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Wideband ipsilateral measurements of middle-ear muscle reflex thresholds in children and adults[a]

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Abstract

The goals of the current study were to: 1) evaluate the feasibility of a new wideband approach to measuring middle-ear muscle reflex (MEMR) status, and 2) to test the hypothesis that ipsilateral thresholds elicited with 1 or 2 kHz tones and broadband noise activators on a wideband acoustic transfer function (WATF) system are lower than thresholds elicited on a clinical system. Clinical MEMR tests have limitations, including the need for high activator levels to elicit a shift in a narrowband probe (e.g., a 0.226 or 1 kHz tone). Wideband MEMR tests using WATFs may elicit the reflex at lower levels because a wideband probe (click) is used and the threshold detection criterion can be wideband. Mean wideband MEMR thresholds across 40 normal-hearing adult ears were 2.2–4.0 dB lower than clinical MEMR thresholds, depending on the activator and specific WATF test used (admittance magnitude or energy reflectance). Wideband MEMR has potential clinical utility beyond the adult population, including use in newborn and preschool hearing screenings. In a newborn hearing screening, for example, wideband MEMR could be completed with the same system as otoacoustic emissions. However, further investigations in infants and young children are needed.

I. INTRODUCTION

The main goal of the current study was to compare standard clinical and wideband acoustic transfer function (WATF) measurements of the middle-ear muscle reflex (MEMR) to test the hypothesis that MEMR thresholds are lower in a prototype WATF procedure than the clinical procedure. The standard clinical MEMR test is described in this Introduction, followed by a description of a wideband MEMR test.

A. Clinical middle-ear muscle reflex test

When an intense sound is presented to the ear, and if the middle ear, cochlea, and neural afferent and efferent systems are functioning normally, the MEMR arc is stimulated (for a review, see Wiley and Fowler, 1997). The MEMR induces a contraction in the stapedius muscle in the middle ear, which then stiffens the middle-ear ossicular chain. This reduces the amount of energy that is absorbed or transferred into the cochlea. Because the ossicular chain is stiffened, the acoustic admittance measured in the ear canal at the tympanic membrane (TM) is also changed. At low frequencies such as 0.226 kHz, admittance is typically reduced by a MEMR, and the amount of energy that is reflected from the TM back through the ear canal is increased.

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1. CMEMR test construction—A clinical middle-ear muscle reflex (CMEMR) test is performed after a tympanometry test (Wiley and Fowler, 1997). In a typical tympanometry test, a probe is placed in the ear canal to produce a hermetic (air-tight) seal, and a 0.226 kHz probe tone is continuously presented while pressure in the ear canal is varied. The pressure at which the acoustic admittance magnitude at the TM has its maximum is the tympanometric peak pressure (TPP). The probe stimulus of the CMEMR is usually the same probe tone used in the tympanometry test, namely, a 0.226 kHz tone. CMEMR measurements are typically made with the ear-canal pressure adjusted to the TPP in the ear receiving the probe stimulus, so that admittance is at its maximum at the probe frequency in the absence of the activator. A second stimulus, the activator, is used in the CMEMR test to elicit the MEMR, and the probe response is compared in the presence and absence of the activator.

Common activators are 0.5, 1, 2 and 4 kHz tones and broadband noise (BBN). In an ipsilateral MEMR test, the probe assembly is placed in the ear canal in which the reflex is to be measured and the activator is presented to the same ear. In a contralateral MEMR test, the probe assembly is placed in the ear canal in which the reflex is to be measured, and a sound source presents the activator in the contralateral ear. The MEMR threshold is defined as the lowest activator level that produces a criterion difference in the acoustic responses to the probe in the presence and absence of the activator. Another criterion is the growth of the MEMR shift in the admittance magnitude (at 0.226 kHz). That is, as the activator level increases the decrement in admittance should become larger. If not, the decrement may not be a true reflex, but perhaps a swallow or some other biological noise.

A CMEMR threshold test may be used to assist in the identification of sensorineural hearing loss, conductive hearing loss, 8th nerve tumors, or 7th nerve pathologies. In a CMEMR decay test, the activator is presented at a suprathreshold level, i.e., a level that is approximately 10 dB higher than the CMEMR threshold, and the change in the admittance magnitude at the probe frequency is assessed over activator durations of approximately 10 s. A CMEMR decay test may be used to detect acoustic neuromas. CMEMR tests may also be used as part of a screening protocol for preschool- and school-aged children (Silman *et al.*, 1992) and at-risk infants (Hirsch *et al.*, 1992). Silman *et al.* compared the sensitivity and specificity of TPP, static admittance, tympanometric width, and ipsilateral CMEMR at 1 kHz at 110 dB HL with a 0.226 kHz probe, alone and in different combinations for detecting middle-ear effusion. They found that the individual measure with the highest sensitivity and specificity was the CMEMR. Overall, they recommended a protocol in which a child is referred if the tympanometric width is greater than the 95th percentile of a normal group, the static admittance is lower than the 90% range, and the CMEMR is absent, OR if TPP is negative and CMEMR is absent. They further recommended that CMEMR should be tested first at 100 dB HL, and if absent, then test at 110 dB HL. Hirsch *et al.* used CMEMR and auditory brainstem response (ABR) to screen infants who were being discharged from an intensive care nursery. Ipsilateral CMEMR thresholds were obtained with a 0.8 kHz probe, and 2 kHz and narrowband noise activators. The authors selected a screening level (for pass/fail) of 90 dB sound pressure level (SPL) for the 2 kHz activator and 80 dB SPL for the narrowband noise. They found that the CMEMR screen identified the same ears that failed the ABR screen, and suggested that the CMEMR test could be used as a faster, cheaper first screen for a CMEMR/ABR protocol. Those who fail the CMEMR screen would then receive an ABR screen.

2. Limitations of CMEMR tests—These CMEMR tests are standard practice complete with associated normative data and a large body of literature regarding test sensitivity across a diverse body of disorders. However, several limitations still exist.

First, the measurement is restricted to a single probe frequency so that only the admittance changes at the probe frequency are evaluated. Because pathologies may not be uniformly

evident at the same frequency in every ear, the 0.226 kHz probe tone used in clinical measurements may not be ideal across a diverse clinical population. Multifrequency tympanometry has been shown to provide improved sensitivity to some middle-ear pathologies (Hunter and Margolis, 1992;Li *et al.*, 1999;Margolis *et al.*, 1999). Normative data in comparison to the Vanhuyse *et al.* 1975 model are available for adults and children (e.g., Calandruccio *et al.*, 2006;Hunter and Margolis, 1992;Margolis and Goycoolea, 1993) and for infants and toddlers (e.g., Calandruccio *et al.*, 2006). Although these methods may increase the probability of detecting middle ear dysfunction, they require extra time to either sweep pressure at multiple probe frequencies or sweep probe frequency at multiple fixed pressures. Higher probe tone frequencies (such as 0.660, 0.8, or 1 kHz) have also been used for CMEMR measurements in infants (e.g., Hirsch *et al.*, 1992;Kankkunen and Liden, 1984;Sprague *et al.*, 1985;Weatherby and Bennett, 1980).

A method using a wideband probe stimulus may reduce test time and increase the probability of detecting dysfunction. This is because a response shift could be detected in a wide range of frequencies that are present simultaneously in the stimulus. For example, Feeney and Sanford (2005) measured thresholds in six-week-old infants and adults of the MEMR elicited by a contralateral BBN activator using wideband energy reflectance and admittance responses. They found that different frequency ranges in infants and adults improved detection of the MEMR. These results suggest that a single probe tone is insufficient to measure MEMR across all ages, and the authors suggested that this wideband technique could be used to track the best frequency for MEMR measurements during postnatal middle-ear development. However, an ipsilateral MEMR test appears preferable in young infants to a contralateral test, because it is simpler: the ipsilateral test is a single-ear test while the contralateral test requires simultaneous sound stimulation in both ears.

