.e., time history), the SP displays a rectified, direct current (DC) version of this pattern more representative of the stimulus envelope (Dallos, 1973). The SP appears as a unidirectional shift in the CM baseline, the polarity of which is dictated by an interactive effect between stimulus parameters (i.e., frequency and intensity) and the location of the recording electrode. When recorded from the tympanic membrane (TM) or ear canal, the SP is often seen as a downward (negative) deflection persisting for the duration of the acoustic stimulus (see Figure 1).

Because of its complexity, the role of the SP in hearing function remains unclear. As DC responses to AC stimuli, however, at least some of its components are thought to represent nonlinearities associated with the transduction processes in the cochlea (Tasaki et al, 1954; Whitfield and Ross, 1965; Davis, 1968; Engebretson and Eldridge, 1968; Dallos et al, 1972; Gulick et al, 1989; Ruth, 1994). Whether or not the SP actually reflected intracellular receptor potentials was uncertain for a period of time following its discovery. However, SP-like potentials have since been observed inside hair cells, and it is now clear and that the SP is not an epiphenomenon (e.g., Dallos, 1973). It also

has long been known that the SP is also sensitive to mechanical and electrical biasing (Durrant and Dallos, 1972; Durrant and Gans, 1977). The nonlinear nature of the SP has made it useful for monitoring certain clinical conditions such as MD/ELH, which may augment nonlinearities in the transduction process. This application will be discussed later.

AP

The AP recorded via ECochG represents the summed response of numerous, at times thousands of, auditory nerve fibers firing synchronously. When evoked by click stimuli, the term "whole nerve AP" is applied since, theoretically, the click has a nearly flat spectrum over the frequency range of interest and thus vibrates essentially the entire basilar membrane. As recorded clinically, however, and regardless of the stimulus, the AP is clearly a compound action potential—-the response of a population of neurons rather than a single unit. A stimulus with a narrower bandwidth, such as a toneburst, excites a more limited segment of the membrane and, consequently, a more restricted population of nerve fibers. Here, then, the term "whole-nerve" can be misleading. More important is the fact that these very different stimuli—clicks and tonebursts—fail to achieve their respective objectives. That is, the spectrum of the click that actually reaches the cochlea generally is far from flat, due to combined earphone, ear canal, and middle ear response characteristics. Likewise, the cochlear response to tonebursts is far from discrete, due to their spectra and limited cochlear resolution (Durrant, 1986). Thus, clicks do not excite the "whole" nerve, and even tonebursts excite several points of vibration along the basilar membrane.

A high degree of synchrony of neural firings is essential to producing a well-defined AP, which accounts for the popularity of click and brief/abrupt-onset tonebursts as evoking stimuli. In either case, however, the response to moderately intense stimulation (i.e., 70 dB nHL or more) tends to be dominated by neural contributions from the basal or high-frequency end of the cochlea (Kiang, 1965), at least in normal ears and pathological ears with no worse than moderate hearing loss. Since the velocity of the traveling wave is the highest in this region, phase shifts caused by cochlear mechanics are minimal.

The AP, like the CM, is an AC voltage. However, unlike either of the cochlear potentials whose waveforms reflect the displacement-time pattern of the cochlear partition (i.e., the CM and SP), the AP waveform is characterized by a series of brief, predominantly negative peaks representative of the distribution of underlying neural firings. At suprathreshold stimulus levels, the first and largest of these peaks is referred to as N1. N1 is virtually the same component as wave I of the ABR and, as such, arises from the distal portion of the auditory nerve (Moller and Janetta, 1983). AP peaks beyond N1 (such as N2 and N3) are analogous to corresponding ABR components (i.e., waves II and III) but have received little if any clinical attention in ECochG.

For clinical purposes, AP magnitude and latency appear to be the most useful features. The former is a reflection of the number of nerve fibers firing. Since the afferent fibers of the auditory nerve primarily innervate the inner hair cells (Spoendlin, 1966), AP magnitude also can be viewed as a reflection of inner hair cell output. AP latency , which is analogous to the "absolute latency" for ABR components, represents the time between stimulus onset and the peak of N1. This value incorporates stimulus travel time from the output of the transducer to the inner ear, traveling wave propagation time along the basilar membrane and time consumed activating synaptic transmission between hair cells and first order neurons. As with all waves of the ABR, reductions in signal intensity at suprathreshold levels for the AP are accompanied by absolute latency prolongations and reductions in N1 magnitude leading to eventual disappearance into the electrical noise floor.

Since its initial recording in humans in 1960, the AP has been the most widely studied product of ECochG. Early interest in the AP, however, was directed toward the development of an electrophysiological index of hearing status in children (Cullen et al., 1972). This effort was overshadowed by the ABR for such purposes, primarily because wave V of the ABR appeared to be more sensitive and easier to measure than the AP-N1. As AEP applications and technology have evolved over the years, the use of the AP to assess and monitor cochlear and auditory

nerve function has received renewed attention, especially in surgical settings. In addition, the use of a combined AP-ABR approach for assessing retrocochlear status in hard-of-hearing subjects is gaining popularity. Finally, an important application of the AP that will be discussed in more detail later in this paper involves the measurement of its magnitude in comparison to that of the SP in patients suspected of having MD/ELH.

ECochG RECORDING APPROACHES

Transtympanic versus Extratympanic ECochG

The terms "transtympanic" (TT) and "extratympanic" (ET) refer to the two general approaches for recording ECochG. TT ECochG is an invasive procedure that involves passing a needle electrode through the TM to rest on the cochlear promontory. A ball electrode on the round window can also be used when the middle ear space is exposed during surgery. TT approaches to ECochG were introduced in the late 1960s (e.g., Yoshie et al, 1967; Aran and LeBert, 1968) and are still used widely in countries other than the United States.

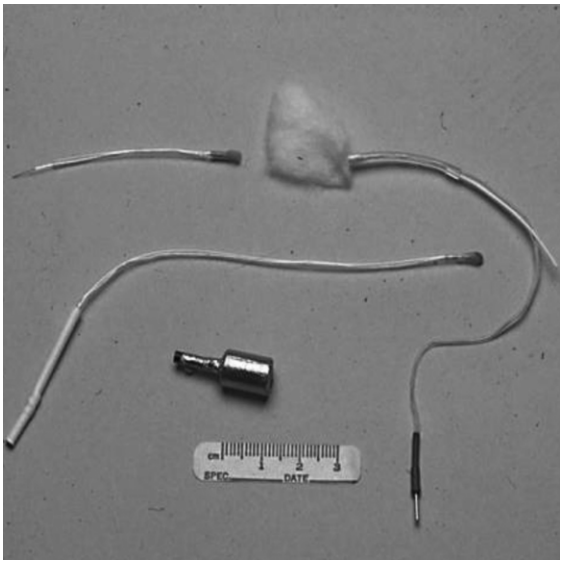

Figure 2. Photographs of extratympanic ECochG electrodes. Tymptrode (modified version of electrode described by Stypulkoswski and Staller [1987]) (top left), Lilly wick electrode (top right), and Bio-Logic ECochGtrode (middle) are placed at the surface of the tympanic membrane. Gold-foil TIPtrode (bottom) rests in the ear canal. From Ferraro (2000, p. 429).

ET recordings are performed with an electrode resting against the skin of the ear canal or surface of the TM. For the latter site, the procedure may be referred to as "tympanic (or TM) ECochG" (Ferraro and Ferguson, 1989), even though this approach is still considered to be ET. Pioneering work in ET recordings was performed by Sohmer and Feinmesser (1967), Coats and Dickey (1970), and Cullen et al (1972), among others. Although ET ECochG can be performed using a needle electrode in the skin of the ear canal, this option is rarely chosen. Therefore, virtually all ET recordings are noninvasive and, by virtue of this feature, have been better accepted in the United States than TT techniques. Examples of currently popular ET electrodes are shown in Figure 2.

Both TT and ET approaches to ECochG have advantages and disadvantages. The primary advantage of the TT approach is the close proximity of the recording electrode to the response generators, which produces components of large magnitude with relatively little signal averaging. The major limitations of TT ECochG relate to its invasiveness. Such procedures must be performed by or require the assistance of a physician and are therefore limited to a medical setting. In addition, penetrating the TM with a needle is painful to the patient, even when local anesthetics are used. These disadvantages certainly have limited the use of TT ECochG in the United States.

By comparison, ECochG responses recorded from ET sites require more signal averaging and tend to yield smaller component magnitudes than TT recordings. The biggest advantage of ET approaches, thus, is that they can be performed in nonmedical settings with minimal discomfort to the patient, obviating the need for sedation/local anesthesia—and a physician. Another factor that has facilitated the use of ET ECochG relates to advances in electrode design (discussed in following section) and the practice of using the TM as a recording site. The TM offers a good and practical compromise between ear canal and TT placements with respect to component magnitudes and, consequently, signal averaging time (Ruth and Lambert, 1989; Ferraro, Thedinger, et al, 1994; Ferraro, Blackwell, et al, 1994; Schoonhoven et al, 1995). Perhaps most importantly for clinical purposes, however, the waveform patterns

that lead to the interpretation of the TT electrocochleogram tend to be preserved in TM recordings (Ferraro, Thedinger, et al, 1994). When performed correctly, TM ECochG should cause minimal-to-no discomfort to the patient. However, the technique of placing an electrode on the highly sensitive TM can sometimes result in more patient discomfort than is customary for other, noninvasive ET approaches (but certainly not as much as is usually associated with TT ECochG).

