Observations on Mastoid versus Ear Canal Recorded Cochlear Microphonic in Newborns and Adults

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Abstract

The cochlear microphonic (CM) may play an important role in the diagnosis of auditory neuropathy (AN) in newborns. However, since the CM tends to mirror the waveform of the acoustic stimulus, conscientious recording methodology must be applied to separate true response from artifact. The difficulty in achieving this separation has limited the clinical usefulness of the CM. In an effort to call attention to the importance of recording protocol when measuring the CM, the present study was designed to optimize CM recordings in humans by investigating the following parameters: (1) secondary minus electrode recording site (mastoid versus ear canal [EC]), (2) stimulus parameters, and (3) grounding and shielding conditions. Normative data were collected in full-term newborns (n = 7) and adults (n = 4) with no known risk factors for cochlear or retrocochlear pathology. Results suggest that the CM is easier to separate from stimulus artifact using an EC electrode and toneburst stimuli. In addition, electromagnetic shielding and grounding of the electrode cables and the acoustic transducer were effective in reducing and/or eliminating stimulus artifact. Results from this normative study may be helpful in improving the diagnostic utility of the CM in AN and other hearing-related disorders.

Key Words: Auditory neuropathy, cochlear microphonic, ear canal electrode, electromagnetic shielding, stimulus artifact

Abbreviations: ABR = auditory brainstem response; AN = auditory neuropathy; CM = cochlear microphonic; EC = ear canal; ECochG = electrocochleography; EP = evoked potential; F_z = high forehead; IHC = inner hair cell; OAE = otoacoustic emissions; OHC = outer hair cell

Sumario

La microfónica coclear (CM) puede jugar un papel importante en el diagnóstico de la neuropatía auditiva (AN) en recién nacidos. Sin embargo, dado que la CM tiende a reflejar la forma de onda del estímulo acústico, debe aplicarse una metodología concienzuda de registro de estímulos para separar la verdadera respuesta del artefacto. La dificultad para lograr esta separación ha limitado la utilidad clínica de la CM. En un esfuerzo por llamar la atención respecto de la importancia del protocolo de registro cuando se mide la CM, el estudio presente fue diseñado para optimizar los registros de la CM en humanos, por medio de la investigación de los siguientes parámetros: (1) sitio secundario menor del electrodo de registro (mastoides vs. canal auditivo [EC], (2) parámetros del estímulo, y (3) condiciones de aterrizaje y de escudo protector. Se colectaron datos normativos en recién nacidos de término (n =

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7) y adultos (n = 4), sin factores de riesgo para patología coclear o retro-coclear. Los resultados sugieren que la CM es fácil de separar de los artefactos del estímulo utilizando un electrodo EC y un estímulo de tipo burst tonal. Además, el aterrizaje de los cabes de los electrodos y del transductor acústico, así como un escudo electromagnético fueron efectivos para reducir y/o eliminar los artefactos del estímulo. Los resultados de este estudio normativo pueden ser útiles para mejorar la utilidad diagnóstica de la CM en la AN y otros trastornos relacionados con la audición.

Palabras Clave: neuropatía auditiva, microfónica coclear, electrodo del canal auditivo, escudo electromagnético, artefacto del estímulo

Abreviaturas: ABR = respuesta auditiva del tallo cerebral; AN = neuropatía auditiva; CM = microfónica coclear; EC = canal auditivo; ECochG = electrococleografía; EP = potencial evocado; Fz = frente alta; IHC = células ciliadas internas; OAE = emisiones otoacústicas; OHC = células ciliadas externas

Although the cochlear microphonic (CM) is the most extensively studied inner ear potential in animals, applications and procedures for recording the CM in humans have received relatively limited attention (Ferraro and Ruth, 1994). The CM is generated in response to the excitatory deflection of inner hair cell (IHC) and outer hair cell (OHC) stereocilia and primarily reflect OHC (Davis, 1958; Keidel, 1962; Dallos, 1973; Dallos and Wang, 1974) alternating current receptor currents (Dallos and Cheatham, 1976). As such, the CM predominately reflects the "instantaneous motion pattern of the basilar membrane in the vicinity of the recording electrode" (Dallos and Cheatham, 1976, p. 510). Due to this feature, the CM is often described as the "cochlear electrical correlate of an acoustical stimulus" (Withnell, 2001, p. 75). Since the CM mimics the stimulus waveform (Dallos, 1973), however, it is often difficult to differentiate from stimulus artifact especially in far-field recordings (Ferraro and Ruth, 1994; Ferraro and Durrant, 2002). Acoustical stimulus artifact is produced by an electromagnetic field generated around the acoustical transducer used to deliver the signal to the ear. In far-field human recordings, conscientious methodology is necessary to separate true CM from other electrical events (both physiological and electromagnetic) (Ferraro and Ruth, 1994; Ferraro and Durrant, 2002). Failure to do so can lead to misinterpretation of the response and false diagnoses.

