Electrocochleography: A Review of Recording Approaches, Clinical Applications, and New Findings in Adults and Children

DOI: 10.3766/jaaa.21.3.2

John A. Ferraro*

Abstract

Research related to expanding and improving the clinical use of electrocochleography (ECochG) has been ongoing for 25 yr at the University of Kansas Medical Center. This article presents highlights of findings from our laboratory during this period that have contributed to current ECochG recording approaches and clinical applications. A review of new data related to improving the sensitivity of ECochG in the diagnosis of Ménière’s disease, the use of an ear canal recording approach for improving auditory brain stem response testing in newborns, and technical aspects related to recording the cochlear microphonic in newborns also will be presented.

Key Words: Action potential, auditory brain stem response, auditory evoked potential, auditory neuropathy, cochlear microphonic, condensation, electrocochleography, endolymphatic hydrops, extratympanic, Ménière’s disease, rarefaction, summating potential, transtympanic, tympanic membrane

Abbreviations: ABR = auditory brain stem response; AEP = auditory evoked potential; AN = auditory neuropathy; AP = action potential; C = condensation; CM = cochlear microphonic; ECochG = electrocochleography; ELH = endolymphatic hydrops; ET = extratympanic; MD = Ménière’s disease; R = rarefaction; SP = summating potential; TM = tympanic membrane; TT = transtympanic

The ability to record the receptor potentials of the cochlea and the whole nerve/compound auditory nerve action potential (AP) in humans via electrocochleography (ECochG) has led to numerous investigations in the Hearing and Speech Department’s auditory evoked potential laboratory at the University of Kansas Medical Center (KUMC) during the past 25 yr. Some of this research has been done in collaboration with colleagues from other universities, most notably John Durrant (University of Pittsburgh) and Roger Ruth (University of Virginia). In general these studies have been designed to improve the techniques and approaches for recording ECochG noninvasively and painlessly; identifying, modifying, and expanding its clinical applications; and seeking ways to improve both the sensitivity and the specificity of these measurements in the diagnosis, assessment, and management of inner ear and auditory nerve disorders.

Although it has been available to the hearing scientist since the 1930s, ECochG’s emergence as a clinical tool was due in part to the discovery and application of the auditory brain stem response (ABR) over 40 yr later. Utilization of improved signal-averaging approaches for recording the minuscule and extremely early responses of auditory centers in the brain stem helped to direct attention back to the periphery. Another important factor that has facilitated the clinical popularity of ECochG, at least in the United States, is the development and refinement of noninvasive recording techniques. Ruben and his coworkers (1960), for example, measured the AP intraoperatively from patients undergoing middle ear surgery. A few years later, nonsurgical techniques that involved passing a needle electrode through the tympanic membrane (TM) to rest on the cochlear promontory were introduced (e.g., Yoshie et al, 1967; Aran and LeBert, 1968). This transtympanic (TT) recording approach to ECochG is still used in Europe and other countries outside the United States. Extratympanic (ET) alternatives to TT recording methods began to appear in the early to mid-1970s. Cullen and colleagues (1972) performed recordings from the lateral surface of the TM, while Coats (1974) used a silver ball electrode glued to a small plastic leaf to achieve recordings from the...
ear canal. My initial research utilizing eCoG was based on ear canal measurements made with the Coats Mylar leaf electrode (Ferraro et al., 1983; Ferraro et al., 1985). In subsequent studies we employed a gold foil electrode wrapped around a compressible foam earplug (i.e., the TIPtrode™), which tended to produce less discomfort for subjects than the leaf electrode (e.g., Ruth, Lambert, et al., 1988). Since around 1990, however, virtually all of our adult studies have utilized a modified version of the electrode described by Stypulkowski and Staller (1987), which directed and facilitated attention back to the TM as the primary site of choice for eCoG recordings. Figure 1 is an illustration of the “tymptrode” we currently use for our recordings.

The purpose of this article is to provide a review of recent research in our clinic/laboratory at the KUMC related to the recording methods and clinical applications of eCoG. These studies include a 5yr retrospective review of our patient database to evaluate the sensitivity and specificity of the recording protocol we use when eCoG is administered to help identify/rule out Ménière’s disease/endolymphatic hydrops. Other research utilizing an eCoG approach to record the ABR and cochlear microphonic (CM) in newborns also will be described. For a more complete review of current eCoG procedures and applications that includes a discussion of electrode and patient preparation, recording parameters, waveform interpretation, and normative values, the reader is referred to Ferraro and Durrant (2006) and Ferraro (2007).