Given the advantages and disadvantages of both approaches, the decision to perform ET or TT ECochG often depends on the traditional practices, personnel, and attitudes of the clinic. Obviously, TT recordings are dependent on the availability of a physician who has the time and interest to perform the examination. While a physician is not needed for ET ECochG, placing an electrode on the TM is certainly a more delicate maneuver than attaching surface electrodes to the scalp or resting them in the ear canal. With proper instruction and materials, however, this procedure is relatively easy to learn and well within the scope of professional practice for audiologists (American Speech-Language-Hearing Association, 1990).

Unfortunately, one factor that is virtually overlooked in the decision to perform TT or ET ECochG is the attitude/preference of the patient. Given the choice with an understanding of the benefits and limitations of each approach, which one would you choose if you were the patient?

ECochG RECORDING PARAMETERS

Selection of recording parameters for ECochG varies according to the components of interest. Since these components generally occur within a latency epoch of 5 msec following stimulus onset, they can be considered to be in the family of "early-latency" or "short-latency" AEPs (Picton et al, 1974). As members of the same family, ECochG components and the ABR can be recorded using similar parameters. A notable exception occurs in the selection of the bandpass of the preamplifier for ECochG when the SP is of interest. That is, the filter setting must be wide enough to accommodate both a quasi-steady-state DC component (the SP) and an AC component with a fundamental frequency of approximately 1 kHz (the AP). Other differences between ECochG and ABR recording parameters involve the electrode array and the number of samples to be averaged. For ECochG, the latter is dependent on the choice of recording approaches, with TT requiring considerably fewer repetitions than ET. Table 1 illustrates suitable ET (TM) protocol for recording the SP and AP together, which often is done when ECochG is used in the diagnosis of MD/ELH. A description of these parameters is provided below.

Table 1. Extratympanic (Tympanic) ECochG Recording Protocol

Electrode Array	
Primary (+)	Tympanic Membrane
Secondary (-)	Contralateral Mastoid or Earlobe
Common	Nasion
Recording Parameters	
Timebase	10 milliseconds
Amplification	50,000 X
Analog Filter Bandpass	5 Hz--3000 Hz
Repetitions	750--1000
Stimuli	
Type	Broadband Clicks (BBC), Tonebursts (TB)
Duration of Electrical Pulse (BBC)	100 microseconds
Frequency (TB)	1000 Hz, 2000 Hz
Envelope (TB)	2 millisecond linear rise/fall, 10 millisecond plateau
Polarity	Rarefaction, Condensation (BBC); Alternating (TB)
Repetition Rate	11.3/second
Beginning Level	80 dB nHL

Electrode Array

If your preference is an electrode array that displays the AP as a downward (negative) deflection. The primary electrode (i.e., the electrode connected to the +/noninverting input of the differential preamplifier) should rest on the TM. Sites for the secondary (-/inverting) electrode include the vertex of the scalp, high forehead, contralateral earlobe, or mastoid process. We prefer the earlobe or mastoid for the location of the secondary (-) electrode simply because electrodes tend to be easier to attach and secure to these sites. The nasion, ipsilateral earlobe, or ipsilateral mastoid may serve as sites for the electrode connected to the "common" or "ground" input to the preamplifier. If you prefer the AP to be displayed as an upward deflection (such as in the way conventional ABR components are displayed), simply reverse the + and - inputs to the preamplifier.

Timebase

As indicated above, ECochG components generally occur within the first few milliseconds after stimulus onset. For brief transient stimuli (such as clicks), we use a timebase (or signal averaging window) of 10 msec, which also allows for visualization of ABR components that follow N1. For longer duration stimuli (such as tonebursts), the timebase should extend beyond the duration of the stimulus envelope so that the entire response is observable within the averaging window (recalling that both the SP and CM persist for the duration of the stimulus).

Amplification Factor

Amplification factor is selected to maximize the signal-to-noise ratio for a given recording condition. The amount needed for suitable recordings of the SP and/or AP for ET measurements generally ranges between 20,000 and 100,000X, whereas the factor for TT recordings can be much lower (by 5 to 10 times). In part, selection of this parameter is based on the level of the electrical noise floor, which comprises several elements (i.e., myogenic and electroencephalographic activity, electrical artifact from the equipment and/or testing environment). The sensitivity setting of the computer's analog-to-digital converter also must be taken into account. Thus, amplification/sensitivity settings may vary from laboratory to laboratory and also among evoked potential units from different manufacturers. However, the manipulation of these variables to provide settings appropriate to recording conditions generally is easily accomplished. The goal here is to amplify enough to extract a good (and real) response without triggering the artifact rejection routine inordinately throughout the recording.

Analog Filter Settings

Adaptation notwithstanding, the SP, as fundamentally a DC potential, could last as long as the stimulus of any duration. Ideally, then, a DC recording amplifier is needed to record this component. However, particularly for the amount of gain needed, such amplifiers are notoriously unstable for electrophysiological recordings. Fortunately, the SP, as evoked for practical/clinical purposes, is only quasi-steady-state, permitting the use of the AC-coupled amplifiers typically found in commercially manufactured AEP units. Indeed, the click evokes a rather brief transient DC component that is readily recorded with low-pass cutoffs in the vicinity of 5–100 Hz, depending upon filter characteristics. Such recordings (i.e., using familiar ABR settings) can be accomplished without significant distortion of the SP-AP complex for purposes of measuring the SP/AP magnitude ratio (Durrant and Ferraro, 1991). However, when recording the SP to tonebursts, this approach creates a DC-step-like waveform, and, even if only quasi-steady-state, the waveform is likely to be significantly distorted unless the low-frequency cutoff of the amplifier is low (generally 10 Hz or below, depending on duration of the sound and the filter characteristics).

The low-pass (or high-frequency cutoff) setting of the filter should be set to allow transmission of the AC components of interest. In the case of the AP-N1, 3000 Hz is a suitable setting as the fundamental frequency of this component is approximately 1000 Hz. Filter settings for CM recordings would depend on the frequencies of the evoking stimuli (and thus the resultant responses).

Repetitions

The number of individual responses needed to extract a well-defined electrocochleogram from the background noise generally varies with recording conditions, and also the subject's degree of hearing loss. The former depends on the recording approach. That is, TT recordings require considerably fewer repetitions than ET approaches. More repetitions may be necessary for subjects with hearing loss than normally hearing subjects, especially if the loss is in the 1–4 kHz range. In our experience, when sensorineural hearing loss in these frequencies exceeds 50–60 dB HL, the use of ET ECochG in MD/ELH populations is questionable. The basis for this statement is that losses of this magnitude reduce the output of the population of hair cells contributing to the responses of interest and render them too small for reliable ET recordings. On the other hand, when hearing loss precludes the identification of wave I in the presence of wave V in the conventionally recorded ABR, ECochG can be very useful (Ferraro and Ferguson, 1989).

Stimuli

As mentioned earlier, the broadband click (BBC) is a popular stimulus for short-latency AEPs because it excites synchronous discharges from a large population of neurons to produce well-defined peaks in the response. In addition, 100 msec is a popular choice for the duration of the electrical pulse driving the transducer because the first spectral null for a click of this duration occurs at 10,000 Hz (i.e., 1/100 msec). In reality, the frequency range of the transducer is usually lower than 10,000 Hz and the acoustic signal receives additional filtering by the outer and middle ears. Thus, the spectrum of the stimulus reaching the cochlea is far from flat, and considerably narrower than 10,000 Hz.

Since the duration of both the CM and SP are stimulus dependent, the brevity of the click makes it a less-than-ideal stimulus for studying either of these potentials. Despite this limitation, the use of clicks has proven effective in evoking the SP-AP complex for ECochG applications related to MD/ELH, even though the duration of the SP is abbreviated under these conditions (Durrant and Ferraro, 1991). This feature will receive more attention later.

Although the click continues to remain popular, toneburst stimuli also have been used in several ECochG studies involving MD/ELH populations (e.g., Levine et al, 1992; Orchik et al, 1993; Ferraro, Blackwell, et al, 1994; Ferraro, Thedinger, et al, 1994; Koyuncu et al, 1994; Margolis et al, 1995). Tone bursts provide a higher degree of response frequency-specificity than clicks (depending on stimulus envelope and duration), which can be useful for monitoring cochlear status in progressive disorders where hearing may not be affected at all frequencies. In addition, the use of longer stimuli allows for better visualization of the SP and CM (Durrant and Ferraro, 1991).

A lack of standardization regarding stimulus parameters presents a problem when using tonebursts to record ECochG components and other AEPs. Most studies employ signals of only one or two frequencies; stimulus envelopes are different, and there is no standardized approach to defining stimulus intensity. These inconsistencies make it difficult to compare data from different studies/clinics. For tone bursts, we use an envelope with a linear rise-fall time of 1–2 msec and a plateau of 10 msec or longer. Shorter plateaus (e.g., 5 msec) can sometimes be used to inhibit (but generally not eliminate) interference by ABR components (Levine et al, 1992).