Findings from several studies suggest that the CM may be useful in the differential diagnosis of disorders such as auditory neuropathy (AN) (Deltenre et al, 1999; Rance et al, 1999; Starr et al, 2001; Berlin et al, 2003) and Meniere's disease (Gibson and Beagley, 1976; Moriuchi and Kumagami, 1979; Morrison et al, 1980; Kumagami et al, 1982; Gibson and Prasher, 1983; Ge et al, 1997; Zou et al, 2006). Although the CM may improve the sensitivity and specificity of identifying hearing-related disorders, there have been a limited number of studies investigating the CM in humans. The paucity of research in human CM recordings may be due in part to intersubject amplitude variability in both normal and abnormal ears (Ferraro and Ruth, 1994) as well as the technical difficulty of separating CM from stimulus artifact (Ferraro and Ruth, 1994; Ferraro and Durrant, 2002).

Renewed interest in the CM has resulted from the finding that it may be the only recordable cochlear response in patients with AN (Deltenre et al, 1999; Rance et al, 1999; Starr et al, 2001). Consequently, the CM may play an important role in the diagnosis of AN, a disorder characterized by preserved cochlear receptor activity (otoacoustic emissions [OAE] and/or CM) and an absent or severely abnormal auditory brainstem response (ABR) (Deltenre et al, 1999). Approximately 50% of early-onset AN patients described by Rance et al (1999) showed absent OAE and preserved CM. Absent OAEs and preserved CMs may occur in the presence of middle ear pathology (Stein et al, 1996; Starr et al, 2001). Differences in OHC and IHC cochlear micromechanics may also explain the absent OAE and preserved CM combination. That is, the preservation of the CM may result from differences in the dynamic ranges of OAEs and CMs (Deltenre et al, 1999). Therefore, CM may be preserved when there is only a partial loss of OHCs that is significant enough to result in absent OAEs (Deltenre et al, 1999;
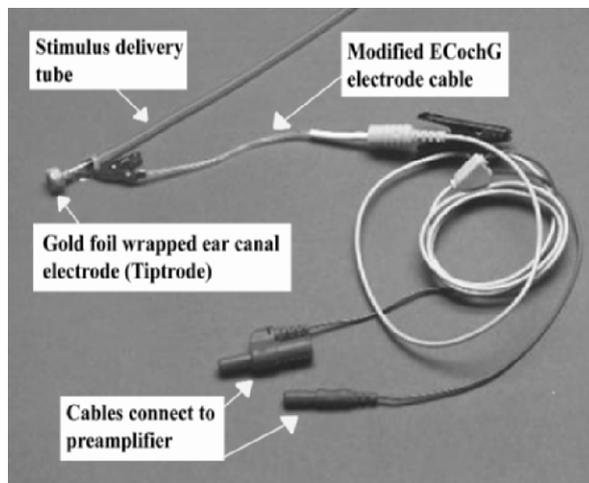
Figure 1. Photograph of the ear canal (EC) electrode assembly.

Figure 2. Schematic of the ear canal (EC) electrode assembly.

Rance et al, 1999). The preserved CM and absent OAE combination may also occur in patients with extensive cochlear OHC damage. In this instance the CM may be solely generated by cochlear IHCs (Rance et al, 1999).

In the present study, we examined techniques that can be employed to optimize the recording of far-field CM recordings in humans. Noninvasive CM recording conditions were examined by (1) comparing different recording sites and stimulus parameters and (2) examining various shielding and grounding conditions aimed at inhibiting/reducing artifactual contamination of the CM. Based on theoretical concepts (near-field recordings) and ABR studies, it is hypothesized that CM amplitude will be enhanced with the use of an EC (ear canal) electrode. Thus, two-channel CM recordings comparing EC to mastoid electrode configurations were employed. This study also examined whether electromagnetic stimulus artifact is reduced when a grounded cable and/or shielded and grounded transducer is utilized. The ultimate goal of this research is to provide techniques to optimize human recordings of the CM by separating it from other electrical events that can contaminate the response and lead to misinterpretation of results and inaccurate diagnoses.

METHOD

CM was recorded from nonsedated full-term newborns (n = 7) and adults (n = 4) with no known risk factors for cochlear or re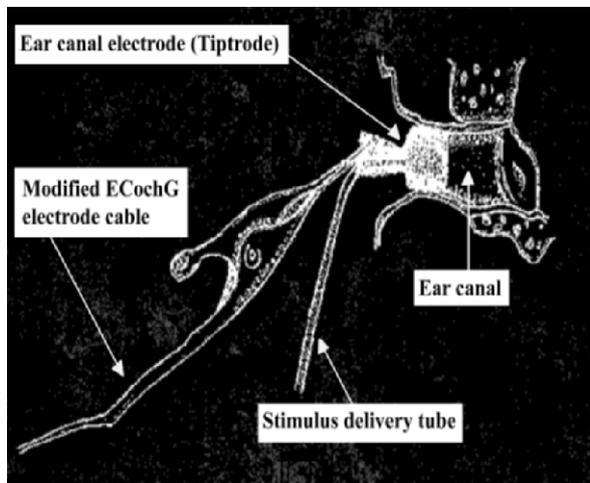trocochlear pathology. All pediatric subjects were born dur-ing the time between completion of 38 to 41 weeks of gestation and had passed their transient evoked otoacoustic emission hearing screening. With the pediatric subjects, the aim and methodology of the study were discussed with a parent, and a "Parental Permission Form," approved by the University of Kansas Medical Center Human Subjects Committee, was signed prior to data collection.