**eCoG RECORDING METHOD**

As indicated above, there are two, general recording approaches for eCoG: TT and ET. The TT method involves penetrating the TM with a needle electrode so that the tip rests on the cochlear promontory. ET approaches utilize primary recording sites that are peripheral to the tympanic cavity (thus the name “extratympanic”). The skin of the ear canal and the external surface of the TM have evolved to be the most popular recording sites. I use the term TM eCoG for the latter approach (Ferraro and Ferguson, 1989) even though this procedure is still considered to be an ET one. As my colleagues and I have reported numerous times (e.g., Ferraro, 2000; Ferraro and Durrant, 2002, 2006), both TT and ET approaches to eCoG have advantages and disadvantages. An advantage of the TT approach is the proximity of the primary recording electrode to the response generators, which produces large components with relatively little signal averaging. ET recordings require more signal averaging and are smaller in magnitude but do not require the assistance of a physician to place the electrode or a topical (usually) anesthetic to dull the pain of puncturing the TM. In 1994, my colleagues and I compared TT and ET (TM) recordings from the same patients. Figure 2 illustrates our findings from this study (Ferraro et al., 1994). The eCoG tracings in the top panel were recorded from the cochlear promontory of a patient with suspected Ménière’s disease (MD), while the lower tracings were measured from the TM. Although the magnitude of the TT recordings is approximately four times larger than the TM responses, both sets of waveforms display an enlarged summating potential (SP)/action potential (AP) amplitude ratio, which was the primary diagnostic criterion we used for reporting a positive finding for MD. In other words, the features of the waveform that were essential to interpreting the electrocochleogram were

![Figure 1](image1.png)

**Figure 1.** Illustration of the “tymptrode” used for recording electrocochleography from the tympanic membrane (from Ferraro, 2007, p. 401).

![Figure 2](image2.png)

**Figure 2.** Abnormal electrocochleograph responses to clicks recorded from the promontory (trans tympanic [TT]) and tympanic membrane (TM) of the affected ear of a patient with Ménière’s disease. Although the magnitudes of the TT responses are approximately 4× greater than the extratympanic recordings, both sets of waveforms display an enlarged summating potential (SP)/action potential (AP) amplitude ratio, which is a positive finding for Ménière’s disease. “Base” indicates the reference point for SP and AP amplitude measurements. The amplitude scale is in microvolts; the time scale is in milliseconds. Stimulus onset was delayed by 2 msec (from Ferraro et al., 1994, p. 27).
apparent in both TT and TM recordings. Furthermore, Stypulkowski and Staller (1987) and Ferguson and I (Ferraro and Ferguson, 1989) showed that ECochG components recorded from the TM displayed magnitudes that were at least twice as large as corresponding measurements made from the ear canal. Thus, the TM offers a good and practical compromise between ear canal and TT recording sites, producing components with larger magnitudes than corresponding ET measurements while eliminating the discomfort and medical-related requirements associated with TT approaches and, most importantly, preserving the features of the waveform essential to the diagnosis of MD.

It also should be noted that the technique of placing the tymptrode is partially “blind” since the TM is obscured by the electrode tip during this process. Proper placement is verified by having the subject acknowledge when he or she feels it touching the membrane and monitoring of the electrical noise floor as the electrode is inserted into the ear canal. The noise floor drops dramatically and becomes free of cyclic artifact and clipped peaks when the tip makes proper contact with the TM. In addition, although TM recordings can be made using circumaural headphones, tubal earphones by comparison offer at least two important advantages: (1) the speaker diaphragm is farther away from the ear, which helps to reduce electromagnetic artifact in the recording, and (2) the compressible foam tip of the sound tube helps to stabilize and hold the tymptrode in place.