Stimulus polarity depends on the initial deflection of the transducer diaphragm and is an important factor for ECochG. Presenting clicks or tonebursts in alternating polarity inhibits the presence of stimulus artifact and CM, as their phases are locked to the signal. Stimulus artifact can sometimes be large enough to obscure early ECochG components, and CM generally overshadows both the SP and AP features that are problematic when these latter two components potentials are the components of interest. Alternating stimulus polarity can be applied to help overcome this problem. However, recording separate responses to condensation and rarefaction clicks then adding them together off-line may be a more preferable solution, since certain subjects with MD/ELH display abnormal latency differences between AP-N1 latencies to condensation versus rarefaction clicks (Margolis and Lilly, 1989; Levine et al, 1992; Margolis et al, 1992; Margolis et al, 1995; Orchik et al, 1997; Sass et al, 1997).

As with the majority of signal-averaged AEPs, it is important for ECochG that the cochlear/neural responses to one stimulus be complete before the next stimulus is introduced. This requirement allows for considerable latitude in the selection of stimulus repetition rate for click-evoked AEPs. For ECochG, however, increasing this rate beyond 10–30/second may cause unacceptable adaptation of the AP (Suzuki and Yamane, 1982). Click repetition rates on the order of 100/second cause extensive (nearly total) adaptation of the AP while leaving the SP relatively unaffected (Gibson et al, 1977; Coats, 1981). 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) (Harris and Dallos, 1979; Durrant, 1986). In addition, rapid clicks presented at loud levels tend to be very annoying for patients.

When ECochG is performed to help diagnose MD/ELH, the stimulus should be intense enough to evoke a well-defined SP-AP complex. Thus, stimulus presentation typically begins at a level near the maximum output of the stimulus generator. Unfortunately, as mentioned earlier, the lack of standardization for AEP stimuli regarding signal calibration and dB reference is true for both tonebursts and BBCs. Common references include dB hearing level (HL, or hearing threshold level [HTL]), dB normal hearing level (nHL), dB sensation level (SL), and dB peak equivalent sound pressure level (pe SPL). Since the latter one is determined by matching the SPL of a transient signal to that of a continuous sinusoid, it represents the only physical measure of intensity of the three common references. It may be necessary to calibrate ECochG signals in both nHL and pe SPL. As with conventional audiometry, nHL values are referenced against normal subjects. For dB pe SPL, an oscilloscope is used to match the level of the click to that of a continuous sinusoid (e.g., a 1000 Hz signal). Consistent with the findings of Stapells et al (1982), 0 dB nHL for clicks corresponds to approximately 30 dB pe SPL.

The use of high stimulus levels raises the question of the need for masking to assure unilateral stimulation of the intended ear. This concern is irrelevant for ECochG, however, since the magnitude of any electrophysiological response from the nontest ear is very small. In addition, ECochG components are generated prior to crossover of the auditory pathway. Finally, the potential for crossover stimulation can be further minimized by the use of tubal insert earphones.

A final note regarding stimuli relates to stimulus artifact, which can be quite large for ECochG. The nature of ET (especially TM) electrodes is that they tend to have high impedance and are vulnerable to radiation from the transducer and other electrical sources in the environment. The following factors can help to inhibit such artifact: using a tubal insert transducer; separating the transducer from the electrode cables as much as possible; braiding the electrode cables; testing subjects in a shielded sound booth with the examiner and AEP unit located outside of the booth; plugging the AEP unit into an isolated socket equipped with a true-earth ground; using a grounded cable for the primary electrode (such cables are commercially available); turning off the lights in the testing room and unplugging unnecessary electronic equipment (it also may be necessary to turn off the lights in the examiner room); encasing the transducer in grounded Mu metal shielding.

PREPARING FOR AN EXAMINATION

Recording Approach

Virtually all ECochG recordings performed in the authors' clinics/laboratories are ET and made from the TM because of the advantages this site offers over other locations along the ear canal (i.e., increased component magnitudes, more stable/repeatable responses, and reduced testing time because less signal averaging is needed) (Stypulkowski and Staller, 1987; Ruth et al., 1988; Ruth and Lambert, 1989; Ferraro and Ferguson, 1989; Ruth, 1990; Arsenault and Benitez, 1991). Given our preference for TM ECochG, the following information emphasizes this particular approach.

Subject/Patient Considerations

Most patients are unfamiliar with ECochG and therefore confused as to what it is, why they need it, how it will be performed,

and whether or not it will be painful. For the lay person (i.e., most patients) the lengthy term "electrocochleography" adds to this confusion. Instructions to the patient can begin on the way to the testing room with an assurance that the examination is noninvasive and painless, that the test will take approximately one hour, and they can sleep through it if they wish. The patient also is informed as to why their physician has requested this examination (e.g., to help determine if there is too much fluid in the inner ear). Engaging patients in conversation at this point and watching them walk also provides some insight regarding the status of their hearing and balance, although the results of other auditory and vestibular testing should be available in their files. Once in the sound booth, the patient is placed in a supine position on an examining bed or semireclined in an examination chair or recliner. Good and comfortable head and neck support is particularly important. Eyeglasses and/or earrings are removed (usually by the patient), and food/chewing gum/candy/etc. must be swallowed or discarded. When the patient is comfortable and attentive, he or she is informed that devices called electrodes will be attached to the scalp, a small, sponge- or cotton-tipped electrode will be inserted along the ear canal to rest on the TM, and an earplug will be used to hold the electrode in place and deliver click and beeping-type sounds to the ear. The patient should be alerted that the TM electrode might feel strange and maybe a little uncomfortable, but that it should not be particularly painful. If pain should occur, repositioning the electrode usually helps. In very rare instances (i.e., less than 0.5% in the first author's experience), the exam may have to be terminated, or an ear canal electrode used instead of the tymptrode. The procedures for preparing the skin and placing the surface electrodes are identical to those used for conventional ABR examinations. Prior to inserting the tymptrode, otoscopy is performed to assess the patency of the ear canal and normalcy of the TM. Cerumen removal may be necessary to visualize the TM and clear a pathway along the ear canal large enough for the electrode. If either the ear canal or TM appear abnormal or damaged, ECochG is not advisable in general, and certainly not without consulting the patient's physician.

As with most audiometric examinations, both ears should be tested, even if unilateral disease is suspected. Comparison between affected and unaffected sides in particular can provide important diagnostic information. We always test the affected side first in case the patient becomes restless as the examination progresses.

Construction and Placement of the TM Electrode (Tymptrode)

The photograph of ET electrodes in Figure 2 includes the tymptrode (originally described by Stypulkowski and Staller, 1987, and modified by Ferraro and Ferguson, 1989), the Lilly wick electrode (Lilly and Black, 1989), the TM-ECochGtrode manufactured by Bio-Logic, and the gold-foil TIPtrode, which has long been available for ear canal recordings. The latter three electrodes are commercially available. The tymptrode can be fabricated using the "store bought" materials listed below (see Durrant, 1990; Ferraro, 1992; and Ferraro, 1997):

- medical grade silicon (Silastic™) tubing (0.058" inner diameter, 0.077" outer diameter;
- Teflon™-insulated silver wire (0.008" bare diameter, 0.011" insulated diameter);
- a wad of cotton;
- electrode gel (not paste or cream);
- fine, needle-nosed forceps;
- 1 cc disposable tuberculin syringe with needle;
- copper microalligator clip soldered to the end of an electrode cable.

Briefly, the procedure for constructing the tymptrode involves cutting the wire and tubing into segments a few centimeters longer than the ear canal, threading the wire through the tubing, scraping the Teflon insulation off of both ends of the wire, hooking one of the bared ends into the cotton wad, and stuffing the hooked portion of the cotton back into the tubing with fine forceps. A small portion of the cotton extends beyond the tubing to serve as the electrode tip. Figure 3 is a drawing of the tymptrode constructed as described above. Tymptrodes, at this stage, can be made and stockpiled for indefinite periods of time. Immediately prior to use, the cotton tip of the tymptrode is impregnated with electrode gel using the tuberculin syringe. We attach the microalligator clip of

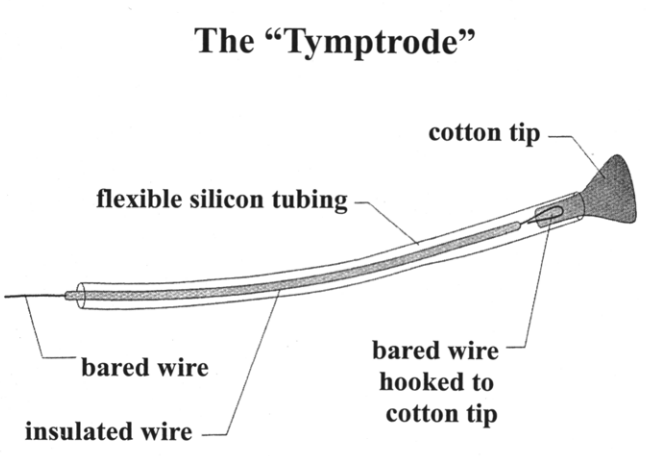

Figure 3. Components of the "tymptrode" electrode used for surface recordings from the tympanic membrane.

the electrode cable to the other, bared end of the wire, before inserting the tymptrode.