CM was recorded utilizing surface disc and EC electrodes (Tiptrode, Nicolet Biomedical). Figures 1 and 2 provide a photograph and schematic of the EC electrode assembly, respectively. The Tiptrode, which consists of a foam eartip wrapped by gold foil, was attached to the end of the stimulus delivery tube and inserted into the EC of the subject. The Tiptrode was covered with electrolyte gel prior to EC insertion. For the pediatric subjects, the Tiptrode was reduced to 1/4 to 1/2 of its original size. As shown in Figures 1 and 2, a modified electrocochleography (ECochG) electrode cable was attached to the Tiptrode via an alligator clip. The surface and Tiptrode electrodes picked up analog electroencephalogram signals that were then delivered to the preamplifier of the evoked potential (EP) unit.

A simultaneous two-channel recording was performed comparing EC (channel 1) and mastoid (channel 2) electrode configurations, since conventional recordings of the ABR utilize either the mastoid or ear lobe as the secondary site. Research in our laboratory shows no differences in recordings between these two secondary locations. A surface electrode placed on the high forehead (F_z) served as the primary/noninverting/positive (+) recording site for both channels. For channel 1, a Tiptrode
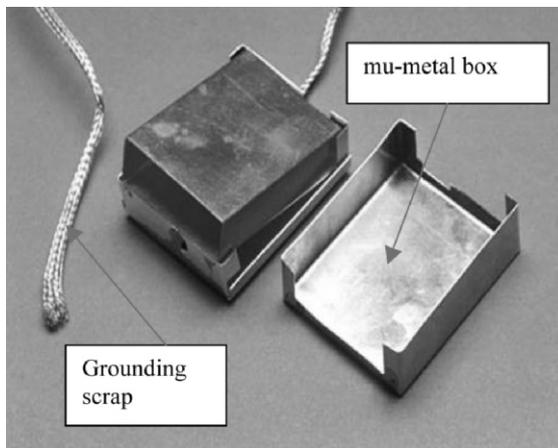
Figure 3. Photograph of the mu-metal box.

placed in the EC of the stimulated ear served as the secondary/inverting/negative minus electrode site. For channel 2, a surface electrode placed on the test ear mastoid served as the secondary minus electrode site. A surface electrode placed on the nontest ear mastoid served as ground. Positive events were displayed upward.

Adult recordings were collected at an electrically shielded laboratory utilizing the Nicolet Spirit EP system. In an attempt to identify features that may contribute to stimulus artifact as well as precautions necessary to inhibit it, the following recording conditions were examined in adult subjects: (1) ungrounded/unshielded transducer, ungrounded cable; (2) ungrounded/unshielded transducer, grounded cable; (3) ungrounded/ shielded transducer, ungrounded cable; (4) grounded/ shielded transducer, ungrounded cable; (5) ungrounded/shielded transducer, grounded cable; and (6) grounded/shielded transducer, grounded cable. Due to time constraints, all

pediatric recordings were performed using a grounded cable (preamplifier input was grounded) and mu-metal shielded transducer in an electrically unshielded environment (full-term nursery) utilizing the Biologic Navigator Pro EP unit. To differentiate between CM and stimulus artifact, the stimulus delivery tube was pinched with a hemostat. That is, pinching the stimulus delivery tube has no effect on stimulus artifact (electromagnetic field) but eliminates CM (biological response).

Responses were amplified (100 kHz gain) and analog filtered (100 Hz to 3 kHz) across 500 Hz to 1 kHz sweeps. Both click (100 μsec square wave pulses) and toneburst (500 Hz, 1 kHz, 2 kHz) stimuli were presented monaurally via insert earphones (Biologic: E.A.R.TONE 3A; Nicolet: Etymotic ER-2). The transducer was encased with a mu-metal box. Pictured in Figure 3, the mu-metal box provided electromagnetic shielding around the transducer. Grounding scrap was soldered to the mu-metal box.

Due to difficulty recording CM in nonsedated newborns, stimulus parameter manipulation was limited. Both click (5/7 subjects) and 1 kHz toneburst (6/7 subjects) stimuli were utilized in the pediatric subjects. Pediatric recordings were conducted at 70 dBnHL with repetition rates of: 11.3/sec (4/7 subjects), 33.3/sec (5/7 subjects), and 66.1/sec (2/7 subjects). Adult recording parameters include 500 Hz, 1 kHz, and 2 kHz toneburst stimuli presented at 70 dBnHL and 95 dBnHL. With the adult recordings, toneburst stimuli were presented at a rate of 11.3/sec and 33.3/sec. Tables 1 and 2 provide a summary of adult and pediatric signal averaging parameters and stimulus parameters, respectively.

