J Am Acad Audiol 29:337–347 (2018)

Measurement of the Electrically Evoked Stapedial Reflex Response with Wideband Acoustic Reflectance Measurement

DOI: 10.3766/jaaa.16176

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Abstract

Background: The electrically evoked stapedial reflex threshold (ESRT) has been shown to be a good predictor of upper stimulation level for cochlear implant recipients. Previous research has shown that the ESRT may be recorded at lower stimulation levels and with a higher incidence of success with the use of higher frequency probe tones (e.g., 678 and 1000 Hz) relative to the use of the conventional 226-Hz probe tone. Research has also shown that the acoustic reflex may be recorded at lower stimulus levels with the use of wideband reflectance when compared to the acoustic reflex threshold recorded with a conventional acoustic immittance measurement.

Purpose: The objective of this study was to compare the ESRT recorded with acoustic immittance and wideband reflectance measurements.

Research Design: A repeated measures design was used to evaluate potential differences in ESRTs with stimulation at an apical, middle, and basal electrode contact with the use of two different techniques, acoustic immittance measurement and wideband reflectance.

Study Sample: Twelve users of Cochlear Nucleus cochlear implants were included in the study.

Data Collection and Analysis: Participants' ESRTs were evaluated in response to simulation at three different electrode contact sites (i.e., an apical, middle, and basal electrode contact) with the use of two different middle ear measurement techniques, acoustic immittance with the use of a 226-Hz probe tone and wideband reflectance with the use of a chirp stimulus.

Results: The mean ESRT recorded with wideband reflectance measurement was significantly lower when compared to the ESRT recorded with acoustic immittance. For one participant, the ESRT was not recorded with acoustic immittance before reaching the participant's loudness discomfort threshold, but it was successfully recorded with the use of wideband reflectance

Conclusions: The ESRT may potentially be recorded at lower presentation levels with the use of wideband reflectance measures relative to the use of acoustic immittance with a 226-Hz probe tone. This may allow for the ESRT to be obtained at levels that are more comfortable for the cochlear implant recipient, which may also allow for a higher incidence in the successful recording of the ESRT.

Key Words: acoustic admittance, cochlear implant, electrically evoked stapedial reflex threshold, wideband acoustic reflectance

Abbreviations: ASRT = acoustically evoked stapedial reflex threshold; EABR = electrically evoked auditory brainstem response; ECAP = electrically evoked compound action potential; EDR = electrical dynamic range; ESRT = electrically evoked stapedial reflex threshold; RM ANOVA = repeated measures analysis of variance; SPL = sound pressure level; WAI = wideband acoustic immittance; WBR = wideband reflectance

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INTRODUCTION

Outcomes with cochlear implants are influenced by a number of patient-specific variables (Knutson et al, 1991; Rubinstein et al, 1999; Tait et al, 2000) as well as the quality of the program created for the external signal processor. In particular, investigators have demonstrated the important role that upper stimulation levels (i.e., M levels) play in the performance and outcomes of persons with cochlear implants (Moog and Geers, 2003; Sainz et al, 2003; Overstreet, 2004). For instance, Moog and Geers (2003) reported that speech recognition as well as speech and language outcomes were better for children who used signal processors programmed with wider electrical dynamic ranges (EDRs) (i.e., higher upper stimulation levels relative to their T levels). Additionally, Pfingst et al (1999) showed that spectral discrimination improved with increases in upper stimulation levels. Also, Franck et al (2003) suggested that temporal discrimination and speech recognition improved with increases in upper stimulation levels. Further, Sainz et al (2003) demonstrated that speech recognition and sound quality deteriorated when users' perception of loudness at upper stimulation levels was not balanced across the electrode array. Collectively, these studies suggest that a cochlear implant user's speech recognition is only optimized when upper stimulation levels are set appropriately for the individual. Finally, upper stimulation levels that are excessively high can result in undesirable effects, such as facial nerve stimulation, pain, excessive channel interaction, adaptation of loudness, voltage compliance issues, and reduced battery life.