With the test ear is facing up, the tymptrode is inserted into the entrance of the ear canal and gently advanced (by hand or using the fine forceps) until the tip touches the TM. Contact is confirmed via otoscopy and electrophysiological monitoring. It also helps to ask the patient when they feel that the electrode is touching the TM. Even with an otoscope, it is difficult to actually see the point of contact between the tymptrode tip and TM in most cases. However, monitoring the electrophysiological noise floor during electrode placement helps to achieve proper contact. The noise floor, peak-clipping, and cyclic activity associated with an "open-line" condition drop dramatically, and the baseline EEG becomes more stable when the TM is contacted. Repositioning and sometimes reinsertion of the tymptrode may be necessary to achieve proper contact. However, using both visual and electrophysiological monitoring provides the best opportunity for success on the "first try."

Once the tymptrode is in place, the foam tip of the sound delivery tube is compressed and inserted into the ear canal alongside the electrode tubing. Care must be taken to not push the electrode further against the TM when inserting the earplug. Although the materials that comprise the tymptrode are relatively soft and flexible (which allows the tip to compress or bend at the TM rather than penetrate the membrane), such a condition usually causes discomfort to the patient. Only a portion of the transducer earplug needs to be inserted into the canal to hold the tymptrode in place and deliver the signal for ECochG applications. Figure 4 is a schematic representation of the tymptrode and sound delivery tube in place. Even with the most delicate contact, the TM does react somewhat in most cases by displaying a slight blushing spot at the point of contact with the tymptrode. In hundreds of subjects and patients examined by the authors, this condition has never proven to be an untoward reaction, clears up within minutes or hours, and may even be a useful indicator of exactly where the electrode was situated.

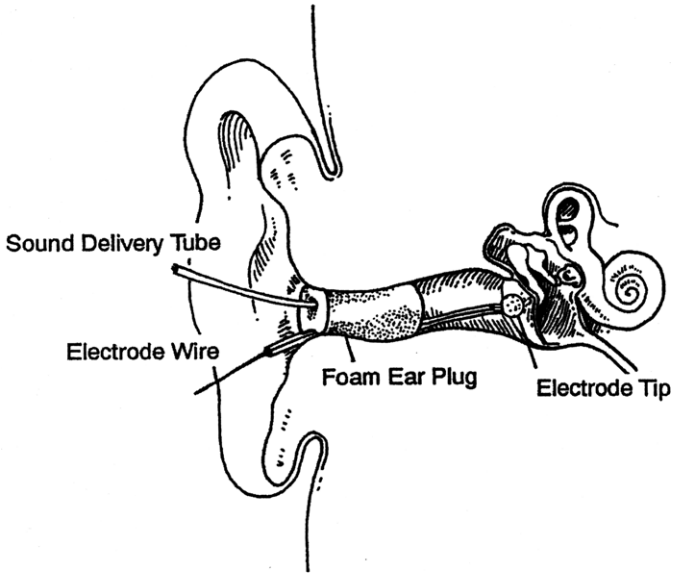

Figure 4. Schematic illustration of the tymptrode in place. Modified from Ferraro (1992, p. 28).

INTERPRETATION OF THE ELECTROCOCHLEOGRAM

As with most AEPs, component magnitude and temporal features form the bases for interpreting the electrocochleogram. Figure 5 depicts normal TM recordings to alternating polarity clicks (which enhances the SP and AP at the expense of the CM). Component magnitudes can be measured as absolute values (defined by single points)

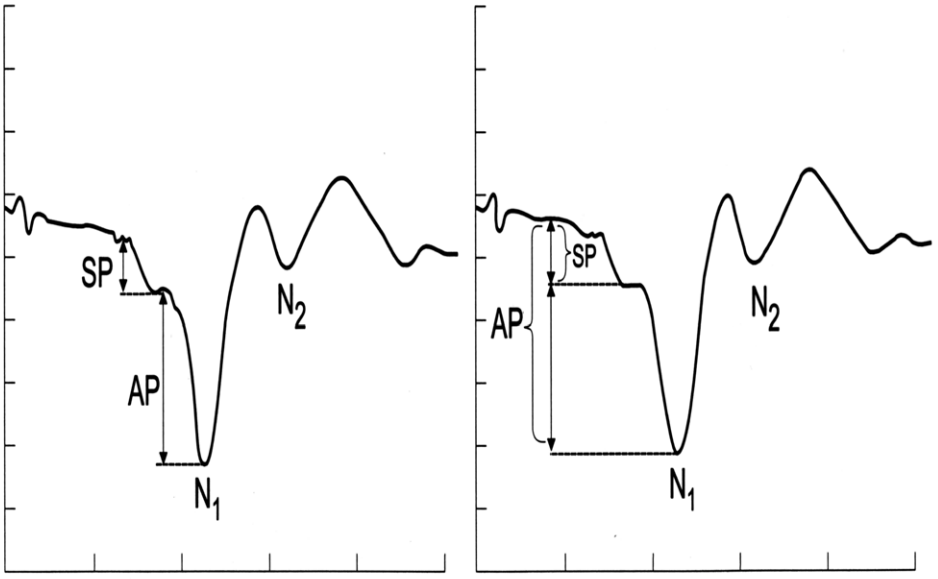

Figure 5. ECochG recordings from the tympanic membrane to clicks presented in alternating polarity at 80 dB nHL. The magnitudes of the Summating Potential (SP) and Action Potential (AP) can be measured from peak-to-trough (left panel), or with reference to a baseline value (right panel). Magnitude/time scale is 1.25 microvolts/1 millisecond per gradation. Insert phone delay is 0.90 milliseconds. From Ferraro (2000, p. 435).

(left panel) or using a baseline reference (right panel). The authors are split on which of these two approaches is best, showing that even authorities of similar background and generally similar views can still have differing opinions on how to interpret an electrocochleogram. In this instance, rights and wrongs are difficult to define, particularly under the electrically "noisy" circumstances of minimally/non-invasive recording conditions in awake patients. The first author finds the single-point calculations to be the more useful and potentially reliable as it minimizes the judgmental factor of defining an unstable or electrically skewed baseline common to ET recordings in general. Theoretically, this approach is subject to no more or no less noise than single points chosen to represent the SP and AP magnitudes. However, the second author prefers using a value representing the average through a millisecond or two of baseline before the response. At least for one of the measurements, the noise can be reduced (the average being inherently a "variance reducer"). This method is equally useful in determining the SP magnitude for tonebursts, for the same reason in both cases—minimizing bias by some noise peak. In the final analysis, individual circumstances may favor one approach over the other, but it probably is the best idea, above all else, to try to be as consistent as possible across measures in the normative sample and clinical patients. Here, for simplicity, the single-point approach is adopted, in which case, the normal SP measured from the TM in response to 80 dB nHL clicks may be expected to range from 0.1–1.0 microvolts, with a mean of 0.4 microvolts. AP magnitudes can be as large as 5.0 microvolts, although our mean value is approximately 2.0 microvolts. AP-N1 latency is measured from stimulus onset to the peak of N1 and, as mentioned earlier in this manuscript, should be identical to the absolute latency of ABR wave I. At 80 dB nHL, normal N1 latencies generally range from 1.3–1.7 msec with a mean of approximately 1.5 msec. Since a tubal insert earphone was used to deliver the stimulus, the above latency values have been corrected for the 0.9 msec delay attributable to the sound tube. Although labeled in Figure 5, N2 has received little interest for ECochG applications.

Also as shown in Figure 5, we measure SP and AP magnitudes from the leading edge of both components. The resultant values are then used to derive the SP/AP magnitude ratio, which is a key measure when ECochG

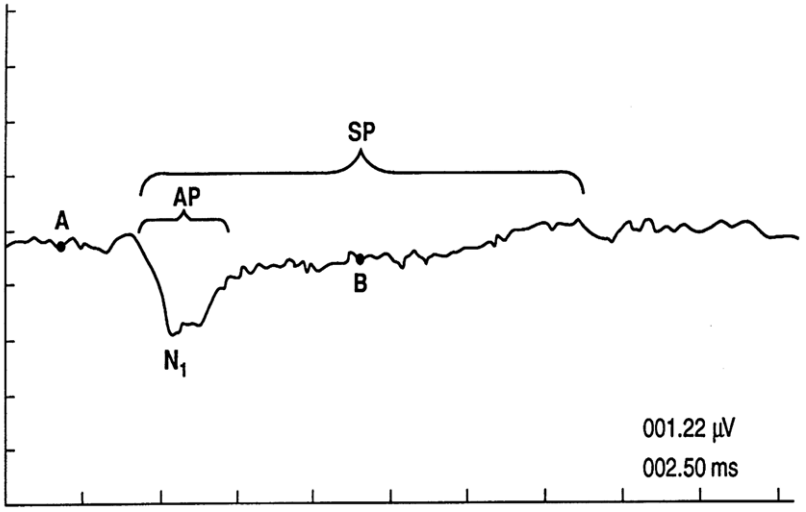

Figure 6. ECochG recording from the tympanic membrane to a 2,000 Hz toneburst (alternating polarity, 80 dB nHL, 2 msec rise/fall, 10 msec plateau). Action Potential (AP) and its first negative peak (N1) are seen at the onset of the response. Summating Potential (SP) persists as long as the stimulus. SP magnitude is measured at midpoint of response (point B), with reference to a baseline value (point A). From Ferraro, Blackwell, et al. (1994, p. 19).

is used to help diagnose and monitor MD/ELH. This value tends to occur within a relatively small range (i.e., 0.1–0.5), especially in comparison to the individual magnitudes of both the SP and AP (Ferraro and Krishnan, 1997).