**ECochG IN THE DIAGNOSIS OF MÉNIÈRE'S DISEASE/ENDOLYMPHATIC HYDROPS**

As shown in Figure 2, and documented in the literature for over 30 yr, ECochG responses recorded from patients with MD/endolymphatic hydrops (ELH) often are characterized by an enlarged SP and SP/AP amplitude ratio (e.g., Schmidt et al, 1974; Eggermont, 1976; Gibson et al, 1977; 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, Lambert et al, 1988; Ruth, 1990; Ferraro and Krishnan, 1997). One rationale that has been offered (but not verified) for this finding is that an increase in endolymph volume creates mechanical biasing of vibration of the organ of Corti that amplifies the SP since at least some of its components represent non-linearities in the transduction process. Whether the nature of this increased distortion is mechanical (Gibson et al, 1977) and/or electrical (Durrant and Dalsos, 1972; Durrant and Gans, 1975) 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). Despite verification of its bases, an enlarged SP/AP amplitude ratio has evolved as the primary characteristic of an electrocochleogram that is positive for MD.

While the specificity of the SP/AP amplitude ratio in the diagnosis MD has been reported to be 90% or higher (Ferraro et al, 1983; Fou et al, 1996; Murphy et al, 1997), the sensitivity of this measurement in the general Ménière's population is only between 55 and 65% or less (Gibson et al, 1977; Coats, 1981; Kitahara et al, 1981; Kumagami et al, 1982; Campbell et al, 1992; Margolis et al, 1995; Fou et al, 1996; Ferraro and Tibbils, 1999). In other words, patients who display enlarged SP/AP amplitude ratios are very likely to receive a positive diagnosis for MD, but only around half of the individuals with MD have enlarged ratios. Fluctuations in symptoms, deterioration of outer hair cells in more advanced stages of the disease, differences in recording conditions and techniques among researchers/clinicians, and other factors are possible reasons to account for this lack of sensitivity (Ferraro and Ruth, 1994). Nonetheless, there is no question that this factor has limited the clinical usefulness of ECochG in the diagnosis of MD.

Attempts to improve the sensitivity of ECochG have included studies designed to correlate positive findings with symptoms at the time of testing (Ferraro et al, 1985) and manipulation of various recording parameters such as stimulus type, rate, and polarity (Durrant and Ferraro, 1991; Levine et al, 1992; Margolis et al, 1992; Margolis et al, 1995; Orchik et al, 1998). Although differences between MD and non-MD subjects were reported under all of these conditions, data on whether they led to an overall improvement of ECochG sensitivity were not reported.

Some of the above studies (Levine et al, 1992; Margolis et al, 1992; Margolis et al, 1995; Orchik et al, 1998) reported abnormal AP–N1 latency differences between the electrocochleograms evoked by condensation versus rarefaction clicks in MD patients. The rationale for this finding was that the vibration of the cochlear partition under hydropic conditions may be abnormally restricted (or enhanced) in one direction over the other. As a result, the velocity of the traveling wave (on which the AP–N1 is dependent) will differ depending on whether the initial deflection of the partition is in condensation or rarefaction phase. This relationship is obscured when stimuli are presented in alternating polarity, giving way to an SP–AP complex that appears to have a prolonged duration. Near 20 yr earlier, Morrison and colleagues (1980) also observed a widened SP–AP duration in MD patients but attributed this finding to a prolonged after-ringing of the CM under hydropic conditions. Since this earlier study employed alternating polarity stimuli, it may be likely that Morrison and colleagues were observing the same phenomenon as Levine and colleagues that occurs when phase-disparate AP–N1 components from two different waveforms are added together.
Regardless of the rationale for a widened SP–AP complex, the above studies motivated us to begin measuring both the amplitude and the duration of these components to possibly improve the sensitivity of ECochG in the diagnosis of MD. We accomplished our area measurements using a special software routine from Nicolet designed to measure the area under a curve defined by a straight line connecting two cursors placed at selected points on the ECochG waveform. Figure 3 from Devaiah and colleagues (2003, p. 548) illustrates this method. The results of our measurements yielded two studies (Ferraro and Tibbils, 1999; Devaiah et al, 2003) that showed a significant improvement in ECochG’s sensitivity to MD in the relatively small populations that were studied when area values are included in the assessment. After 5 yr of collecting data that included area measurements we recently performed a retrospective chart review of our patient database to evaluate the sensitivity and specificity of all of the ECochG parameters we measure from suspected MD patients (Ferraro and Al-Momani, 2008; Al-Momani et al, 2009). In this study, ECochG results from 178 suspected MD patients were compared to the eventual diagnoses these individuals received from their physicians. Our protocol included recording ECochG to broadband clicks presented in alternating polarity and measuring the amplitudes and areas of the SP and AP (from which SP/AP amplitude and area ratios are derived), the absolute latency of the AP–N1, and the amplitude of the SP to 1000 and 2000 Hz tone bursts (two-cycle rise–fall, 10-cycle plateau). The results of this study revealed the sensitivity and specificity of our recording protocol leading to the diagnosis of MD to be 92% and 84%, respectively. The sensitivity value in particular is considerably higher than previously reported and was attributable to the inclusion of area values in our measurements, especially the SP/AP area ratio. Thus, when measuring the area of the SP–AP complex is included in the testing protocol, ECochG is both a highly specific and sensitive tool for diagnosing MD.