Table 1. Adult and Pediatric Signal Averaging Parameters

Acquisition Parameters	
Number of Recording Channels	2
Electrode Configuration	Channel 1: F_z (+) - to - TEC (-) Channel 2: F_z (+) - to - TEM (-) Ground: NTEM
Amplifier Gain	100,000X
High- and Low-Pass Filter Settings (Hz)	100–3000
Test Epoch/Timebase (msec)	Toneburst: 21.33; Click: 5.33, 16.0, 21.33
Sweeps	500–1,000
Artifact Rejection	Enabled

Note: F_z = High Forehead; TEC = test ear canal; TEM = test ear mastoid; NTEM = nontest ear mastoid.

Table 2. Adult and Pediatric Stimulus Parameters

Type	Polarity	Frequency	Intensity (dBnHL)	Repetition Rate
Toneburst	Condensation	500 Hz, 1 kHz, 2 kHz	70, 95	11.3/sec, 33.3/sec
Click	Rarefaction			66.1/sec

RESULTS

Normative data were collected in full-term newborns (n = 7) and adults (n = 4) with no known risk factors for cochlear or retrocochlear pathology. The following terminology will be applied to describe CM results: present, possibly present, or absent. CM was determined to be present if the following conditions were met: (1) time delay between stimulus onset and potential, (2) reversal in polarity with a reverse in stimulus polarity (i.e., condensation vs. rarefaction polarity), and (3) absence of stimulus artifact in the pinched stimulus tube delivery condition. The term "possibly present" was applied when CM was contaminated with stimulus

Figure 4. Example of toneburst generated CM recorded from a full-term infant (subject CMR2). CM is present in record A7 only. Record A7 was recorded from channel 1 (F_z [+] - to - TEC [-]; test ear canal [TEC]). CM were recorded utilizing 70 dBnHL, 1 kHz toneburst presented at a rate of 11.3/sec. Records A1, A5, A7, and B1 were obtained from channel 1. Records A2, A6, A8, and B2 were obtained from channel 2 (F_z [+] - to - TEM [-]; test ear mastoid [TEM]). The stimulus delivery tube was pinched in records A5, B1, A6, and B2. Note the presence of stimulus artifact under the pinched stimulus delivery tube condition (records A5, A6, B2). Stimulus envelope = 5 msec r/f, 10 msec plateau; Test Epoch = 21.33 msec; R = rarefaction polarity; C = condensation polarity.

artifact. CM was determined to be absent if CM could not be differentiated from stimulus artifact. Representative records will be provided to clarify our nomenclature.

Pediatric Findings

Study results indicate that CM was present in only one pediatric subject (CMR2) with toneburst stimuli (Figure 4) and possibly present in another subject (CM6) with click stimuli only (Figure 5). Figure 4, recorded from subject CMR2, provides a representative example of a recording from a pediatric subject utilizing toneburst stimuli. Figure 4 illustrates that CM is present in record A7 (recorded from channel 1, EC electrode). The presence of CM was confirmed by the absence of stimulus artifact in the pinched condition (record B1). The presence of CM could not be determined in records A1, A2, and A8 due to the presence of stimulus artifact in the pinched stimulus delivery tube condition (records A5, A6, and B2). An intrasubject (subject CM6) comparison of toneburst and click recordings is provided in Figure 5.

Figure 5A illustrates that only stimulus artifact was recorded when condensation polarity toneburst stimuli were employed. Note the presence of stimulus artifact in the pinched stimulus delivery tube condition (records A7 and A8). Figure 5B provides an example of when the terminology "possibly present" was applied. Due to the transient nature of a click-generated CM as well as the presence of stimulus artifact, it is difficult to differentiate between CM and stimulus artifact. However, the initial deflection that reverses polarity with a change in stimulus polarity is most likely CM.