Figure 6 depicts a normal waveform evoked by an 80 dB nHL, 2000 Hz toneburst (2 msec rise/fall, 10 msec plateau, alternating polarity). Recall that for tonebursts the SP persists as long as the stimulus and therefore is not seen as a small shoulder preceding the AP (which is still seen near the onset of the response). To minimize the influence of the AP, SP magnitude is measured at the midpoint of the waveform with reference to baseline magnitude. The polarity of the SP depends on whether this voltage is above (positive SP) or below (negative SP) the baseline voltage. Figure 7 illustrates toneburst SPs at several frequencies recorded from both the TM and promontory (TT) of the same normally hearing subject. Three important features should be noted from these tracings: (1) The polarities of the SPs may vary slightly across frequencies. (2) Despite these slight variations, the magnitudes of toneburst-SPs in normal ears are very small, which renders the actual polarity of the SP in this population somewhat inconsequential. (3) Although the magnitudes of the TM responses are approximately one-quarter that of the promontory responses (note magnitude scales), the corresponding patterns of the TM and TT recordings at each frequency are virtually identical (as indicated earlier in this manuscript).

Although clicks and tonebursts are the stimuli of choice for ECochG, it is important to note that comparisons among studies from different laboratories/clinics remain difficult at best. This problem persists because of a lack of consistency and standardization regarding such aspects as choice of recording approach, recording and stimulus parameters, stimulus calibration, and measurement preferences. All of these conditions continue to necessitate the establishment of laboratory-/clinic-specific norms for ECochG.

ECochG's Role in the Evaluation of MD/ELH

Although much has been learned about MD (or idiopathic ELH) since its initial description in the literature over 140 years ago (Ménière, 1861), the true pathophysiology of this disorder(s) continues to be elusive. As a result, neither a cure nor an effective treatment strategy that works for all patients has been developed. The symptoms upon which diagnosis of MD/ELH is based include recurrent, spontaneous vertigo, hearing loss, aural fullness, and tinnitus (American Academy of Otolaryngology—Head and Neck

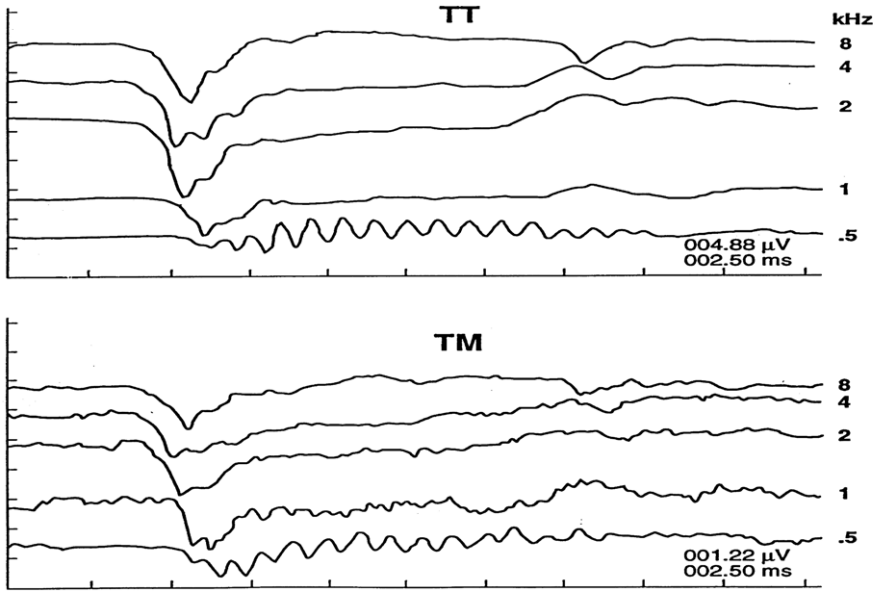

Figure 7. Transtympanic (TT) and Tympanic Membrane (TM) electrocochleograms evoked by tonebursts of different frequencies presented at 80 dB nHL (2 msec rise fall, 10 msec plateau). Stimulus frequency in kHz indicated at the right of each waveform. Despite differences in magnitudes (see magnitude scale), TT and TM response patterns are virtually identical. From Ferraro, Blackwell, et al, (1994, p. 20).

Surgery Committee on Hearing and Equilibrium, 1995). However, the presence and severity of these symptoms tend to vary over time both among and within patients. The capricious nature of this disorder makes it difficult to diagnose and evaluate with a high degree of specificity and/or sensitivity.

As mentioned throughout this paper, ECochG has emerged as one of the more powerful tools in the diagnosis, assessment, and monitoring of MD/ELH, primarily through the measurement of the SP and AP. In particular, it is now well documented that the electrocochleograms of patients with MD/ELH often display abnormally enlarged SP magnitudes (e.g., Schmidt et al, 1974; Gibson et al, 1977; Gibson, 1978; Moriuchi and Kumagami, 1979; Morrison et al, 1980; Coats, 1981, 1986; Kitahara et al, 1981; Goin et al., 1982; Kumagami et al, 1982; Ferraro et al, 1983; Ferraro et al, 1985; Staller, 1986; Dauman et al, 1988; Ruth et al, 1988; Ferraro and Krishnan, 1997). The conventional rationale for this finding is that an increase in endolymph volume creates mechanical biasing of vibration of the organ of Corti to which, again, the SP is sensitive. Whether the nature of this increased distortion is mechanical (Gibson et al, 1977) and/or electrical (Durrant and Dallos, 1972, 1974; Durrant and Gans, 1977) has not been resolved, and other factors such as biochemical and/or vascular changes may also be responsible (Eggermont, 1976; Goin et al; 1982; Staller, 1986). Regardless of the specific pathophysiology, measurement of the SP to help diagnose, assess, and monitor MD/ELH has emerged as a primary, and probably the most popular, application for ECochG.

Although it is the enlargement of the SP magnitude that often characterizes the electrocochleograms of patients with MD/ELH, the consistency of this finding when using click stimuli improves when this value is compared to the magnitude of AP-N1 to form the SP/AP magnitude ratio (Eggermont, 1976; Coats, 1981; Coats, 1986). An enlarged SP/AP magnitude ratio to click stimuli, therefore, would be considered a positive finding for ELH. This feature is illustrated in Fig. 8, which displays the click-evoked electrocochleogram of a patient with MD/ELH on the left side. As can be seen from these tracings, the left SP/AP magnitude ratio (when measured using the "single point"

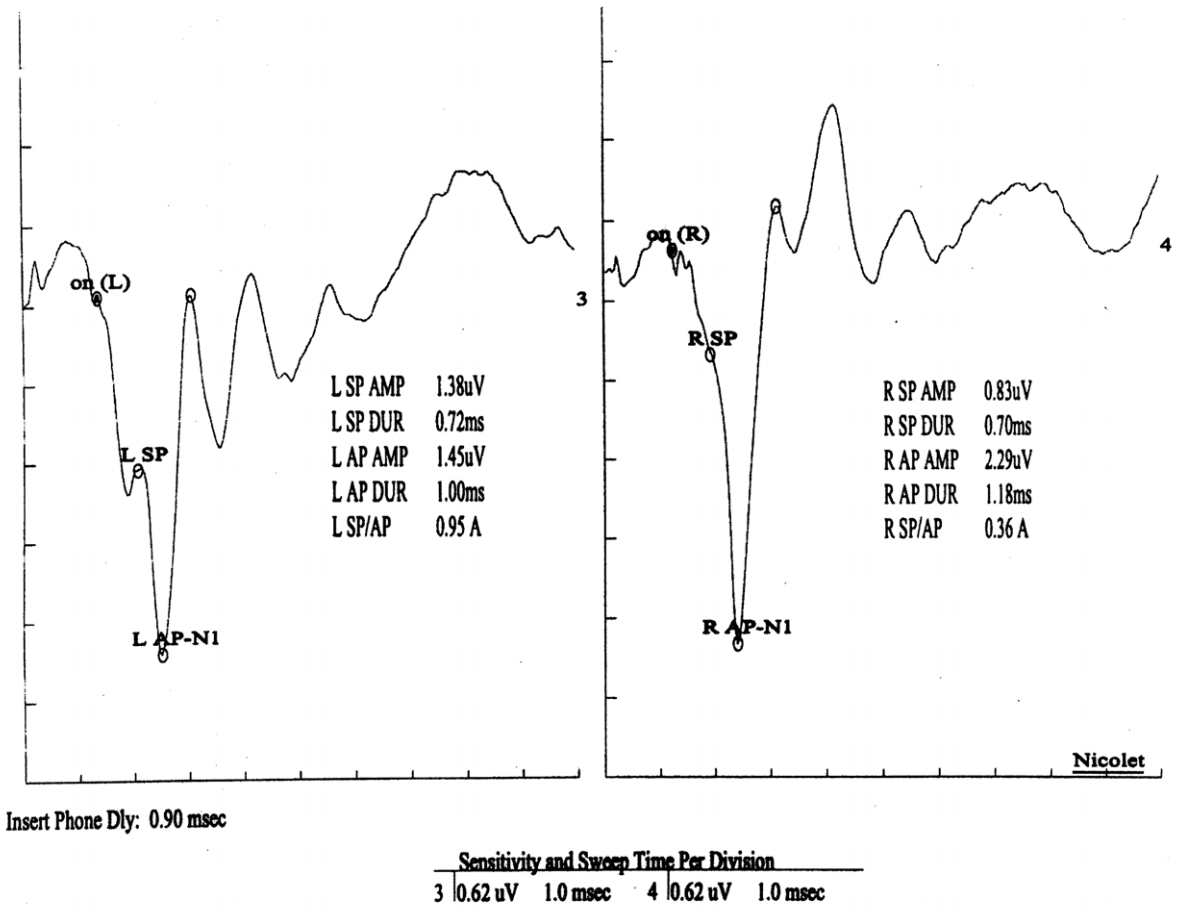

Figure 8. ECochG tracings to broadband clicks (alternating polarity, 80 dB nHL) from a patient with endolymphatic hydrops. Affected side (left) shows a magnitude-enlarged summating potential (SP), and SP/action potential (AP) magnitude ratio. SP-AP relationship on the unaffected side (right) is within normal limits.