A second potential limitation is that CMEMR testing requires a hermetic seal and pressurization of the ear canal. Pressurization can displace the extremely compliant ear-canal walls of normal infants up to approximately two months of age (Holte *et al.*, 1990). Normal tympanograms can be obtained in ears diagnosed with otitis media with effusion (OME) in infants less than five months of age, with procedural limitations at younger ages possibly due in part to ear-canal wall movement (e.g., Schwartz and Schwartz, 1980). Hirsch *et al.* 1992 were able to elicit reflexes in most of their infants (who also passed the ABR screen). However, an ambient-pressure, i.e., nonpressurized, test of middle-ear status could potentially improve newborn hearing screening (NHS) outcomes (Feeney and Sanford, 2005;Keefe *et al.*, 2003b;Keefe *et al.*, 2003a;Keefe *et al.*, 2000) by avoiding the difficulties associated with pressurization. Such a MEMR test may also provide a means to identify newborns at risk for auditory neuropathy. Individuals with auditory neuropathy have present otoacoustic emissions (OAEs) and absent ABR and MEMR (Berlin *et al.*, 2005;Hood, 1999). A valid MEMR test might be used to screen for auditory neuropathy, inasmuch as it can provide evidence of retrocochlear dysfunction in a test that is faster and less costly than an ABR test.

A third limitation with current clinical immittance systems, especially in terms of application to NHS programs, is that the operator must determine whether a MEMR response is present. This may not be practical for NHS and other screening programs in which personnel without audiological training perform the screenings. An objective method for determining the presence of a MEMR response would be of potential benefit to these programs.

A final, safety-related, limitation relates to the level of the activators required to elicit the MEMR for threshold, and especially, decay tests. Hunter *et al.* 1999 reported a case in which an acoustic reflex decay test at 1 kHz at 120 dB HL produced a temporary threshold shift above 1 kHz, and a permanent threshold shift at 1 kHz in both ears. They recommended a maximum activator level of 115 dB SPL, for this activator type, and expressed similar concerns for other

activator types. With that criterion, MEMR decay tests would have been contraindicated in over half of their patients with acoustic neuromas because test levels would likely have had to exceed 115 dB SPL. Arriaga and Luxford (1993) reported a similar case in which a 120 dB HL, 2 kHz activator caused a permanent hearing loss in one ear of an older patient with preexisting sensorineural hearing loss. Arriaga and Luxford recommended limiting stimulus level to 105 dB HL in reflex decay measurements. Miller *et al.* 1984 reported another case in which an 84-year-old patient suffered from increased hearing impairment and temporary decrease in speech discrimination after acoustic reflex testing. The precise amount of pure-tone threshold and speech discrimination shift could not be determined because these tests were not performed prior to the reflex tests. The change in hearing was identified by patient report of sudden decrease in hearing during the reflex test and no measurable speech discrimination directly after the reflex tests. Serial testing over the next few months demonstrated a gradual improvement in speech discrimination. Even when the MEMR activator levels are within safe limits, they may be considered uncomfortable to many patients. Measuring MEMR thresholds at lower activator levels using a wideband rather than a single-frequency probe would also reduce the activator levels used in the MEMR decay test, and might make MEMR testing possible in those patients whose thresholds exceed clinical equipment (Feeney *et al.*, 2003;Feeney and Keefe, 1999).

B. Wideband middle-ear muscle reflex test

WATF tests include such measures as acoustic impedance, acoustic admittance, which is the inverse of acoustic impedance, and acoustic reflectance. In contrast to single-frequency tympanometry, these WATFs assess ear-canal and middle-ear functioning over a wider bandwidth, typically 0.25–8 kHz. The main rationale to construct a wideband test to measure the MEMR threshold (WMEMR) is that the threshold may be detected more easily using a wideband probe response than a single-frequency probe response. Moreover, the best frequency range to use for measuring MEMR thresholds in children may differ from that in adults and the wideband probe would allow for identification of the most sensitive frequency range in each ear, regardless of age. Finally, the WMEMR test may provide a better signal-to-noise ratio in comparison to the CMEMR test. In the version of the WMEMR test used in the current study, the response is averaged across three repetitions of the activator at each level. In contrast, the stimulus may be presented only once at each level in the CMEMR test, and it is not averaged even if presented more than once at a particular level.

A number of studies, which have discussed the above potential advantages of wideband MEMR measurements, have reported measurements of contralateral MEMR shifts in WATFs, with emphasis on shifts in energy reflectance and admittance magnitude in adults (Feeney *et al.*, 2003;Feeney and Keefe, 1999;Feeney and Keefe, 2001). MEMR-induced shifts in the acoustic power absorbed by the middle ear have also been used in these studies. Power measures are grouped with WATF measures inasmuch as acoustic power can be expressed as the product of the squared pressure and the wideband acoustic conductance, which is the real part of the admittance.

Objective rules have been developed to decide whether a particular MEMR shift differs significantly from zero or whether it is dominated by noise alone. Feeney and Keefe (2001) and Feeney *et al.* 2003 proposed the joint use of two objective tests, one based on the magnitude of the shift across the selected frequency range using an analysis of variance (ANOVA), and another based on the correlation of the MEMR shift across frequency to a suprathreshold MEMR shift measured at the highest activator level. A magnitude test is well suited to a threshold determination and is used in the present study. The correlation test is well suited to excluding a large shift due to an intermittent noise source with a spectrum different from that of a MEMR shift. However, a correlation test is not necessarily well suited to a WMEMR

threshold measurement, because: (1) the MEMR shift measured at the highest activator level is assumed to be suprathreshold, but this may not be the case, and (2) the correlation test requires at least two activator levels to classify a WMEMR shift at a given level as present or absent, whereas the ANOVA test requires only one activator level. No correlation test was used in the present study.

An alternative approach to the measurement of the MEMR has been based on techniques used to measure OAE responses in combination with the known latency range of MEMR effects. Neumann *et al.* 1996 compared responses to two identical brief tone bursts that were separated in time by 110 ms. The ipsilateral MEMR, if elicited by the first tone burst, would affect the response to the second tone burst but not the first, so the difference in responses served as a measure of MEMR threshold. Müller-Wehlau *et al.* 2005 used an ipsilateral MEMR that was similar to that of Neumann *et al.* in comparing responses to two identical brief signals, but each of the signals used by Müller-Wehlau *et al.* was wideband (0.1–8 kHz) while the detection rule for the MEMR used the phase coherence between the first and second responses at a single frequency (near 1 kHz). Goodman and Keefe (2006) described a technique that combined a MEMR elicited with a BBN activator and a low frequency probe tone near 0.25 kHz, with a higher frequency tone (1.5–3.5 kHz) to elicit a stimulus frequency OAE (SFOAE). These studies have in common the measurement of an ipsilateral MEMR through the use of some change in the acoustic pressure response at a single frequency.