Unfortunately, many cochlear implant users, such as children, adults with long-term deafness, and persons with cognitive disabilities, are unable to reliably provide precise feedback about the loudness and comfort of electrical stimulation. For these users, it is difficult to determine optimal upper stimulation levels. Several researchers have investigated the potential of using electrically evoked auditory potentials, such as the electrically evoked compound action potential (ECAP) or the electrically evoked auditory brainstem response (EABR), to estimate upper stimulation levels for patients who cannot complete psychophysical loudness scaling procedures. These studies suggest that electrically evoked potential measures are poor predictors of upper stimulation levels (Hughes et al, 2000; Polak et al, 2004; 2006; Cafarelli-Dees et al, 2005; Holstad et al, 2009). In contrast, numerous studies indicate that the electrically evoked stapedial reflex threshold (ESRT) is highly correlated to upper stimulation level (Spivak and Chute, 1994; Hodges et al, 1997; Buckler and Overstreet, 2003; Polak et al, 2004; 2006).

ESRT in Cochlear Implant Programming

A host of examiners have shown that the ESRT is consistently obtained at stimulation levels that approximate M levels/C levels (Spivak and Chute, 1994; Shallop and Ash, 1995; Hodges et al, 1997; Stephan and Welzl-Müller, 2000; Allum et al, 2002; Gordon et al, 2004; Lorens et al, 2004; Polak et al, 2004; 2006; Brickley et al, 2005; Walkowiak et al, 2011). Jerger and colleagues (Jerger et al, 1986; 1988) were the first to report on the measurement of the stapedial reflex from cochlear implant users. They noted that a high correlation existed between the ESRT and C level for persons using the Cochlear Corporation (Sydney, Australia) Nucleus 22 cochlear implant. Stephan et al (1988; 1990; 1991) measured the ESRT to analog stimulation with cochlear implant users and also concluded that the ESRT was strongly related to upper stimulation levels preferred by adult cochlear implant recipients. In a relatively large reported study on the ESRT at the time of publication, Battmer et al (1990) measured the ESRT for 25 adult users of the Cochlear Corporation Nucleus 22 cochlear implant and concluded that the ESRT was obtained at stimulation levels that approached the participants' C levels.

Studies that have directly compared the relationship between the ESRT and upper stimulation levels have obtained correlation coefficients ranging from 0.85 to 0.99 (Hodges et al, 1997; Buckler and Overstreet, 2003). Additionally, Hodges et al (1996) found that participants reported that upper stimulation levels were judged to possess equal loudness when based on ESRT assessment, which is desirable considering that a program possessing upper stimulation levels that are balanced in loudness across the electrode array should result in optimal sound quality and speech recognition. This finding is further supported by reports of Spivak and Chute (1994) and Hodges et al (1997) who both found that programs that were based on ESRT testing possessed better sound quality than programs based on conventional means of psychophysical loudness assessment.

Finally, Spivak et al (1994) and Hodges et al (1997) showed the speech recognition performance with ESRT-based programs was equivalent to conventional programs. Specifically, Spivak et al (1994) reported that several participants using Cochlear Corporation Nucleus 22 cochlear implants obtained better speech recognition with ESRT-based programs relative to their performance with behavioral programs. Similarly, Wolfe and Kasulis (2008) measured the ESRT in a group of postlingually deafened adults using the Advanced Bionics (Valencia, CA) HiResolution cochlear implant system. The ESRT was measured with biphasic electrical pulse trains delivered to the participants' cochlear implants and the conventional acoustic immittance probe placed in the ear opposite the implanted ear (i.e., contralateral measurement). Wolfe and Kasulis reported significantly better mean speech recognition performance with ESRT-based programs relative to participants' conventional programs.

Fewer reports exist describing use of the ESRT to set upper stimulation levels in children. However, Gordon et al (2004) conducted a study with 68 pediatric cochlear implant users to evaluate the potential of using objective measures to estimate signal processor program levels. They reported that mean ESRTs were within 15 clinical units of C levels for children using the Cochlear Corporation Nucleus 24 cochlear implant and concluded that the ESRT is the most effective method to estimate upper stimulation levels for children with cochlear implants.