EFFECTS OF HEARING LOSS

In our experience, my colleagues and I have found that patients with sensorineural hearing loss greater than 40–50 dB HL in the 1000–4000 Hz range are not good candidates for ECochG. First, the relationship between the SP and AP is altered as threshold increases (Asai and Mori, 1989; Mori et al, 1993), which could affect both amplitude and area values. Second, the reduction of component amplitudes that tends to accompany increased hearing loss makes both the SP and AP difficult to identify and separate from each other in extratympanic recordations. Finally, when hearing loss is greater than 60 db HL above 500 Hz both components may be unrecordable from the TM or at least so poorly defined as to render ECochG ineffective for diagnosing MD/ELH. Thus, ECochG is best applied in suspected MD/ELH patients in the earlier stages of the disorder, when hearing (at least in the higher frequencies) may still be normal, or in the mild to low moderate loss range, and not “after the fact,” when the disease and its accompanying hearing loss have progressed over time.

PEDIATRIC APPLICATIONS OF ECochG

We have not confined the utilization of electrocochleographic recording approaches to adult populations in our clinic/laboratory. Several years ago we began studying the feasibility of ear canal recordings in newborns and infants, primarily as a way to improve the amplitude and thus detectability of ABR components measured during pediatric hearing screening/assessment procedures. These studies were motivated by previous investigations in adult populations showing that such improvements can be achieved by the use of various ear canal electrodes in combination with more conventional ABR recording procedures (Coats, 1974; Harder and Arlinger, 1981; Lang et al, 1981; Walter...
and Blevgad, 1981; Yanz and Dodds, 1985; Durrant, 1986; Ruth, Mills, et al, 1988; Ferraro and Ferguson, 1989; Bauch and Olsen, 1990). In all of these studies, the amplitude of wave I was substantially larger in both normal- and hard-of-hearing subjects when the ABR was recorded using an ear canal (vs. a mastoid or earlobe) site. Ruth, Mills, et al (1988) compared scalp and ear canal ABR recordings in adults and demonstrated more sensitive wave I thresholds when the secondary electrode was seated in the ear canal. In 1989, Ferguson and I found no differences between the thresholds of waves I and V utilizing a forehead-to-TM electrode configuration (Ferraro and Ferguson, 1989). Furthermore, both waves I and V were measurable in subjects with hearing loss who did not display a wave I when the ABR was recorded using a forehead-to-mastoid approach.

Our experiments with ear canal recordings in newborns began in 1994, when Bealer and colleagues utilized gold foil wrapped around a pediatric sound-delivery tube to record the ABR from the ear canal in a small sample of newborns. Comparison between forehead (+)-to-mastoid (−) and forehead (+)-to-ear canal (−) recordings were made at 60 and 30 dB nHL, which are the two levels most commonly used in newborn screening protocols. Wave I was consistently larger at both stimulus levels and identifiable more frequently at 30 dB nHL in the ear canal recordings. Another interesting aspect of this study was that once constructed, the ear canal electrodes were easier and took less time to apply than the scalp electrodes. Furthermore, because preparation of the ear canal merely involved slight cleansing of the outer portion with a cotton swab without scrubbing the site with water/alcohol/abrasive compound, sleeping infants were less likely to awaken during preparation.