method), is approximately 2½ times larger than the normal right ratio. Figure 9 displays normal and abnormal toneburst-evoked electrocochleograms (2000 Hz, 2 msec r/f, 10 msec plateau) from another MD/ELH patient. For these measurements, SP magnitude represents the difference between baseline and midpoint voltages (recalling that the SP persists for the duration of the stimulus). The left panel displays an enlarged, negative SP from the affected left ear, whereas the right response is barely measurable and well within normal limits. It also should be noted for toneburst responses that the measurement of interest is the magnitude of the SP trough rather than the SP/AP magnitude ratio. Indeed, it often is the case that the AP to tonebursts may not even be visible in the face of an abnormally enlarged SP.

Although the specificity of ECochG in the diagnosis of MD/ELH has been reported to be higher than 90% (Ferraro et al, 1983; Pou et al, 1996; Murphy et al, 1997), the incidence of an enlarged SP and SP/AP magnitude ratio in the general Ménière's population is only approximately 55%–65% and has been reported to be as low as 20% (Gibson et al, 1977; Coats, 1981; Kitahara et al, 1981; Kumagami et al, 1982; Margolis et al, 1995; Pou et al, 1996; Ferraro and Tibbils, 1999). These statistics demand a continuing search for ways to make ECochG more sensitive, particularly for patients whose symptoms are not "classic" and for whom the clinical profile is unclear (Campbell et al, 1992).

The episodic nature of MD/ELH certainly plays a role in the sensitivity of any diagnostic tool used for this disorder. In addition, MD/ELH is characterized by various stages during its evolution within a given patient, which manifest differently electrophysiologically (Aran et al, 1984; Horner and Cazals, 1988). Thus, one might expect the sensitivity of ECochG to vary according to when the test was administered in the course of the disease. In support of this notion, Ferraro et al (1985) found positive

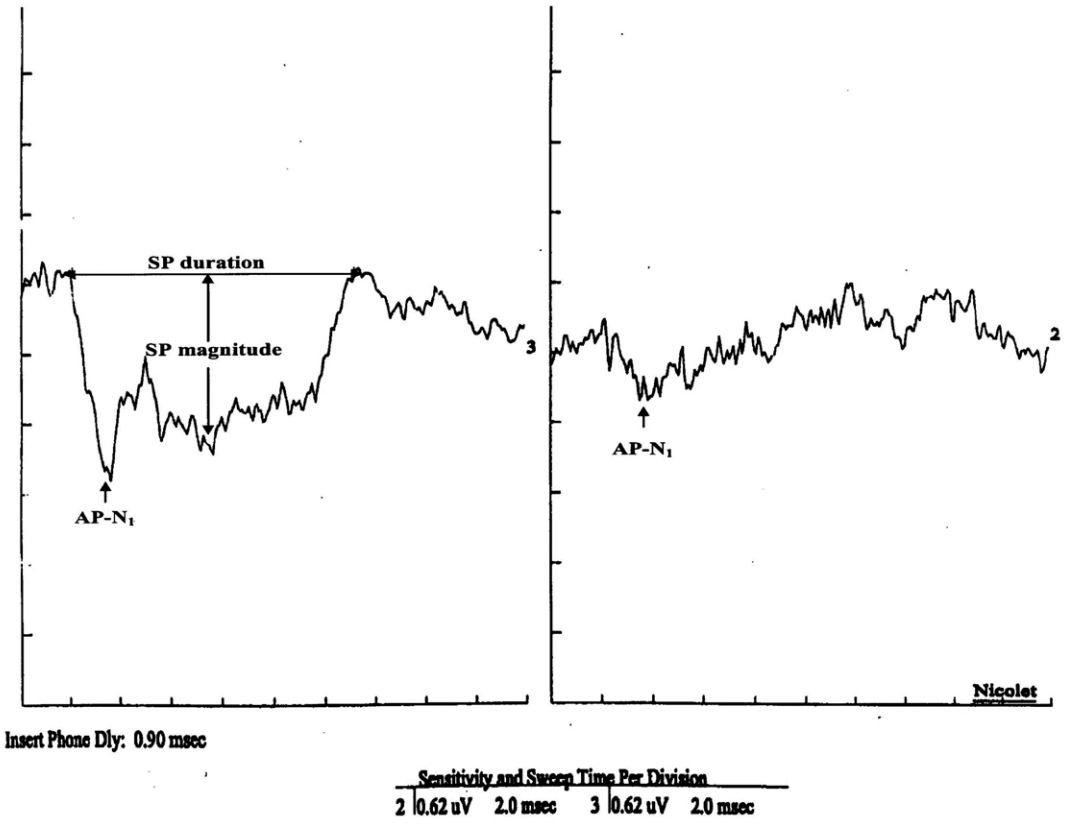

Figure 9. ECochG tracings to a 2,000 Hz toneburst (alternating polarity, 80 dB nHL, 2 msec rise/fall, 10 msec plateau) from another patient with endolymphatic hydrops. Affected side (left panel) displays an enlarged SP trough, while SP magnitude on unaffected side (right panel) is very small and within normal limits. AP-N1 component is seen at the onset of the response to toneburst stimuli.

electrocochleograms in over 90% of patients who had active symptoms at the time of testing that included aural fullness and hearing loss. Pou et al (1996) observed changes in the SP-AP relationship as a function of degree of hearing loss. Such loss may be initially episodic but also tends to progress with duration of disease. Given these associations, one way to make ECochG more sensitive is to test patients when they are experiencing symptoms. Unfortunately, the practicality of this idea is questionable given the fluctuating nature of the disorder (especially in its early stages), the general operating hours of most clinics, and the inability and/or unwillingness of patients to complete an examination during an "attack." Nonetheless, testing patients during or as soon as possible after an episode will significantly improve the chances of obtaining a positive electrocochleogram if indeed the patient has MD/ELH. We also have found it helpful, especially in the early stages of the disorder, to test patients when they are asymptomatic and then retest them when symptoms are present. Comparing electrocochleograms under these conditions often reveals differences that are diagnostically significant.

Additional evidence for the close relationship between ECochG and the acute status of the inner ear can be seen in cases involving intraoperative ECochG monitoring in patients undergoing endolymphatic decompression/shunt surgery for treatment of MD/ELH. Although still controversial, decompression or shunting of the endolymphatic sac is an option for patients who fail nonsurgical treatments. During such surgeries, instantaneous measurements of the mechanoelectrical processes of the inner ear can be achieved via ECochG (Gibson et al, 1988; Gibson and Arenberg, 1991; Arenberg et al, 1993; Wazen, 1994; Mishler et al, 1994). Figure 10 exemplifies intraoperative changes in the electrocochleogram induced by probing for the endolymphatic duct in a patient with MD/ELH. The uppermost tracings display

an enlarged SP and SP/AP magnitude ratio. However, the SP becomes smaller and remains that way after a metal probe is passed into (and therefore decompresses) the duct (bottom three tracings). Probing of surrounding tissue did not alter the electrocochleogram. Figure 11 displays selected tracings measured from another patient undergoing endolymphatic sac decompression surgery. A noticeable reduction in the SP/AP magnitude ratio to click stimuli, and the SP magnitude to tonebursts were observed when the sac was decompressed. Although not always the case, this particular patient reported an improvement in symptoms following surgery.

Beyond the SP/AP Magnitude Ratio

Other approaches to increasing the sensitivity of ECochG have been directed toward the parameters associated with recording and interpreting the electrocochleogram, and looking beyond comparatively simple measures of SP magnitude. An example of such a method involves measuring the AP-N1 latency difference between responses to condensation versus rarefaction clicks (as described earlier in this chapter). Figure 12 illustrates this procedure. The AP-N1 latency difference (LD) between clicks of opposite polarity for this MD/ELH patient was 0.75 msec, which was considerably above the upper limit 0.38 msec seen in normal ears. The basis for comparing AP-N1 latencies to clicks of opposite polarity relates to changes in the velocity of the traveling wave in an endolymph-loaded cochlea. That is, the vibratory cycle of the cochlear partition under such conditions may be abnormally restricted (or enhanced) in one direction over the other. If this condition occurs, the velocity of the traveling wave (on which the AP-N1 latency is dependent) will differ if the initial movement of the cochlear partition is upwards (as with rarefaction clicks) versus downwards (as with condensation clicks).