In another study, Bresnihan et al (2001) successfully recorded the ESRT in 20 pediatric cochlear implant users and compared the participants' performance with newly established ESRT-based maps to their previous maps, which were based on conventional behavioral measures. The authors reported that upper stimulation levels based on the ESRT were actually lower than upper stimulation levels based on behavioral measures. They also noted that children were more likely to use their cochlear implants for longer periods of time and experienced fewer episodes of discomfort to speech and environmental sounds with the ESRT-based program. In short, the ESRT was shown to be a valuable tool to identify instances in which upper stimulation levels were excessively high leading to poorer cochlear implant outcomes. Polak et al (2006) reported a similar finding for prelingually deafened adults such that ESRT levels were lower than upper stimulation levels obtained behaviorally for Nucleus 24 recipients. They reported ESRT levels at ~84% to 94% of the behavioral EDR for prelingually deafened adults, whereas ESRT levels were 103% to 116% of the EDR for postlingually deafened adults. However, they found no significant difference between upper stimulation levels obtained behaviorally and those obtained via ESRT for either the postlingual or the prelingual group.

Spivak and Chute (1994) measured the ESRT in 19 children and 16 adults using the Cochlear Corporation Nucleus 22 cochlear implant and reported a mean difference between ESRT and upper stimulation levels of ~9 clinical units for children and 19 clinical units for adults. They concluded that the ESRT serves as a good guide for setting upper stimulation levels for cochlear implant recipients, and like Bresnihan et al (2001), they stressed the value of the ESRT in identifying stimulation levels that are excessively high.

ESRT: Clinical Methods and Limitations

The examiners who conducted the aforementioned studies used conventional acoustic immittance measurements to attain the ESRT. Conventional acoustic immittance measurement systems typically possess a pneumatic pump, a low-noise microphone with high sensitivity, and two receivers, one for the presentation of a probe tone signal and one for the presentation of a reflex-eliciting stimulus. The measure involves the placement of a small probe into the external auditory meatus. The probe is coupled to a pneumatic pump to allow for an introduction of air pressure into the external auditory meatus to approximate the static air pressure in the middle ear space. This step, which prevents subtle variations in middle ear pressure from influencing the measure, requires the clinician to acquire and maintain a hermetic seal between the probe and the external auditory meatus. A probe tone (usually at 226 Hz) is presented into the external auditory meatus at a known sound pressure level (SPL), and the microphone in the probe is used to record the SPL that accumulates in the external auditory meatus. The general premise of the test is that higher SPL readings obtained in the external auditory meatus are indicative of reduced middle ear compliance (i.e., the sound does not easily pass through the middle ear system), whereas lower SPL readings are associated with relatively high middle ear compliance to sound.

In conventional acoustic immittance assessment, the stapedial reflex is measured by presenting a relatively high-level pure tone (usually at 500, 1000, or 2000 Hz) and recording a subsequent increase in SPL of the 226-Hz probe tone in the external auditory meatus. This increase in SPL of the 226-Hz probe tone in the ear canal is associated with a contraction of the stapedial muscle in response to the stimulus. Stapedial contraction results in an increase in stiffness of the tympanic membrane and a concomitant reduction in the transmission of the probe tone into the middle ear system. In summary, the presence of the stapedial reflex results in a decrease in acoustic admittance at the tympanic membrane that is manifested through increases of the probe tone SPL in the external auditory meatus. This response is time locked to the presentation of the stimulus.

To measure the ESRT, the acoustic immittance probe is typically placed in the external auditory meatus contralateral to the cochlear implant. A 226-Hz probe tone is continuously presented into the external auditory meatus, and the acoustic admittance is recorded while biphasic pulses are presented via the cochlear implant in an ascending manner. When the level of the stimulus from the cochlear implant is sufficiently intense to elicit the stapedial reflex, a decrease in admittance, which is time locked with stimulus presentations, will be observed (see Figure 1 for a visual display of the ESRT obtained with a cochlear implant recipient). This decrease in admittance may be observed in the ear contralateral to the cochlear implant because the stapedial reflex is a bilateral response.