A system to measure ipsilateral MEMR shifts in WATFs was used to compare contralateral and ipsilateral MEMR thresholds in 27 young adults (Feeney *et al.*, 2004). The ipsilateral test relied on the spectral separation between a probe signal, which was a bandpass filtered click (0.2–2 kHz), and a 4 kHz activator signal. The probe and activator signals were delivered simultaneously to the same ear, and the MEMR-induced shift in the WATFs (admittance magnitude and energy reflectance) was compared across the probe bandwidth by also measuring the WATFs in a probe-alone condition. A WMEMR shift was judged as present based on the joint use of a magnitude and correlation decision rule. They compared these ipsilateral WMEMR thresholds with contralateral WMEMR and CMEMR thresholds in the same subjects using a 4 kHz activator and a click probe. The WMEMR thresholds were measured using either an admittance or a reflectance wideband response. Of the 27 subjects tested, five subjects had no MEMR shift on any test and were excluded. Of the remaining 22 subjects, contralateral CMEMR thresholds were measured in 14 subjects, contralateral WMEMR thresholds were measured in 16–17 subjects (depending on WATF response type), and ipsilateral WMEMR thresholds were measured in 18–20 subjects (depending on WATF response type). The average contralateral WMEMR thresholds were 3 dB lower than the average contralateral CMEMR thresholds, but no comparison of ipsilateral WMEMR and CMEMR thresholds was reported. The requirement for spectral separation between probe and activator signals may constrain the accuracy of the measurement, and it certainly limits the choice of ipsilateral activators that can be used. It might be desirable to use a wideband activator signal such as BBN to elicit a MEMR shift in a wideband probe signal or it might be desirable to use a tonal activator whose frequency was within the bandwidth of the probe signal.

C. Goals of current study

The initial goal was to evaluate the feasibility of measuring the presence of ipsilateral MEMR using a wideband response and procedure that does not require separation of the probe and activator spectra. Second, ipsilateral WMEMR thresholds were measured and compared in groups of normal-hearing adults and children to ipsilateral CMEMR thresholds measured with a clinical system. These data were used to test the hypothesis that WMEMR thresholds are lower than CMEMR thresholds.

II. METHODS

A. Subjects

Two groups of subjects were consented to the study and tested at Boys Town National Research Hospital. The first group of 22 adults received an otoscopic evaluation and the following tests. Air and bone conduction thresholds were obtained on clinical Grason-Stadler audiometers calibrated to ANSI S3.6-2004 and using ER-3A insert earphones. Tympanometric tests were obtained on a Grason-Stadler GSI-33 or Tympstar calibrated to ANSI S3.39-1987, with a nominal 85 dB SPL, 0.226 kHz probe tone and a pressure range of +200 to −400 daPa. Ears with impacted cerumen or cerumen that precluded visualization of the TM upon otoscopy were excluded. Other inclusion criteria included: (1) air-conduction thresholds <=15 dB HL at octave frequencies from 0.5 to 8 kHz, bilaterally, (2) air-bone gaps <=15 dB, and (3) 0.226 kHz tympanometry tests in the range 0.2–1.8 mmho for peak-compensated static admittance and −150 to 100 daPa for TPP. These tympanometry ranges were slightly wider than the Margolis and Heller (1987) normative data because subjects who were otherwise otologically normal would have been excluded. Forty ears of 21 participants were included in analysis in the adult group. These participants ranged in age from 18 to 36 years (mean=27.2, standard deviation (SD)=5.9; 15 females, six males).

Sixteen children were recruited for the second group. The inclusion criteria were the same, except that audiometric thresholds were obtained using conventional audiometry (i.e., hand raises) for six children and conditioned play audiometry for eight children. For all subjects meeting the inclusion criteria, data were obtained from one ear of six children and both ears of eight children. They ranged in age from 30 to 82 months of age (mean=57 months, SD=15 months; eight females, six males), or 2.5 to 6.8 years. Twenty-one ears were included in analyses of the child group.

Each session lasted approximately 1–1.5 h for the adults and older children, with longer session devoted to younger children. All audiometric and experimental tests were completed within one session.

B. CMEMR procedures

CMEMR thresholds were obtained at the same time the tympanogram was obtained. The probe tone was the same as for the tympanometry tests, and it was on continuously throughout testing. Activators were 1 and 2 kHz tones, and BBN (0.125–4 kHz, Grason-Stadler, 2005, p. A-4), and the duration of each activator was 1.5 s (Grason-Stadler, 2005, pp. 4–31). The initial activator level was at a moderate level, for example, typically 95 dB HL for tonal activators. A CMEMR response was defined as a decrease in admittance magnitude of at least 0.02 mmho that was time locked to the stimulus (to avoid identifying swallows, movements, etc., as related to a MEMR). Although in clinical practice audiologists may use an admittance change of 0.02 mmho as the criterion for presence of an acoustic reflex (e.g., Gelfand, 2001;Silman and Silverman, 1991), that value is essentially arbitrary. The 0.02 mmho criterion was used in the current study to avoid defining threshold with questionable responses of 0.01 mmho, and to avoid higher thresholds that would have resulted if a larger magnitude criterion was used. The activator level was decreased in 5 or 10 dB steps until the response was <0.02 mmho. If a response was not produced with the initial activator level, the activator level was increased until a response of 0.02 mmho was obtained. An additional criteria for threshold was the observation of response growth, that is, the response using activator levels below the maximum level had to increase at a higher level (e.g., from 0.02 mmho at 85 dB to 0.04 mmho at 90 dB). The CMEMR threshold was the lowest activator level at which a MEMR response was observed.

C. Wideband testing

1. WATF procedures—The WATF measurement system was calibrated daily according to procedures described elsewhere (Keefe and Abdala, 2007;Keefe and Simmons, 2003). The system software ran on a computer within the Windows operating system, and the computer included a high quality sound card (CardDeluxe), which delivered and recorded signals using a sample rate of 22.05 kHz. The probe assembly was an Etymotic model ER10C, which was modified by Etymotic to allow 20 dB higher output levels from the receivers. This modification was required in order to output the activator at a level sufficient to elicit a MEMR in most normal-functioning ears (as described below). The level of the click probe was 61 dB sound pressure level based on the peak-to-peak amplitude.

2. WMEMR procedures—Each WMEMR buffer was chosen to have an approximately 1 s duration, such that the activator was on for half of this duration and off for the remainder. The activator duration of approximately 0.5 s was sufficient to elicit a MEMR response, and the silent (i.e., activator-absent) duration of approximately 0.5 s was assumed to be sufficient for the MEMR response, if present, to decay back to the base line condition. The WMEMR test was based on the difference in the WATF responses measured in a base line condition, prior to the presentation of the MEMR activator, and in a postactivator condition, just after the presentation of the MEMR activator.

The response buffer of the WMEMR test is illustrated in Fig. 1, which shows the base line, activator, and postactivator sections of the mean response buffer. This response buffer consisted of the responses to 22 clicks, with each click interval containing 1024 samples and comprising a WATF response buffer. The probe stimulus (22 clicks over the 1.02 second buffer) was presented to Receiver 1 through the digital-to-analog converter (DAC) 1 of the sound card as shown in the top row. The activator stimulus, either a pure tone or a BBN (BBN is shown), was presented to Receiver 2 through DAC 2 over the same time period as DAC 1, as shown in the middle row. This set was repeated three times and averaged.

The microphone response to one presentation of the WMEMR buffer at a fixed attenuation level was recorded using the analog-to-digital converter (ADC) of the sound card, and is illustrated in the bottom row of Fig. 1. To extract the WMEMR response, the four probe clicks preceding the activator (shaded area A) were averaged to form a base line click response. Two probe clicks presented after the end of the activator (shaded area B) were averaged to form a post-activator click response. The probe click that occurred directly after the offset of the activator was not included in the postactivator response because its 46.4 ms duration includes effects of any OAEs generated in response to the activator. Because the cochlear delay times associated with OAEs are short compared to 46.4 ms, it was assumed that all OAE energy was attenuated by the time of the postactivator buffers shown in shaded area B. Nevertheless, any OAE generated in response to the click stimulus in the mean base line and postactivator responses would be cancelled in the subtraction process. Any such OAE amplitudes were also much smaller than the amplitude of the middle-ear response. The 92.9 ms duration of the pair of postactivator responses was relatively short compared to the offset latency of the MEMR so that both click responses could be averaged in the postactivator response in order to improve the signal to noise of any MEMR shift.