Another interesting feature in Figure 12 is that the AP-N1 latency difference is obscured when responses to rarefaction and condensation clicks are combined (lowest tracing). This approach is analogous to presenting clicks in alternating polarity. What appears instead is

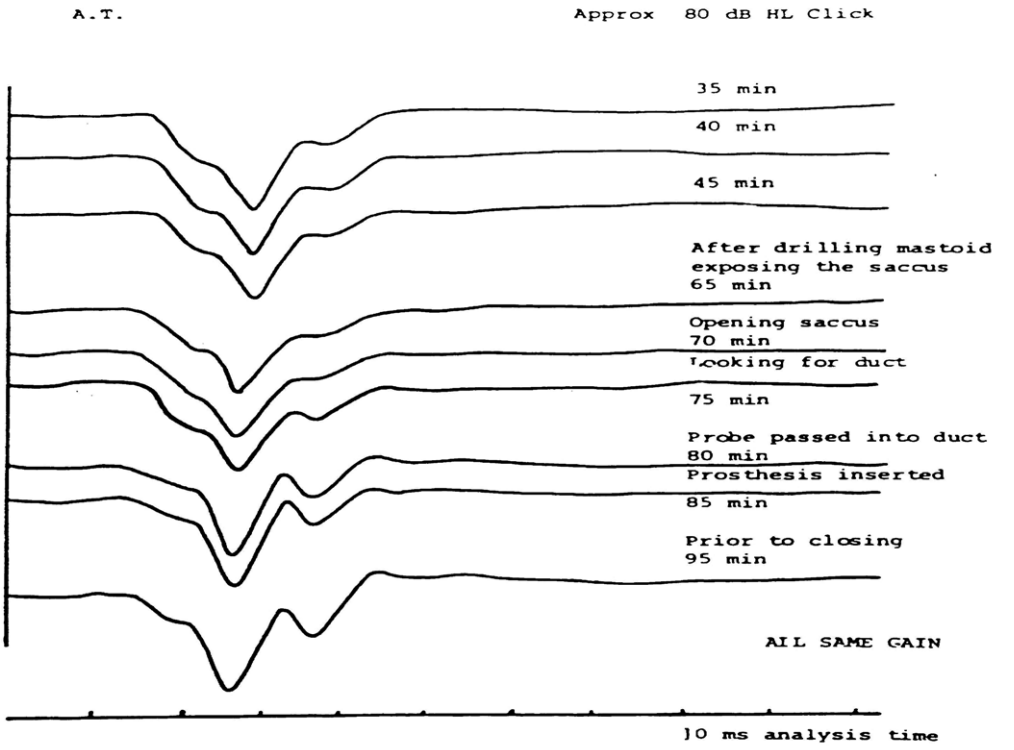

Figure 10. ECochG recordings measured at various events during endolymphatic sac decompression surgery. Note the reduction in SP magnitude in the "Probe passed into duct" tracing, which illustrates the relationship between the electrocochleogram and the acute status of the endolymphatic system. This feature is used to help to differentiate the location of the endolymphatic duct from surrounding tissue during surgery. From Gibson and Arenberg (1991, p. 300).

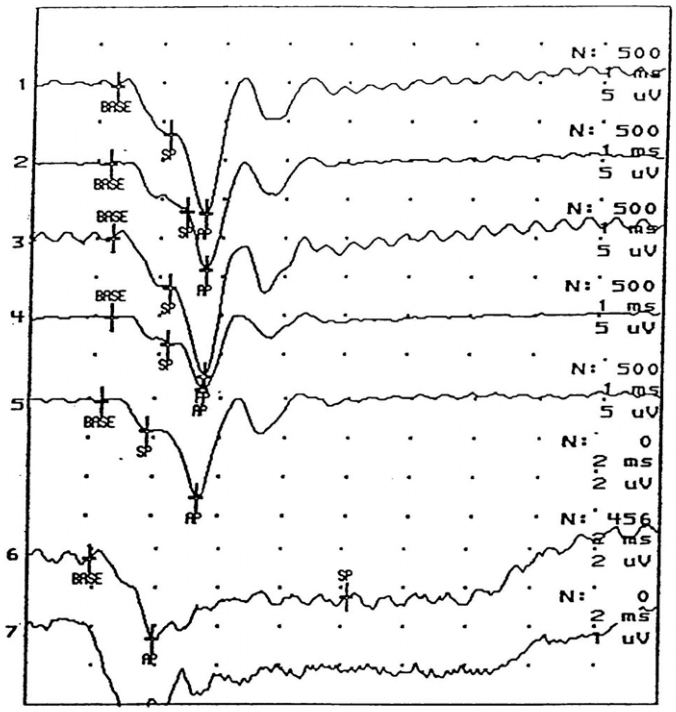

Figure 11. ECochG tracings recorded during endolymphatic shunt decompression surgery: baseline tracing (1), drilling on mastoid (2), probing for endolymphatic duct (3), inserting prosthesis (4), closing (5). Tracing 5 shows a reduction in the summating potential (SP)/action potential (AP) magnitude ratio compared to tracing 1. Tracings 1–5 are in response to clicks, whereas tracings 6–7 were recorded to tonebursts at the onset of surgery and display an enlarged SP magnitude. From Ferraro (2000, p. 446).

an abnormally widened SP-AP complex. It is interesting to note that Morrison et al (1980) reported a widening of the SP-AP duration in Ménière's patients over 20 years ago. This finding was attributed to an "after-ringing" of the CM caused by endolymphatic hydrops. In light of recent studies, it may be more likely that differences in AP-N1 latency to condensation versus rarefaction clicks accounted for the widened SP-AP complex observed by Morrison et al (who used click stimuli presented in alternating polarity).

Even though the underlying mechanisms may be unclear, the above studies suggest that the width (i.e., duration) of the SP-AP complex may be important to consider in the interpretation of the electrocochleogram. Ferraro and Tibbils (1999) explored this notion by combining both magnitude and duration features of the response to measure the "areas" of the SP and AP. Area measurements were accomplished using a special software routine that allowed us to measure the "area under the curve" defined by a straight line connecting two cursor points. Figure 13 displays representative tracings from this study. The waveforms in the left panel are from a normal subject, whereas the right tracings are from an MD/ELH patient. The shaded portions of the top tracings in both panels represent the area of SP, which was defined by the onset of the SP (baseline) and that point in the tracing where the waveform returned to the baseline magnitude. Despite its label, this measurement also includes the areas of components other than the SP (such as the AP-N1, and often AP-N2). The shaded portions of the lower tracings represent the AP-N1 area. The results from this study revealed that virtually all MD/ELH patients with enlarged SP/AP magnitude ratios also have enlarged SP/AP area ratios. However, enlarged area ratios also were seen in several patients suspected of having MD/ELH but whose SP/AP magnitude ratios were within normal limits. Subsequent research in our laboratory using data from 138 patients with MD/ELH has shown that measurement of the SP/AP area ratio significantly improves the diagnostic sensitivity of ECochG in comparison to the SP/AP magnitude ratio (Devaiah et al, 2003).

Given the above findings, we routinely

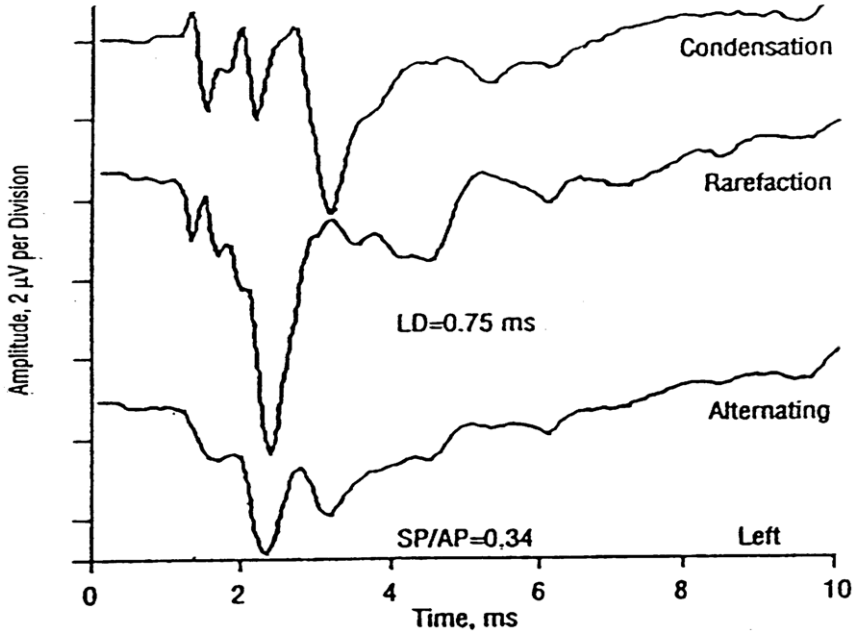

Figure 12. ECochG tracings to broadband clicks presented in opposing polarity from a patient with Meniere's disease. Top tracing evoked with condensation-polarity clicks; middle tracing evoked with rarefaction-polarity clicks. The latency difference of 0.75 milliseconds between AP-N1 components to condensation versus rarefaction clicks is a positive finding for endolymphatic hydrops since it is greater than 0.38 milliseconds. This feature is obscured if the condensation and rarefaction tracings are combined to derive the response to alternating clicks (bottom tracing). From Margolis et al (1995, p. 52).