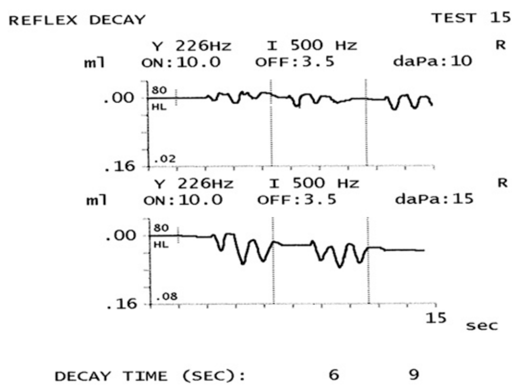

Figure 1. Measurement of the electrically evoked reflex response with acoustic immittance with amplitude growth of the response observed with increases in stimulus amplitude (clinical units).

One limitation of using of using conventional acoustic immittance to measure the ESRT is that this measure is conducted with a probe tone at a single frequency, and thus, conventional acoustic immittance measures may not be sensitive to changes in middle ear admittance that occur across a broad frequency range. Also, there are several potential reasons that the ESRT may not be successfully recorded in all cochlear implant users. First, cochlear implant surgery, or previous pathologies, may lead to disruption of the normal function of the middle ear. Even clinically insignificant middle ear alterations can drastically affect the measurement of the stapedial reflex. For instance, it has been reported that the probability of being able to measure an acoustic reflex was only 50% when the probe ear has an average air-bone gap of just 5 dB (Jerger et al, 1974). The incidence of a measurable acoustic reflex when there is no air-bone gap is not clearly established, but research does indicate that the acoustic reflex is measurable in the vast majority of persons with normal middle ear function. For instance, Golding et al (2007) reported that <2% of adults with completely normal otologic function had absent acoustic reflexes for all stimuli used to elicit the response. Furthermore, Nozza et al (1992) measured a present acoustic reflex in response to a 1000-Hz pure tone presented at 100 dB HL (226-Hz probe tone) in 85% of children who were determined to have normal middle ear function on the basis of otologic examination under a surgical microscope.

Second, middle ear disorders that increase the stiffness present within the middle ear system may lead to a reduction in the ability to record the ESRT with the use of conventional acoustic admittance measures and a 226-Hz probe tone. It should be noted that the ability to successfully measure the ESRT might be less likely when the admittance probe is placed in an ear that has been implanted (Gordon et al, 2012). The cause for this is most likely attributed to an increase in middle ear stiffness associated with subtle changes that can occur with surgical alterations or previous middle ear disease.

Third, a number of clinically insignificant conditions may result in a slight increase in middle ear stiffness. Examples include a history of chronic otitis media, tympanosclerosis, surgery in the middle ear space, etc. (Hunter and Shahnaz, 2014). In essence, the plane of measurement for acoustic admittance measures resides at the tympanic membrane. As a result, any condition that changes the mechano-acoustical properties at the lateral border of the middle ear system may have a disproportionate effect on acoustic admittance measures. This is especially true when the probe tone frequency resides in close proximity to the frequency range in which an increase in impedance may have occurred. Conditions that increase stiffness of the middle ear system are more likely to affect the transmission of low-frequency probe tones (e.g., 226 Hz) than high-frequency probe tones (e.g., 678, 1000 Hz).

Wolfe et al (2017) recently measured the ESRT in a group of 23 adult cochlear implant recipients with the use of conventional acoustic immittance measurement and probe tone frequencies at 226, 678, and 1000 Hz. The ESRT was not measurable in 4 of the 23 participants with the use of the 226-Hz probe tone, but it was successfully measured with the use of the higher probe tone frequencies. Additionally, the ESRT was obtained at lower levels with the use of the higher probe tone frequencies relative to the ESRT measured with a 226-Hz probe tone. There was no difference in the ESRT level obtained with the use of the 678- and 1000-Hz probe tones. In summary, the results of Wolfe et al (2017) suggest that the incidence of successful measurement of the ESRT and the ESRT level are dependent on the frequency of the probe signal.