All measurements were completed at ambient pressure, i.e., without pressurization in the ear canal. Activators were the same as for the CMEMR tests, and were gated on and off with 5 ms ramps. The activators were presented at five levels from 16 dB down from the maximum output of the system, and in 4 dB increments up to the maximum output.

Because the GSI middle ear analyzer reports reflex thresholds in dB HL, which is defined in terms of reference equivalent threshold SPLs according to ANSI S3.39 (1987), it was necessary

to calibrate the activators used in the WMEMR measurement in dB HL. This required determining the sound card attenuation on the DAC for each tonal and BBN activator signal that produced the same SPL in a reference 2 cm^3 coupler (i.e., the HA-1 coupler in ANSI S3.6-2004). This was calibrated to the activator level produced in the coupler when output by the GSI-33 at a particular dB HL. These SPLs in the 2 cm^3 coupler were measured using a sound level meter (Bruel and Kjaer Type 2231) with an octave filter set (Bruel and Kjaer Type 1625) for tonal activators.

One difference between the CMEMR and WMEMR systems was that the maximum HL available on the WMEMR system was less than that of the CMEMR system. This was due to the fact that the Etymotic ER10C probe, which was used in the WMEMR system, was not designed to produce the high activator levels typical of CMEMR instruments conforming to ANSI S3.39 (1987).

Adults were tested in the laboratory. The children were tested either in the laboratory or in the audiology clinic where their hearing was tested. All subjects were awake and sitting quietly during the testing. For each subject, there were three activators, five levels for each activator in the adult group and seven activator levels in the child group, and three repetitions at each level. The test duration was typically 1 min per ear, occasionally 2 min, and 4 min for one child.

III. RESULTS

Wave form responses of a WMEMR test in a normal-hearing human ear, which were recorded using a 1 kHz activator at four different activator levels, are shown in Fig. 2. The vertical range of pressures was increased in panels with increased activator levels. The clicks were presented at the same level in each panel. The activation of the MEMR in this ear is evident with the two highest activator levels (see bottom two panels) as a rapid decline in the activator response after its onset. This large of a shift was not always observed, but when it was observed, it was most often seen with the 1 kHz activator.

WMEMR effects were assessed in the frequency domain using the shift in a WATF in the postactivator condition relative to the base line condition. Based on the acoustic admittance magnitude $|Y_b|$ at the probe tip in the base line condition and $|Y_p|$ in the postactivator condition, the relative admittance magnitude shift ΔY was defined as

$$\Delta Y = \frac{(|Y_p| - |Y_b|)}{|Y_b|}. \quad (1)$$

Based on the acoustic energy reflectance R_b in the base line condition and R_p in the postactivator condition, the relative energy reflectance shift ΔR was defined as

$$\Delta R = \frac{(R_p - R_b)}{R_b}. \quad (2)$$

Each of ΔY and ΔR is a dimensionless relative shift.

Figure 3 shows WMEMR shifts in a normal-hearing human ear in response to a 1 kHz activator from the current data set. The mean shifts and the standard error (SE) of the mean shifts, which were based on the three repetitions of the WMEMR stimulus set, are plotted as third-octave averaged spectra. The ΔY shown in the top row is the wideband analog to a CMEMR measurement, which typically shows the difference in admittance magnitude between a postactivator relative to a base line condition. The difference is in spectral content, inasmuch

as the CMEMR difference is measured at a single probe frequency, whereas the WMEMR shift is measured over a range of 0.25–8 kHz. The ΔY in Fig. 3 was negative at low frequencies, consistent with an increased middle-ear stiffness due to the MEMR, and increased in magnitude with increasing activator level to approximately −0.12, i.e., the MEMR reduced the admittance magnitude by as much as 12%. The ΔY was close to zero in this ear near the third octave at 0.63 kHz, and the zero-crossing frequency increased slightly with increasing activator level. The ΔY was positive at higher frequencies, with a maximum shift that occurred at a higher frequency at higher activator levels (this third-octave frequency ranged from approximately 0.79 to 1.26 kHz). The ΔY above the positive peak frequency decreased with increasing frequency towards zero values, and was close to zero by 2 kHz (except that the ΔY at the highest activator level differed slightly from zero at 2.5 and 4 kHz).

The ΔR for this ear, which is plotted in the bottom panel of Fig. 3, was positive at low frequencies and increased with increasing frequency up to a peak near 0.63 kHz that did not vary with activator level. This means that the energy reflectance was increased by the MEMR at low frequencies relative to the base line condition. A zero-crossing frequency for ΔR increased from 1.0 to 1.26 kHz with increasing activator level. At higher frequencies the ΔR was negative and of reduced magnitude compared to lower frequencies, and ΔR approached zero with increasing frequency. The ΔR did not converge to zero until 5 kHz.

A WMEMR shift, whether ΔY or ΔR, was classified as significantly different from zero based on an one-way analysis of variance (ANOVA) performed over a range of eight third-octave frequencies from 0.32 to 2 kHz. These were selected because the WMEMR shifts were small in magnitude above 2 kHz (as shown in Fig. 3), and the lowest frequency bin at 0.25 kHz was sometimes contaminated by noise (not shown in Fig. 3). With three repetitions of the WMEMR response buffer and eight frequencies, the number of degrees of freedom was 16. The shift was classified as significant if the ANOVA output had a $p<0.05$. In Fig. 3, the WMEMR shift spectra were plotted only for activator levels for which the shift was significant.

Thresholds were defined as the lowest level producing a significant ANOVA test. If this threshold was less than the maximum activator level, an additional stipulation was that the WMEMR shift had to be significant at a higher activator level. The purpose of that rule was to exclude a case, for example, in which only the lowest level produced a significant ANOVA result, so that the apparent significant result was likely due to artifact or noise rather than a MEMR effect. For each activator type, it was verified that the highest activator level did not produce a significant shift in an IEC 711 ear simulator (i.e., the highest activator level did not produce a "response" in a coupler). A preliminary analysis showed that the mean WMEMR thresholds estimated using ΔY were slightly lower in the adult group than those estimated using ΔR. For this reason, the focus is on WMEMR thresholds in adults and children that were estimated based on shifts in ΔY.

To compare WMEMR and CMEMR thresholds across the same range, the data sets were trimmed to adjust for differences in test procedures and hardware limitations. The WMEMR system had a limited range of activator levels and thus a limited range of WMEMR thresholds. Its upper limit was imposed by the maximum output of the ER10C receiver and the lower limit by the lowest activator level selected in the protocol prior to data collection. Clinical reflex thresholds were limited to the same range of thresholds as that on the WMEMR system. For adults, in the 1 kHz activator condition, the range was 74–90 dB HL in 35 ears trimmed from 37 ears (i.e., two of the 37 ears did not have a threshold in the range 74–90 dB HL), for the 2 kHz activator it was 70–86 dB HL in 19 ears trimmed from 25 ears, and for the BBN activator it was 64–80 dB HL in 30 ears trimmed from 38 ears. Thus, thresholds were measured in fewer ears using the 2 kHz activator compared to the other activators.