A comparison of responses to toneburst (6/7 subjects) and click (5/7 subjects) stimuli is shown in Figure 6. Due to difficulty testing nonsedated newborns, an intrasubject comparison of stimulus type could not be performed in every subject. Results indicate that CM was present in only one subject (CMR2) with toneburst stimuli. Due to time constraints recordings were not conducted utilizing click stimuli in subject CMR2. A comparison of toneburst (6/7 subjects) and click (5/7 subjects) stimuli revealed that CM was present in 1/7 subjects (toneburst stimuli), possibly present in 1/7 subjects (click stimuli), and absent in 5/7 subjects.
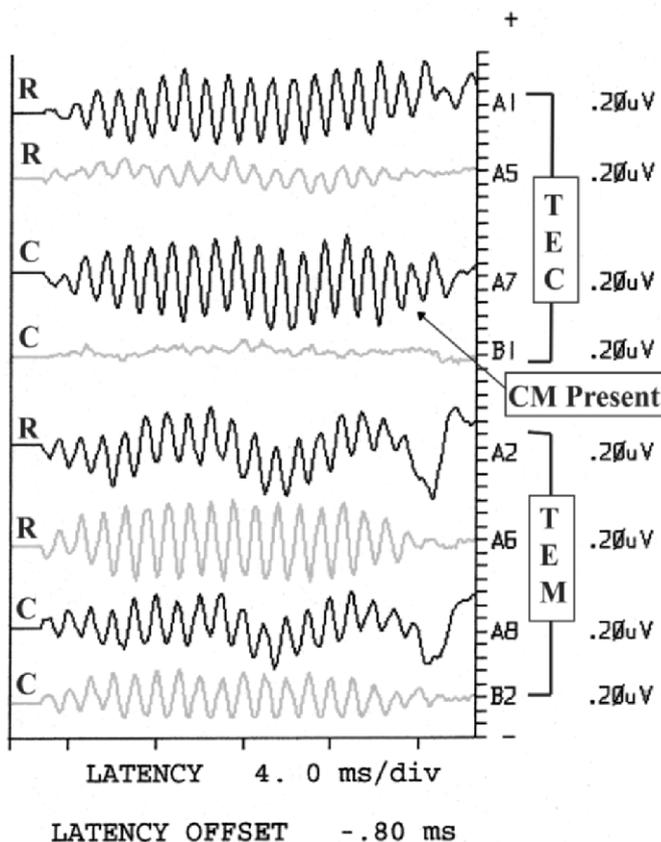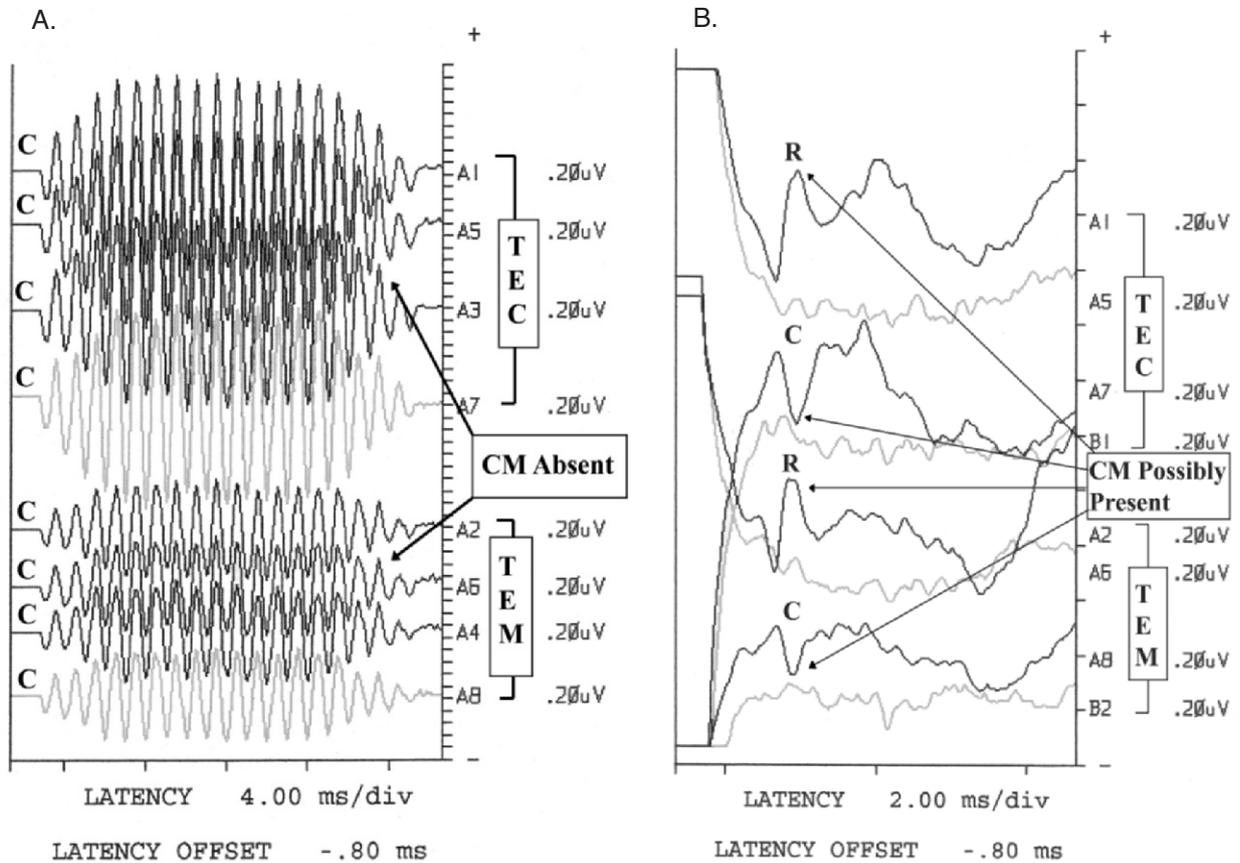
Figure 5. A: Representative pediatric CM recorded utilizing toneburst stimuli: CM absent in both channels. B: Representative pediatric CM recorded utilizing click stimuli: CM possibly present in both channels. Intrasubject