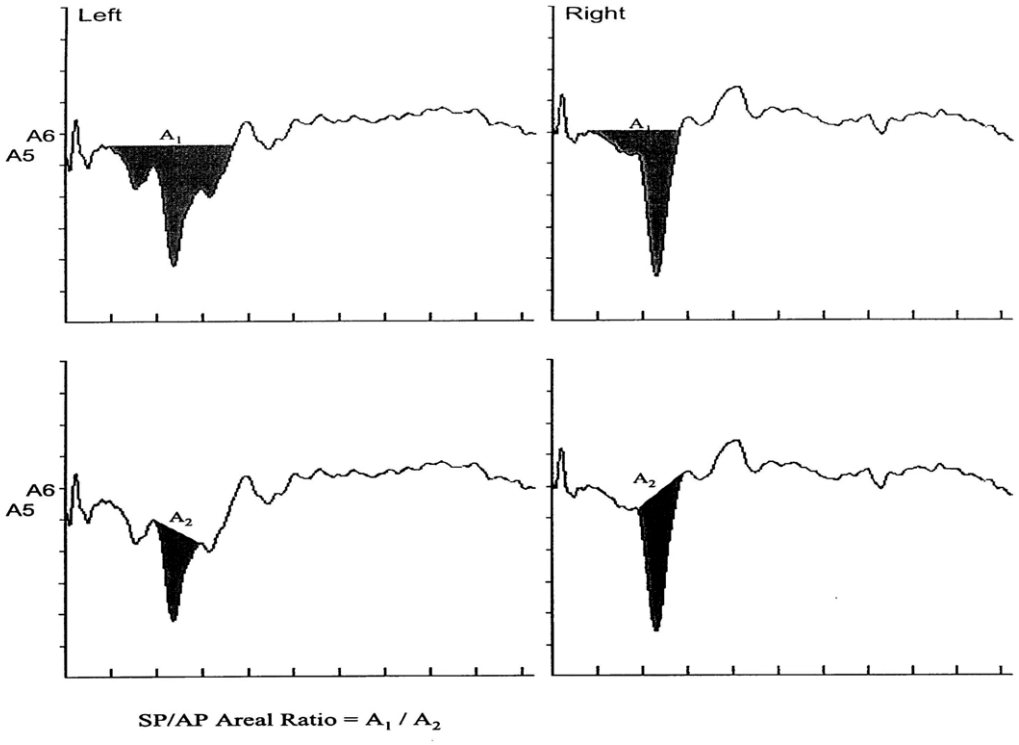

Figure 13. Measurement of the areas of the summating potential (SP) and action potential (AP) to click stimuli to derive the SP/AP area ratio. Area values are obtained using a software routine that allows for measurement of the "area under a curve" defined by a straight line that connects two cursor points. Shaded portions represent these areas. Tracings in the top and bottom left panels are from the affected side of a subject with endolymphatic hydrops and display an enlarged SP/AP area ratio. Normal tracings on the right are from the unaffected side. From Ferraro and Tibbils (1999, p. 24).

include measurement of the SP/AP area ratio in the interpretation of electrocochleograms. However, we continue to measure the SP/AP magnitude ratio to clicks, the SP magnitude to tonebursts (1000 and 2000 Hz), and the N1 latency difference to clicks of opposite polarity. The question as to which of these measurements (or combination of measurements) is most sensitive to MD/ELH remains to be answered. To address this issue, we have begun an outcome study involving several hundred patients seen for ECochG examinations in our clinic during the past five years. This project involves assessing the relationship between the results of an ECochG examination (i.e., the individual measurements described above) and the subsequent diagnosis and treatment of the patient. At this time, the jury is still out regarding the measurement(s) that is most sensitive to MD/ELH.

A final note regarding the specificity of ECochG relates to enlarged SP/AP magnitude ratios in conditions other than MD/ELH. In particular, this feature also has been reported for perilymphatic fistulae (Kobayashi et al, 1993; Ackley et al, 1994; Campbell and Abbas, 1993, 1994). Thus, it may be the case that any change in cochlear fluid pressure that biases cochlear transduction, and therefore the SP, will affect the SP/AP relationship (Storms et al, 1996). However, as implied in earlier discussion, definitive proof of this mechanism remains to be seen. Eggermont (1976) questioned the hydromechanical rationale over two decades ago, suggesting consideration of possible biochemical changes underlying or triggered by the fluid pressure changes—ionic diffusion gradients can be altered by osmosis and vice versa.

Yamasoba et al (1993) observed enlarged SPs in cases of idiopathic low-frequency hearing losses, namely patients who have no balance-related or other symptoms characteristic of MD/ELH. This finding suggests that a positive electrocochleogram may be a manifestation of "cochlear hydrops." Indeed, we have seen numerous patients who fit this profile. That is, a positive electrocochleogram in the face of hearing loss, aural fullness, and tinnitus, but not accompanied by vertigo. Likewise, we also have observed negative electrocochleograms in dizzy patients whose auditory symptoms were minimal at the time of testing but who were eventually diagnosed with MD/ELH. Obviously, more research in this area is needed to ascertain ECochG's sensitivity to cochlear versus vestibular hydrops, assuming that these conditions can exist independently.

As we continue to learn more about the infrastructure and physiology of the inner ear, it is likely that even more basic mechanisms will be revealed to account for normal and impaired hair-cell transduction in general. Molecular biological bases, perhaps even involving genetic coding or related processes may play a role in altering these mechanisms in individuals with MD/ELH to produce the changes in the SP and other features of the electrocochleogram described above.

SUMMARY

ECochG has emerged as an important tool in the diagnosis, assessment, and monitoring of MD/ELH despite continuing debate on the best ways to record and interpret responses. In this case, the "best ways" are those that optimize the sensitivity and specificity of ECochG in the evaluation of MD/ELH—while causing minimal discomfort to the patient. The following is a summary of the features described in this manuscript that should be considered in the selection of ECochG parameters to achieve this goal.

- Although ECochG components include the CM, SP, and AP, measurement of the SP and AP continues to offer the most useful information in the evaluation of MD/ELH. While the CM may indeed have other valuable applications (e.g., in the diagnosis of auditory neuropathy), its utility for MD/ELH purposes has yet to be established.
- The authors prefer an ET recording approach for ECochG that involves placing the primary electrode on the external surface of the TM. This site offers a good compromise between TT and other ET sites regarding component magnitudes, preservation of diagnostic patterns, and testing time, and can be performed by audiologists in a nonmedical setting with minimal-to-no discomfort to the patient.
- The stimulus and signal averaging parameters associated with ECochG should be chosen to favor

measurement of the SP and AP, recorded together or separately, and in response to both BBCs and tonebursts.

- The lack of standardized stimuli and stimulus calibration approaches for ECochG continues to necessitate the establishment of laboratory-/clinic-specific normative data.
- Stimulus and other artifact can be a bigger problem for TM-ECochG than for other AEPs because of the sensitivity/fragility of recording site, the construction, sensitivity, and stability of the recording electrode, and lowering the low-frequency cutoff of the analog filter to allow for measurement of the SP component. Several suggestions are offered in this manuscript to help inhibit such artifact.
- Although the SP/AP magnitude ratio to BBCs appears to be highly specific to MD/ELH (i.e., patients that display an enlarged ratio are usually diagnosed with this disorder), the sensitivity of this measurement (i.e., the likelihood of finding an enlarged SP/AP magnitude ratio in someone who has MD/ELH) in the general MD/ELH population is not as high. This finding demands a continued search for other features of the electrocochleogram that may improve ECochG's sensitivity. These features may include the SP magnitude to tonebursts, the SP/AP area ratio to BBCs, and the latency difference between the AP-N1 components to BBCs of opposing polarity. Although our data suggest that measurement of the SP/AP area ratio may offer the most sensitivity among the above values, additional research is needed to verify this finding.
- There is a significant relationship between ECochG results and the symptoms the patient displays at the time of testing. Thus, one way to make ECochG more sensitive is to test patients when they are symptomatic, even though the practicality of this strategy often is limited.
- Although, as indicated above, ECochG is highly specific to MD/ELH, enlarged SP/AP magnitude ratios also have been reported in cases of perilymphatic fistulae and apparent cochlear hydrops. This finding suggests that the conditions to which ECochG may be most specific are changes in cochlear fluid pressure.
- The relationship between ECochG results and symptoms and also to the acute status of the ear (as observed in intraoperative recordings and conditions other than MD/ELH that cause changes in cochlear fluid pressure), serves to underscore the general truism of ECochG, and all AEP measures for that matter: they are functional indicators and not pathognomonic of a particular disorder/disease. Fortunately for the diagnostician, an increased SP/AP magnitude and/or area ratio, or abnormally prolonged AP-N1 latency difference to BBCs of opposing polarity are rare in retrocochlear cases and other disorders of hearing. Thus, a positive electrocochleogram certainly points strongly to a cochlear disorder and most likely an etiology of MD/ELH.

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