The WMEMR and CMEMR thresholds for adults (see top row of Fig. 4) were similar for right and left ears (triangles and squares, respectively). For the 1 kHz activator, the WMEMR mean (81.3 dB, standard error of the mean SE=0.81 dB) was 2.2 dB lower than the CMEMR mean (83.6 dB, SE=0.78 dB). For the 2 kHz activator, the WMEMR mean (79.6 dB, SE=1.37 dB) was 3.8 dB lower than the CMEMR mean (83.4 dB, SE=0.55 dB). For the BBN activator, the WMEMR mean (67.3 dB, SE=0.77 dB) was 4.0 dB lower than the CMEMR mean (71.3 dB, SE =0.96 dB). Each of these differences in mean thresholds was significant according to a dependent sample *t* test (see Table I). Across the three activator types, the WMEMR thresholds were 3.4 dB lower than CMEMR thresholds. The trimming action eliminated CMEMR thresholds higher than the maximum output of the WMEMR device. Larger differences up to 9.4 dB between CMEMR and WMEMR were observed in the untrimmed data set. Based on the full untrimmed set of measured thresholds and across all three activator types, the WMEMR thresholds were significantly lower by 5.5 dB than the CMEMR thresholds. The WMEMR thresholds based on ΔR were also lower than CMEMR thresholds for all activator types in the trimmed data sets, and for tonal activators, but not the BBN activator, in the untrimmed data set.

Some subjects had significant WMEMR shifts present at the lowest activator level in the protocol, particularly in the broadband noise activator condition in adults (see the bottom horizontal boundary of the white background region in Fig. 4). It is likely that some of these ears had WMEMR thresholds lower than the minimum activator level in the protocol.

Threshold estimates were repeated in five adults. The absolute value of the difference between runs 1 and 2 was calculated, averaged across ear, and then across subject. This value was 5.6, 3.3, and 4.8 dB for the WMEMR thresholds elicited with 1 kHz, 2 kHz, and BBN activators, respectively. For the CMEMR thresholds, the average difference was 3.0, 2.5, and 5.0 dB. Data were collapsed across ear and subject, and the correlation between CMEMR thresholds from the first and second runs were 0.56, 0.35, and 0.54 for 1 kHz, 2 kHz, and BBN activators. Correlations for WMEMR thresholds were 0.16, 0.78, and −0.08 for the same activators. The poor correlations could be the result of comparing data points within in a limited range, particularly in the WMEMR case in which a lower limit was artificially imposed. Thus, a comparison between the measures of reliability based on correlations should be interpreted with caution.

The group of children was tested after the adults. Because the range of activator levels was inadequate in the adult WMEMR protocol, the range of levels in the child WMEMR protocol was broadened to include lower levels. The step size was 5 dB. The data sets of the groups of children were trimmed to a common range of thresholds as for adults. For children, in the 1 kHz activator condition, the resulting range of WMEMR thresholds was 60–90 dB HL in eight ears trimmed from ten ears, for the 2 kHz activator it was 56 to 86 dB HL in three ears trimmed from seven ears, and for the BBN activator it was 50–80 dB HL in 19 ears with no ears trimmed.

The WMEMR and CMEMR thresholds for the child groups of ears (see the bottom row of Fig. 4) were similar for right and left ears, so results were averaged across ears. For the 1 kHz activator, the WMEMR mean (76.9 dB, SE =4.6 dB) was 5.6 dB lower than the CMEMR mean (82.5 dB, SE=1.6 dB). For the 2 kHz activator, the WMEMR mean (77.7 dB, SE=4.4 dB) was 5.6 dB lower than the CMEMR mean (83.3 dB, SE=1.7 dB). For the BBN activator, the WMEMR mean (66.8 dB, SE=2.2 dB) was 2.7 dB lower than the CMEMR mean (69.5 dB, SE =1.3 dB). Based on the small number of ears and large SE for the tonal activators, none of these threshold differences were significant in children for any activator (see Table I). The results in Table I for children were interpretable only for the BBN case, as the degrees of freedom (df) were too few for the tonal activator cases. Across all activator types, the WMEMR thresholds were 4.6 dB lower than CMEMR thresholds. Based on the full untrimmed set of

measured thresholds and across all three activator types, the WMEMR thresholds were 7.6 dB lower than CMEMR thresholds. However, the restricted number of ears and larger variability in testing children than adults limits the practical assessment of whether these differences in thresholds across activator type were significant.

The WMEMR thresholds of adult and child groups were compared across activator type and trimmed and untrimmed groups using a *t* test. The CMEMR thresholds were also compared across activator type and groups using *t* tests. Adult and child thresholds were not significantly different for any condition (see Table I). Again, the results were judged to be interpretable only for df of 10 or more. Nevertheless, the trend in each condition was that WMEMR thresholds were lower than CMEMR thresholds. For the trimmed groups including the WMEMR ΔY test, the mean thresholds in children were lower than those in adults by 1.0 dB for the CMEMR test and 2.3 dB for the WMEMR test. The relatively large 4 dB step size used in the activator levels in the WMEMR test for adults and 5 dB step size in the WMEMR for children and the CMEMR test for all subjects would have constrained the ability to detect any age-related differences on the order of a couple dB in MEMR thresholds.

IV. DISCUSSION

The general patterns in the ΔY and ΔR spectra of ipsilateral WMEMR shifts are similar to previous reports of contralateral WMEMR reflex shifts (Feeney *et al.*, 2003;Feeney and Keefe, 1999;Feeney and Keefe, 2001) and ipsilateral WMEMR (Feeney *et al.*, 2004). In particular, the finding that the zero-crossing frequency in ΔR is higher than that in ΔY (see Fig. 3) was explained by Feeney and Keefe (1999) as an effect in which the zero-crossing frequency of ΔY is reduced by the compliance of the ear-canal volume between the probe and the TM. Because energy reflectance is insensitive to probe location in the ear canal, the zero-crossing frequency in ΔR is independent of the probe location in the ear canal. The zero-crossing frequency in ΔR relates solely to a MEMR change in middle-ear functioning, but the zero-crossing frequency in ΔY depends also on probe location.

The ipsilateral WMEMR shifts in children had a generally similar spectral shape to shifts in adults. In the untrimmed child groups, the BBN activator elicited a WMEMR shift (ΔY) in 19 of 22 ears, the 1 kHz activator in ten of 22 ears, and the 2 kHz activator in seven of 22 ears. Thus, the BBN activator was more successful in eliciting a WMEMR than the tonal activators. In the untrimmed adult groups, the BBN activator was able to elicit a WMEMR (ΔY) shift in 38 of 40 ears, the 1 kHz activator in 37 of 40 ears, and the 2 kHz activator in 25 of 40 ears. The 2 kHz activator was the weakest activator in both CMEMR and WMEMR testing. The 1 kHz activator was much more likely to elicit a WMEMR response in adults than children, while the BBN activator was approximately equally likely to elicit a WMEMR shift in adults and children (the same pattern was evident in the untrimmed data sets). It is unclear why this is the case, but possibly due to increased noise levels in children for measurements with the 1 kHz activator. The finding that the BBN activator was more successful in eliciting a WMEMR than either of the tonal activators in children suggests a potential advantage to using the BBN activator in reflex screening of even younger children, such as in a NHS program.

The mean ipsilateral WMEMR thresholds in children were not significantly different from the mean CMEMR thresholds for any activator type. However, only the trimmed ΔY data obtained with the BBN activator had a sufficient number of responses (19 ears). As stated previously, the BBN activator may be more appropriate for a preschool screen because it is more likely to elicit a response than the pure-tone activators, and because the response has a larger dynamic range (the size of which cannot be completely estimated here due to the lower level limit imposed). A much larger sample of children would be needed to further investigate that hypothesis, however. The lack of a significant difference in the child group contrasts with the

lower WMEMR thresholds in the adult group, which, in any case, contained more responses (30 ears). It is possible that this test outcome relates to some combination of a difference in MEMR functioning in children and adults, a limitation in the WMEMR procedures, increased noise in the child responses, and an insufficient number of ears tested. The threshold determination technique was imprecise. A fixed step size of 4 or 5 dB was used, and there was insufficient control of false positives and false negatives, as the terms are used in signal detection theory.