comparison of toneburst and click recordings in a pediatric subject (CM6). In A, CM was recorded utilizing 70 dBnHL, 1 kHz, condensation polarity toneburst presented at a rate of 33.3/sec (stimulus envelope = 5 msec r/f, 10 msec plateau; test epoch = 21.33 msec). Note the inability to differentiate between CM and stimulus artifact with the use of toneburst stimuli, A (i.e., stimulus artifact is present in the pinched stimulus delivery tube condition [records A7 and A8]). CM absent in both channels with the use of toneburst stimuli. In B, CM was recorded utilizing 70 dBnHL, rarefaction (A1, A2, A5, A6) and condensation (A7, A8, B1, B2) polarity clicks presented at a rate of 66.1/sec (test epoch = 5.33 msec). CM is possibly present in both channels with the use of click stimuli. TEC = test ear canal; TEM = test ear mastoid; C = condensation polarity; R = rarefaction polarity.
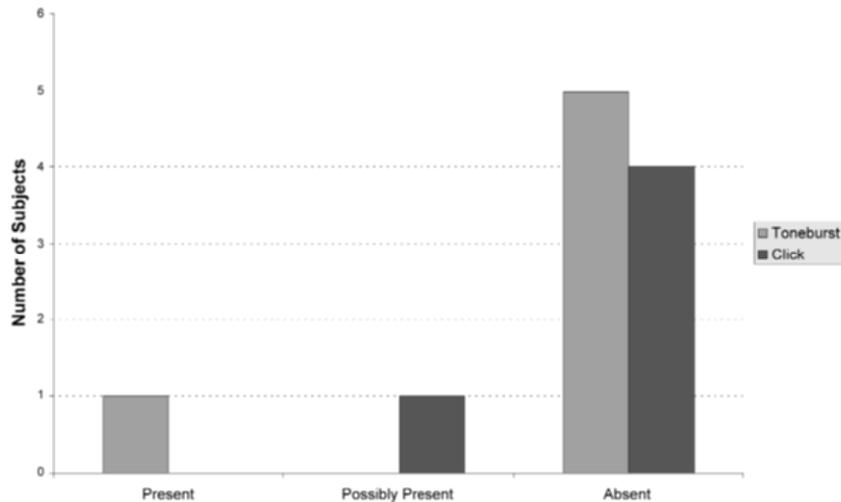