Wideband Acoustic Reflectance

Wideband acoustic immittance (WAI) is an alternative to conventional acoustic immittance for the assessment of middle ear function. WAI systems possess a probe containing a low-noise microphone with high sensitivity and a receiver that is used to present a broadband stimulus such as a click or chirp. The probe is coupled to a computer processor to allow for the analysis of SPL existing in the external auditory meatus after the presentation of the click or chirp. Pressure equalization is typically not performed in WAI measurements, so a pneumatic pump is not required.

A complex calibration process (e.g., Thevenin calibration) is conducted before the initiation of the measurement to determine the output impedance properties of the WAI probe. Then, the probe is placed in the external auditory meatus, and chirp stimuli are presented at a known SPL (an a priori in situ measurement is made to specify the level of the stimulus in the external auditory meatus). Next, the microphone is used to measure the SPL of the chirp after it is presented into the ear canal. Because the SPL of the stimulus and the output impedance of the probe transducers are known, the resulting SPL may be used to calculate the reflectance of the tympanic membrane. WAI measures may be expressed in terms of reflectance and/or absorbance. In short, reflectance (expressed in % or proportion) equals the ratio of the sound power reflected from the tympanic membrane to the incident power presented to the external ear canal. Measurements of reflectance in response to a complex stimulus are often referred to as wideband reflectance (WBR) measures. Absorbance (also expressed in % or proportion) is the counterpart of reflectance and is defined as (1 − reflectance) (Feeney et al, 2013). The result of a WBR measurement obtained from an individual is compared to normative data obtained from otologically normal adults to determine whether middle ear function is normal (see Figure 2).

WBR measurement has been successfully used to record the acoustically evoked stapedial reflex threshold (ASRT). In fact, Feeney et al (2003) reported that the contralateral ASRT measured with WBR is 12 dB lower than the ASRT as measured with acoustic immittance. In a follow-up study, Feeney et al (2004) found the ipsilateral ASRT to be 3 dB lower when measured with WBR relative to acoustic immittance. Furthermore, the aforementioned investigators noted that the ASRT was successfully measured with WBR in several instances in which it was absent when measured with acoustic immittance. They attributed the enhanced sensitivity of the WBR measurement to the fact that the changes in middle ear sound transmission secondary to the stapedial reflex are measured across a broad frequency range rather than just at 226 Hz as with acoustic immittance.

Use of the WAI to obtain the ESRT in cochlear implant recipients may offer advantages relative to the use of acoustic immittance (Feeney and Keefe, 1999). First,

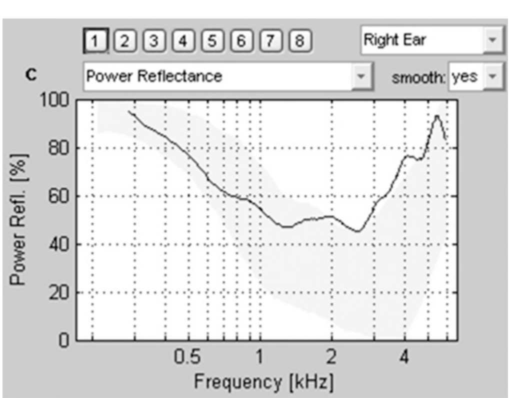

Figure 2. An example of a WBR response curve obtained in the absence of electrical stimulation (i.e., baseline response). The individual's WBR curve is plotted relative to the normative range for adults with normal middle-ear function.

because WAI allows for attainment of the ASRT at lower stimulus levels in persons with normal hearing, it is likely that this may occur for cochlear implant users as well. Second, because WAI allows for assessment of middle ear response properties secondary to elicitation of the ESRT across a broad frequency range, it is possible that WAI will allow for attainment of the ESRT in a higher percentage of cochlear implant recipients when compared to acoustic immittance measurement.