The mean ipsilateral WMEMR thresholds in adults were 2.3–4 dB lower than the mean ipsilateral CMEMR thresholds depending on activator type. The WMEMR threshold averaged across all activator types was 3.4 dB lower than the average CMEMR threshold. There appear to be no other reports of ipsilateral WMEMR and CMEMR thresholds with which to compare these measurements. The ipsilateral threshold differences in the present study are smaller than the contralateral threshold differences reported by Feeney *et al.* 2003 and Feeney and Keefe (1999), and similar to contralateral threshold differences reported by Feeney *et al.* 2004. Feeney *et al.* 2003 reported that, compared to clinical thresholds, the contralateral WMEMR reflectance thresholds were 13.7 dB lower when using a 1 kHz activator and 12 dB lower when using a 2 kHz activator. Feeney and Keefe (1999) elicited contralateral WMEMRs with the 40-ms chirp probe in the right ear and activators of 1 and 2 kHz in the left ears of three normal-hearing adults. They found that WMEMR thresholds were at least 8 dB lower than CMEMR thresholds, and that WMEMRs were produced at the lowest activator levels for all subjects except for one subject test using a 2 kHz activator. Feeney *et al.* 2004 reported that contralateral WMEMR thresholds were approximately 3 dB lower than CMEMR thresholds, which is within the range of differences observed in the present study of ipsilateral thresholds.

The differences across studies may relate to differences in contralateral and ipsilateral MEMR functioning as detected in the WMEMR and CMEMR test procedures, and may also be due to the differences in analysis bandwidth, and the decision rule used to determine the presence of the reflex. The possibility of erroneously defining artifact as a MEMR threshold should be examined. For example, in the current study, responses that occurred at low levels, but not at any higher levels, were counted as no response. However, instances in which a WMEMR effect was observed at both a lower activator level and at least one higher level were assigned the threshold at the lower activator level. In some instances, responses to mid-level stimuli were nonsignificant, but responses to higher and lower stimuli were significant. The probability of triggering a stapedius muscle contraction increases with increasing activator level, so that the same activator level may trigger a MEMR on one trial but not another. It may be useful in future studies to incorporate an adaptive rule to increase or decrease the activator level based on the previous set of WMEMR responses. An automated MEMR test that incorporates signal averaging and adaptive procedures could improve reliability in a clinical setting.

V. CONCLUSIONS

The results demonstrated the feasibility of measuring ipsilateral WMEMR thresholds and suprathreshold shifts using a procedure that compares WATF responses before and after the presentation of an activator signal to elicit the MEMR, based on tonal activators at 1 and 2 kHz and a broadband noise activator. The MEMR thresholds measured ipsilaterally with the wideband system were lower than those measured clinically in adults for all activator types. The ipsilateral MEMR thresholds measured in children's ears using the wideband and clinical tests did not differ when using the broadband noise activator; no valid statistical comparisons were possible with tonal activators due to an insufficient number of test ears. A WMEMR test may avoid temporary or permanent threshold shift and discomfort that may be associated with the high stimulus levels that are often necessary for clinical MEMR threshold and decay tests. Further studies with larger samples of children with normal hearing and middle ear function

are necessary to fully characterize the response and its predictive ability. Potential uses for the WMEMR include a combined OAE/WMEMR newborn and preschool screen for cochlear and retrocochlear function. In particular, the broadband noise activator may have a larger dynamic range that includes much lower levels than the pure-tone activators.

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References

American National Standards Institute. Specifications for instruments to measure aural acoustic impedance and admittance. ANSI; New York: 1987. p. S3.39

American National Standards Institute. Specifications for audiometers. ANSI; New York: 2004. p. S3.6-2004

Arriaga MA, Luxford WM. Impedance audiometry and iatrogenic hearing loss. Otolaryngol-Head Neck Surg 1993;108:70–72. [PubMed: 8437876]

Berlin CI, Hood LJ, Morlet T, Wilensky D, St JP, Montgomery E, Thibodaux M. Absent or elevated middle ear muscle reflexes in the presence of normal otoacoustic emissions: A universal finding in 136 cases of auditory neuropathy/dys-synchrony. J Am Acad Audiol 2005;16:546–553.

Calandruccio L, Fitzgerald TS, Prieve BA. Normative multifrequency tympanometry in infants and toddlers. J Am Acad Audiol 2006;17:470–480. [PubMed: 16927511]

Feeney MP, Keefe DH. Acoustic reflex detection using wide-band acoustic reflectance, admittance, and power measurements. J Speech Lang Hear Res 1999;42:1029–1041. [PubMed: 10515503]

Feeney MP, Keefe DH. Estimating the acoustic reflex threshold from wideband measures of reflectance, admittance, and power. Ear Hear 2001;22:316–332. [PubMed: 11527038]

Feeney MP, Keefe DH, Marryott LP. Contralateral acoustic reflex thresholds for tonal activators using wideband energy reflectance and admittance. J Speech Lang Hear Res 2003;46:128–136. [PubMed: 12647893]

Feeney MP, Keefe DH, Sanford CA. Wideband reflectance measures of the ipsilateral acoustic stapedius reflex threshold. Ear Hear 2004;25:421–430. [PubMed: 15599190]

Feeney MP, Sanford CA. Detection of the acoustic stape-dius reflex in infants using wideband energy reflectance and admittance. J Am Acad Audiol 2005;16:278–290. [PubMed: 16119255]

Gelfand, SA. The acoustic reflex. In: Katz, J., editor. Handbook of Clinical Audiology. 4. Lippincott, Williams and Wilkins; Philadelphia: 2001. p. 205-232.

Goodman SS, Keefe DH. Simultaneous measurement of noise-activated middle-ear muscle reflex and stimulus frequency otoacoustic emissions. J Assoc Res Otolaryngol 2006;7:125–139. [PubMed: 16568366]

Grason-Stadler. GSI TympStar Version 2: Reference Instruction Manual. Viasys Healthcare; Conshohocken, PA: 2005.

Hirsch JE, Margolis RH, Rykken JR. A comparison of acoustic reflex and auditory brain stem response screening of high-risk infants. Ear Hear 1992;13:181–186.

Holte L, Cavanaugh RM Jr, Margolis RH. Ear canal wall mobility and tympanometric shape in young infants. J Pediatr (St Louis) 1990;117:77–80.

Hood LJ. A review of objective methods of evaluating auditory neural pathways. Laryngoscope 1999;109:1745–1748.

Hunter LL, Margolis RH. Multifrequency tympanometry: Current clinical application. Am J Audiol 1992;1:33–43.

Hunter LL, Ries DT, Schlauch RS, Levine SC, Ward WD. Safety and clinical performance of acoustic reflex tests. Ear Hear 1999;20:506–514. [PubMed: 10613388]

Kankkunen A, Liden G. Ipsilateral acoustic reflex thresholds in neonates and in normal-hearing and hearing-impaired pre-school children. Scand Audiol 1984;13:139–144.

Keefe DH, Abdala C. Theory of forward and reverse middle-ear transmission applied to otoacoustic emissions in infant and adult ears. J Acoust Soc Am 2007;121:978–993.

Keefe DH, Folsom RC, Gorga MP, Vohr BR, Bulen JC, Norton SJ. Identification of neonatal hearing impairment: Ear-canal measurements of acoustic admittance and reflectance in neonates. Ear Hear 2000;21:443–461.