Figure 6. Influence of stimulus type on the ability to record CM in newborns. A comparison of toneburst (6/7 subjects) and click (5/7 subjects) stimuli revealed that CM was present in 1/7 subjects (toneburst stimuli), possibly present in 1/7 subjects (click stimuli), and absent in 5/7 subjects.

Adult Findings

Due to difficulty testing nonsedated newborns and separating CM from stimulus artifact in an electrically unshielded environment (full-term nursery), in the second phase of the study data were collected in adults (n = 4) at the KUMC Auditory EP Laboratory. Figure 7 provides an intrasubject comparison of conditions 1 (ungrounded/unshielded transducer, ungrounded cable) and 6 (grounded/shielded transducer, grounded cable). Note the decrease of artifact under condition 6. Figures 8 and 9 illustrate the influence of grounding and shielding condi-

tions on the ability to record 1 kHz generated CM. Results suggest that CM was most likely to be recorded under the following parameters: (1) channel 1 (F_z [+] - to - TEC [-]; test ear canal [TEC]) and (2) condition 6.

DISCUSSION

The CM can be a useful indicator of cochlear pathology and/or altered cochlear micromechanics; unfortunately, the nature of the potential has limited its clinical utility. The aim of this normative study was to examine far-field recorded CM under a variety of stimulus parameters and shielding
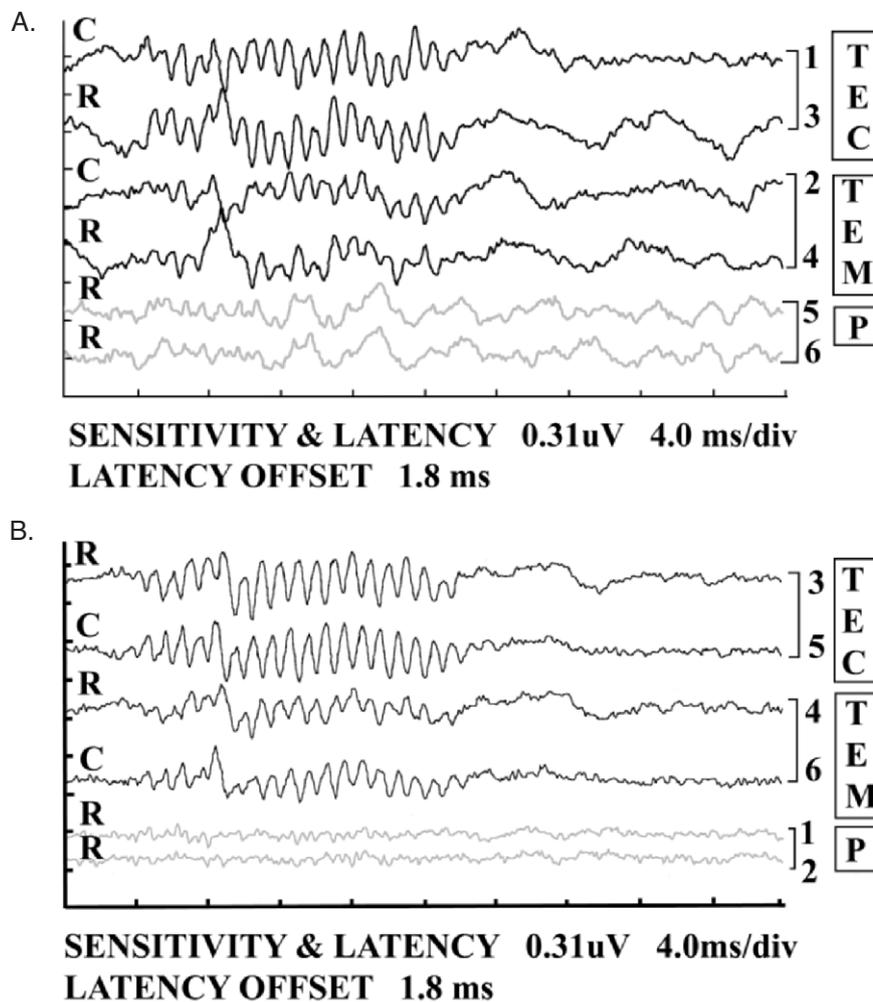

Figure 7. A: Condition 1, 1 kHz toneburst, 95 dBnHL, 11.3/sec. B: Condition 6, 1 kHz toneburst, 95 dBnHL, 11.3/sec. Intrasubject, subject CMMRII, comparison of conditions 1 (ungrounded/unshielded transducer, ungrounded cable) and 6 (grounded/shielded transducer, grounded cable). Recording parameters include 95 dBnHL, 1 kHz, condensation and rarefaction polarity toneburst stimuli presented at a rate of 11.3/sec (test epoch = 40 msec). In A, records 1 and 3 were recorded from channel 1 [F_z (+) – to – TEC (-)]. Records 2 and 4 were recorded from channel 2 [F_z (+) – to – TEM (-)]. Note the presence of artifact under the pinched stimulus delivery tube condition (records 5 and 6). In B, records 3 and 5 were recorded from channel 1 [F_z (+) – to – TEC (-)]. Records 4 and 6 were recorded from channel 2 [F_z (+) – to – TEM (-)]. The stimulus delivery tube was pinched in records 1 and 2. Note the decrease of artifact under condition 6. TEC = test ear canal; TEM = test ear mastoid; P = pinched stimulus delivery tube; C = condensation polarity; R = rarefaction polarity.
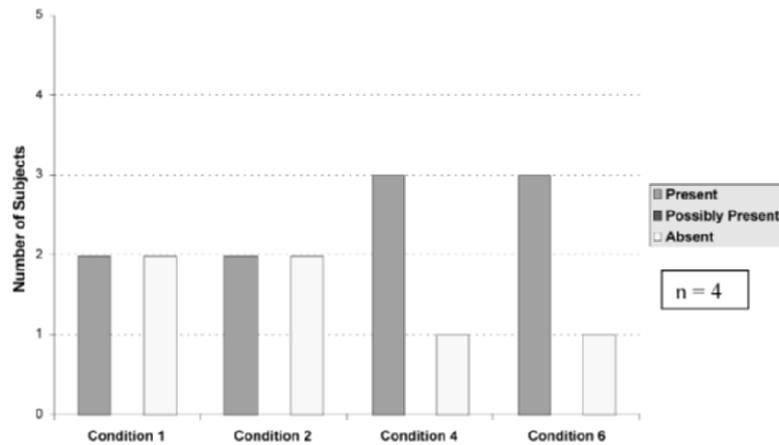
Figure 8. Influence of grounding and shielding conditions on the ability to record CM from channel 1 (F_z [+] - to - TEC [-]); test ear canal [TEC]) in adults utilizing 1 kHz toneburst stimuli. The bar graph illustrates that CM was most likely recorded under conditions 4 (grounded/shielded transducer, ungrounded cable) and 6 (grounded/shielded transducer, grounded cable).
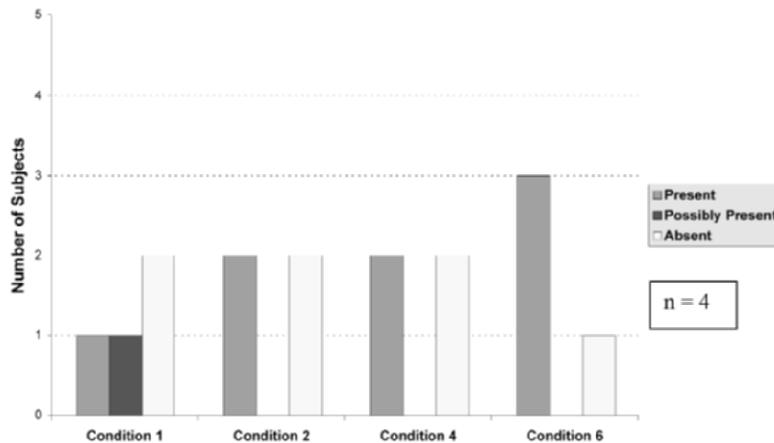