More recently, funding from the Hall Foundation of Kansas City and the Deafness Research Foundation supported two studies in our clinic/laboratory involving ear canal recordings from newborns/infants. Gaddam and I (2008) used a modified (i.e., shortened) TIPtrode to compare ear canal and scalp ABRs in 45 newborns who passed their newborn hearing screening. Figure 4 from this study is an illustration of the modified electrode in place. Figure 5 displays a summary of our findings for wave I amplitude. As can be seen from this graph, wave I from the ear canal is almost twice as large as its mastoid counterpart at sound levels of 80 and 60 dB nHL. Although the amplitude difference at 40 dB was not as dramatic, it was nonetheless statistically significant. At 20 dB, the differences were not significantly different between the two approaches, primarily because many of the ABRs did not display a wave I at this level. When present, however, ear canal–recorded wave I’s always had larger amplitudes than their scalp-recorded counterparts. We are currently applying the ear canal approach to ABR recordings in our clinical pediatric populations and have found it to be particularly helpful for identifying the I–III and I–V interwave intervals in children with suspected retrocochlear disorder (with or without hearing loss).

Additional research in our laboratory/clinic utilizing an ear canal approach for pediatric auditory evoked potential (AEP) testing has been directed at recording the CM from this site. Riazi and I (2008) performed ear canal CM recordings in both newborns and adults in an effort to optimize recording parameters for this potential when it is used to help diagnose auditory neuropathy (AN). Normative data were collected from seven full-term newborns and four adults with no known risk factors for cochlear or retrocochlear disorders. Figure 6 displays the two-channel recordings from one of the
newborns in this study to a 70 dB nHL, 1000 Hz tone burst presented in both rarefaction (R) and condensation (C) polarities. The top four tracings (channel 1) were recorded using a high forehead (1)-to-test ear canal (–) electrode configuration, while the site of the inverting (–) electrode for the bottom tracings (channel 2) was the test ear mastoid. Once again, the ear canal recordings displayed larger amplitudes than their mastoid counterparts, but an even more important finding from this study is apparent in this figure. Namely, CM is present only in record A7. In each set of two tracings (R R and C C), the lower waveforms were recorded with the sound tube pinched shut, indicating the presence of stimulus electromagnetic artifact in all conditions except tracing A7 (from Riazi and Ferraro, 2008, p. 50).

CONCLUSIONS

ECochG has been a topic of considerable interest at the University of Kansas Medical Center for over 25 yr. During this time our research in this area has focused on ways to optimize noninvasive recording protocols, improve the sensitivity and specificity of this tool in the diagnosis of Ménière's disease and other oto-neurological disorders, and expand its clinical applications to include pediatric populations. Among other things, our studies have identified the TM as the optimal noninvasive ECochG recording site for adults. We have used the TM for virtually all of our research studies and clinical recordings since 1990 and accomplish our measurements with minimal/no discomfort to our subjects/patients without ever damaging the membrane.

The use of SP and AP area measurements has significantly improved the sensitivity of ECochG in the diagnosis of MD while maintaining high specificity. Unfortunately, the software for performing these measurements is not yet commercially available. The AEP unit we have used for several years that was equipped with this routine (i.e., the Nicolet Spirit) has been discontinued, and we have devised our own program that allows us to make these measurements from an ASCII file. At the time of this writing, however, two different manufacturers of AEP test instruments are planning to add area-measuring software to their newer units.

Our recent research employing an electrocochleographic (i.e., ear canal) approach to AEP recordings in children has yielded two important findings. First, newborn ABR recordings can be obtained using the ear canal as a recording site, resulting in significantly larger wave I components than observed in more conventional (i.e., scalp) recordings. Second, ear canal recordings and the use of toneburst stimuli facilitate the measurement of the CM in newborns and young children when this component is of interest (such as in the diagnosis of AN). However, strict grounding/shielding approaches must be applied to identify CM from stimulus artifact under these conditions. Without such precautions, it is very likely that stimulus artifact will be mistaken for CM, leading to false-positive diagnoses.

Acknowledgments. I extend my grateful appreciation to the myriad students who have completed research projects, master’s theses, and doctoral dissertations in my laboratory over the past 25 yr. Their work has led to important findings regarding the recording and clinical applications of electrocochleography (ECochG). Recent funding from the Hall.
Foundation of Kansas City and the Deafness Research Foundation has supported our research related to the pediatric applications of ECochG. I dedicate this essay to the memory of Dr. Roger Ruth, a former student, close friend, and collaborator who recently passed away.

REFERENCES