Keefe DH, Gorga MP, Neely ST, Zhao F, Vohr BR. Ear-canal acoustic admittance and reflectance measurements in human neonates. II. Predictions of middle-ear dysfunction and sensorineural hearing loss. J Acoust Soc Am 2003a;113:407–422.

Keefe DH, Simmons JL. Energy transmittance predicts conductive hearing loss in older children and adults. J Acoust Soc Am 2003;114:3217–3238. [PubMed: 14714804]

Keefe DH, Zhao F, Neely ST, Gorga MP, Vohr BR. Ear-canal acoustic admittance and reflectance effects in human neonates. I. Predictions of otoacoustic emission and auditory brainstem responses. J Acoust Soc Am 2003b;113:389–406.

Li Y, Hunter LL, Margolis RH, Levine SC, Lindgren B, Daly K, Giebink GS. Prospective study of tympanic membrane retraction, hearing loss, and multifrequency tympanometry. Otolaryngol-Head Neck Surg 1999;121:514–522. [PubMed: 10547462]

Margolis RH, Goycoolea HG. Multifrequency tympanometry in normal adults. Ear Hear 1993;14:408–413.

Margolis RH, Heller JW. Screening tympanometry: Criteria for medical referral. Audiology 1987;26:197–208. [PubMed: 3632475]

Margolis RH, Saly GL, Keefe DH. Wideband reflectance tympanometry in normal adults. J Acoust Soc Am 1999;106:265–280. [PubMed: 10420621]

Miller MH, Hoffman RA, Smallberg GJ. Stapedial reflex testing and partially reversible acoustic trauma. Hearing Instrum 1984;35(15):49.

Müller-Wehlau M, Mauermann M, Dau T, Kollmeier B. The effects of neural synchronization and peripheral compression on the acoustic-reflex threshold. J Acoust Soc Am 2005;117:3016–3027. [PubMed: 15957771]

Neumann J, Uppenkamp S, Kollmeier B. Detection of the acoustic reflex below 80 dB HL. Audiol Neuro-Otol 1996;1:359–369.

Schwartz DM, Schwartz RH. Tympanometric findings in young infants with middle ear effusion: Some further observations. Int J Pediatr Otorhinolaryngol 1980;2:67–72. [PubMed: 7188055]

Silman, S.; Silverman, CA. Auditory Diagnosis: Principles and Applications. Academic; San Diego: 1991.

Silman S, Silverman CA, Arick DS. Acoustic-immittance screening for detection of middle-ear effusion in children. J Am Acad Audiol 1992;3:262–268. [PubMed: 1421458]

Sprague BH, Wiley TL, Goldstein R. Tympanometric and acoustic-reflex studies in neonates. J Speech Hear Res 1985;28:265–272.

Vanhuyse VJ, Creten WL, Van Camp KJ. On the w-notching of tympanograms. Scand Audiol 1975;4:45–50.

Weatherby LA, Bennett MJ. The neonatal acoustic reflex. Scand Audiol 1980;9:103–110. [PubMed: 7444323]

Wiley, TL.; Fowler, CG. Acoustic Immittance Measures in Clinical Audiology: A Primer. Singular; San Diego: 1997.

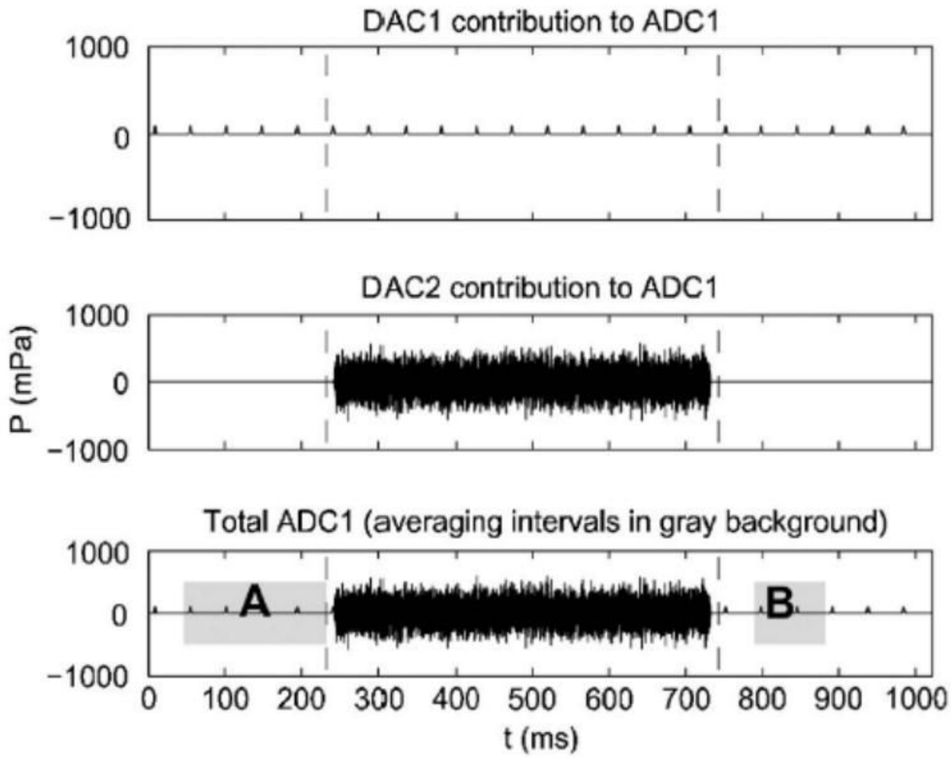

FIG 1.

An example of the stimulus input to each receiver and the response recorded by the microphone for the WMEMR procedure. The probe clicks are presented to Receiver 1 from digital-to-analog converter (DAC) 1 (top row), the activator (broadband noise is shown) is simultaneously presented to Receiver 2 through DAC 2 (middle row), and the entire buffer is recorded by the microphone (bottom row). To extract the WMEMR response, the energy in the ear canal that is present during the four probe clicks that precede the activator (shaded area A) is averaged and compared to the energy in the ear canal during the presentation of the probe clicks after the offset of the activator (shaded area B).