Figure 9. Influence of grounding and shielding conditions on the ability to record CM from channel 2 (F_z [+] - to - TEM [-]; test ear mastoid [TEM]) in adults utilizing 1 kHz toneburst stimuli. The bar graph illustrates that CM was most likely recorded under condition 6 (grounded/shielded transducer, grounded cable).

conditions aimed at inhibiting/reducing artifactual contamination of the CM. Our results suggest that electromagnetic shielding and grounding of the electrode cables and the acoustic transducer (Ferraro and Ruth, 1994) were effective in reducing and/or eliminating electromagnetic stimulus artifact.

Our findings also suggest that CM was more likely to be recorded with an EC electrode compared to a surface electrode on the test ear mastoid process. Our results correspond with the averaged nature of the CM. That is, since the CM is a weighted average of potentials generated by thousands of hair cells within the vicinity of the recording electrode site (Dallos et al, 1974), the closer the primary electrode is to the generator, the stronger the response (i.e., greater vectorial sum of hair cell responses). In addition, CM was also more likely to be recorded utilizing

a high intensity signal (95 dBnHL). This finding is consistent with the fact that CM amplitude is strongly influenced by current flow through both OHCs and IHCs, but primarily OHCs (Dallos and Cheatham, 1976; Neely and Kim, 1986; Zou et al, 2006). Thus, higher stimulus intensities result in greater current flow through the HCs.

As indicated above, the CM is a "weighted average" of potentials that are recorded in the vicinity of the primary recording electrode site (Durrant and Lovrinic, 1995). Consequently, in the normal cochlea, surface and round window recorded CM are predominately generated by OHCs (Davis, 1958; Dallos, 1973; Dallos et al, 1974; Dallos and Wang, 1974; Sellick and Russell, 1980) at the basal end of the cochlea (Tasaki et al, 1952, 1954; Tasaki, 1957; Honrubia et al, 1976; Sohmer et al, 1977). Hence, our failure to

record far-field recorded CM, to a low-frequency pure tone, may have resulted from the fact that we were only able to record the trailing end of the traveling wave, resulting in a low amplitude potential that was difficult to elevate above the electrical noise floor. One study, utilizing round window recorded CM generated by high intensity 200 Hz input stimuli, suggests that the apical regions of the cochlea (≤ 8 kHz) contribute "less than 2% to the total round window microphonic" (Patuzzi et al, 1989, p. 186). Several animal studies have also demonstrated that round window recorded CM is predominately generated at the basal end of the cochlea, regardless of test frequency (Tasaki et al, 1952, 1954; Tasaki, 1957; Honrubia et al, 1976). Consequently, OHC integrity should not be determined by the presence of CM alone (Withnell, 2001).

The CM may be a useful tool in the diagnosis of AN (Deltenre et al, 1999; Rance et al, 1999; Starr et al, 2001) and Meniere's disease (Gibson and Beagley, 1976; Moriuchi and Kumagami, 1979; Morrison et al, 1980; Kumagami et al, 1982; Ge et al, 1997; Zou et al, 2006). Unfortunately, problems associated with differentiating between CM and stimulus artifact, as well as CM response pattern variability, have limited its clinical utility (Ferraro and Ruth, 1994). Renewed interest in the CM has resulted from the finding that the CM may be the only recordable cochlear response in patients with AN (Deltenre et al, 1999; Rance et al, 1999; Starr et al, 2001). In addition, a DC bias of the basilar membrane toward the scala vestibuli, such as the bias resulting from Meniere's disease, may create an excitatory stereocilia displacement bias toward the opening of OHC mechanoelectrical transduction channels (Ge et al, 1997; Zou et al, 2006). This excitatory bias may in turn result in an enlarged CM amplitude. Consequently, improvement in CM recording techniques can potentially assist with the differential diagnosis of a spectrum of disorders/conditions.

SUMMARY

Findings from this study indicate that we were unable to differentiate between CM and stimulus artifact using commonly applied recording conditions in both newborns and adults. Failure to differentiate between CM and stimulus artifact can lead to misinterpretation of the response and false diagnoses. Our findings suggest that it is necessary to apply strict recording and shielding/grounding techniques when attempting to record the CM in a clinical setting. We recommend using a grounded and shielded transducer and grounded cable during diagnostic testing. Thus, although recording far-field CM in humans continues to be technically difficult, application of the above protocols should contribute to more accurate diagnoses when using this tool.

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