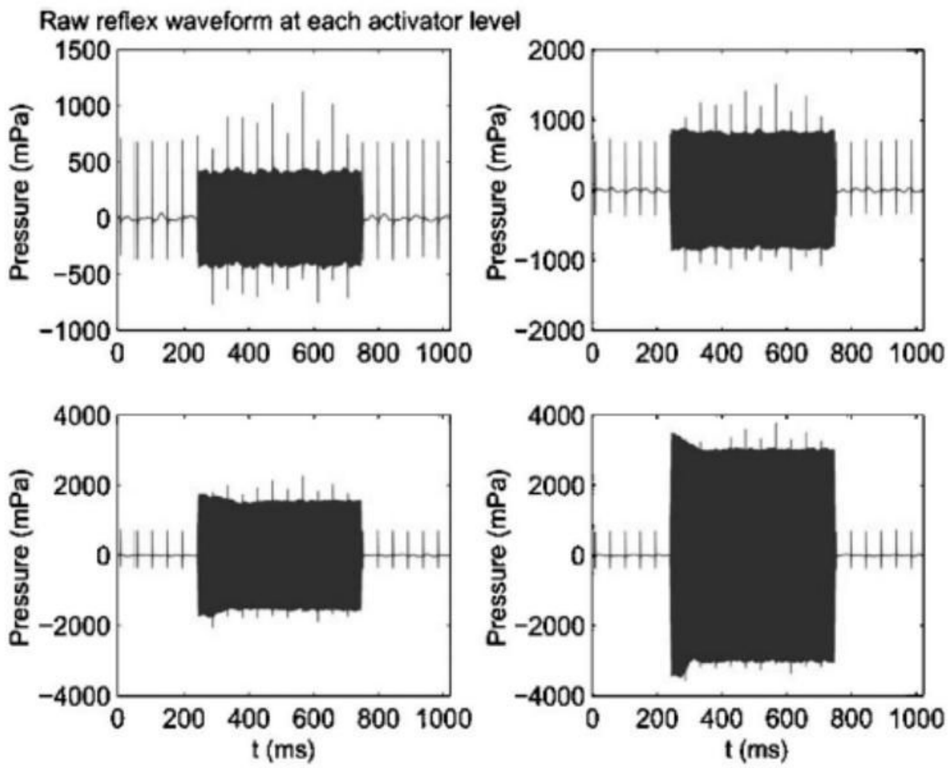

FIG 2.
Wave form responses in a normal-hearing human ear in response to a 1 kHz activator at four different activator levels. The vertical axis scale differs across panels to accommodate the level of the activator. The probe clicks are fixed in level as the activator level increases from left to right, top to bottom.

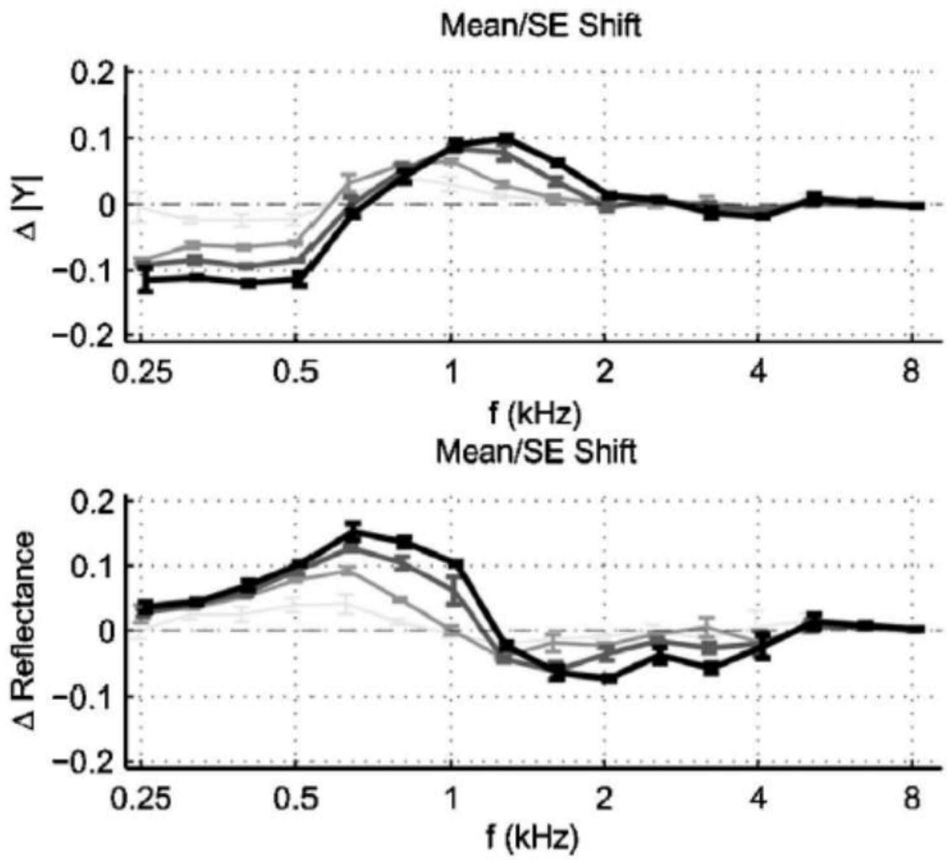

FIG 3.

Example of WMEMR shift spectra (1/3 octave averages) for admittance (top row) and reflectance (bottom row) in a normal-hearing human ear in response to a 1 kHz activator at different levels (from a maximum of 90 dB in 4 dB descending steps represented by lighter and thinner lines). Error bars represent the standard error of the mean WMEMR shift across three repetitions of the activator.

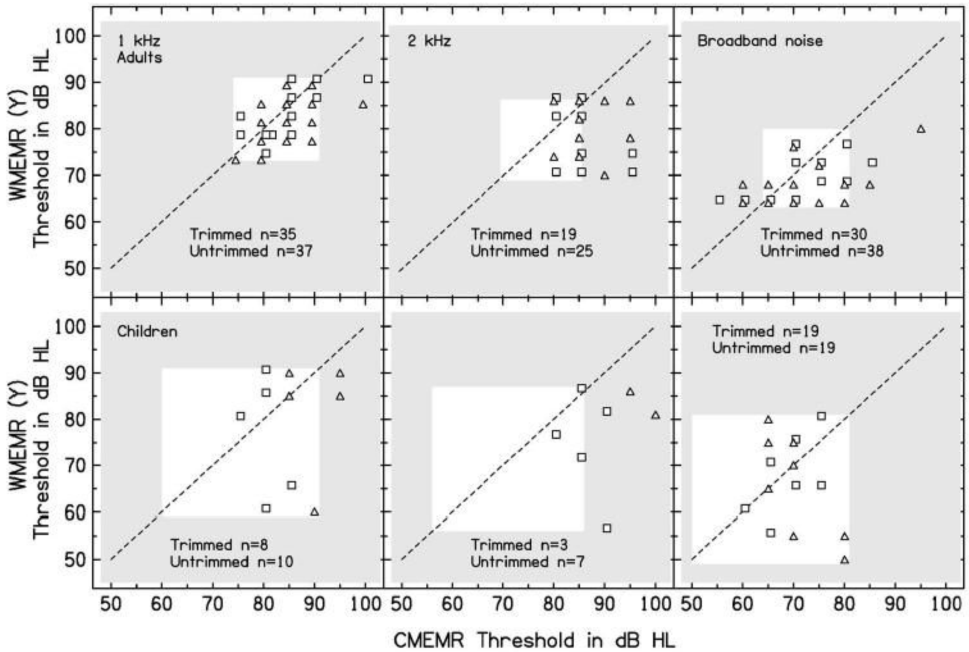

FIG 4.

Ipsilateral MEMR thresholds estimated using CMEMR and WMEMR tests in normal-hearing adult ears on the top row and children on the bottom row, with a 1 kHz activator (left panel), 2 kHz activator (middle panel), and BBN activator (right panel). Thresholds plotted within the boundary of the white square were part of the "trimmed" data set. The number of test ears *n* with thresholds in this trimmed range and the total *n* are shown for each activator type. Left-ear thresholds are plotted using squares, and right-ear thresholds using triangles, with symbols slightly offset to make right and left symbols visible (but some same-ear symbols overlap).

TABLE I

Comparison between CMEMR and WMEMR thresholds for each activator.

	t	Df	Sig (2-tailed)
Adults, 1 kHz	2.82	34	0.01
Adults, 2 kHz	2.45	18	0.03
Adults, BBN	4.23	29	0.00
Children, 1 kHz	1.05	7	0.33
Children, 2 kHz	1.29	2	0.33
Children, BBN	0.97	18	0.35
Comparison of thresholds between children and adults			
CMEMR, 1 kHz	0.76	10	0.47
WMEMR, 1 kHz	0.99	7	0.35
CMEMR 2 kHz	0.05	2	0.96
WMEMR, 2 kHz	0.39	2	0.73
CMEMR, BBN	1.18	37	0.25
WMEMR, BBN	0.21	22	0.84