Schairer and colleagues (2007) measured the ipsilateral ASRT in children and adults with both conventional acoustic immittance and WAI. For measurement of stapedial reflex response with WAI, they used an automated system to deliver probe clicks during the measurement with responses elicited by broadband noise and 1000- and 2000-Hz pure tones. Baseline responses were obtained while only the probe click was present (i.e., no activator stimulus), and WAI at the baseline measure was compared to WAI measured during stimulus delivery in one-third octave bands from 320 to 2000 Hz. Analysis of variance was conducted to determine whether a statistically significant difference existed between WAI at baseline relative to WAI measured during stimulus delivery. Schairer et al found no differences in the mean ipsilateral ASRT between the conventional acoustic immittance and WAI measures, a finding they suggested should be interpreted cautiously because of the small number of study participants and the large standard error in participant responses.

Recently, Feeney et al (2017) described a detailed procedure for the measurement of the ipsilateral ASRT with WAI. In short, a series of four broadband noise activator stimuli were delivered in each stimulus set. A probe click was delivered before the first stimulus and also immediately after each of the four proceeding stimuli in each set. WAI was measured after the presentation of the first click (i.e., baseline condition) and then after each of the proceeding stimuli/click pairs. Statistical analysis was completed to analyze difference in the WAI measured at baseline compared to WAI measured after the four click/stimuli pairs. In contrast to the Schairer et al (2007) study, Feeney and colleagues found ASRTs that were obtained at significantly lower levels (12.3-dB mean difference) with WAI relative to conventional acoustic immittance.

Primary Study Objective

The primary purpose of this study was to demonstrate feasibility of WAI-mediated ESRT measurements. The secondary purpose of this study was to compare WAI and acoustic immittance measurements of ESRTs to determine whether differences exist in the ESRT levels obtained with the two different approaches. We hypothesized that (a) WAI would serve as a reliable measure for demonstrating ESRTs and (b) the ESRT would be obtained at lower levels in a larger proportion of individuals with use of WAI relative to conventional acoustic immittance measurement.

METHODS

Participants

The following inclusion criteria were used for selection of participants for this study:

1. All participants were ≥18 yrs old.
2. All participants had normal tympanograms (defined as peak compensated static acoustic admittance ranging from 0.3 to 1.3 mmho and tympanometric peak pressure between –50 and +20 daPa) (Shahnaz and Bork, 2008).
3. All participants had used their cochlear implants for ≥3 months.
4. All participants could read written instructions and complete questionnaires in English.
5. All participants used spoken language as their primary mode of communication.
6. Both unilateral and bilateral cochlear implant users were included.

Of note, persons with abnormal tympanometric findings and/or a significant history of substantial middle ear disorder were excluded from this study. Twelve adults who were unilateral users of Cochlear Nucleus 24RE cochlear implant recipients participated in this study. Demographic data for the 12 participants are provided in Table 1.

Procedures

The ESRT was measured using conventional acoustic immittance and WAI in all 12 participants with the eliciting stimulus delivered to an apical (electrode 22), a middle (electrode 11), and a basal (typically electrode 3) electrode contact. For all WAI measurements, WBR was analyzed to determine the ESRT, and as a result, the term "WBR" will be used when discussing ESRT measured with WAI. The ESRT was recorded with the acoustic admittance and WBR probes in the ear contralateral to the implanted ear for all participants. For acoustic immittance measurements, acoustic admittance was continuously recorded with use of the Grason-Stadler (Eden Prairie, MN) Industry Tympstar while trains of biphasic pulses were presented at a rate of 900 pulses per second (pps) with an on/off duty cycle of 500 msec. The probe tone used for acoustic immittance assessment was set at 226 Hz for all participants. Three trains of biphasic pulses (each 500 msec in duration) were presented at each stimulation level. The presentation level of the electrical stimulus was increased in two-clinical-unit increments until a visible, time-locked, repeatable change in admittance was observed (i.e., the admittance decreased within an expected latency following each of the three pulse trains at a given stimulus level). To confirm the presence of the ESRT, the stimulus was delivered at the same level to confirm the presence of the time-locked response to each pulse train. Then, for additional confirmation, the stimulus level was increased by two clinical units to demonstrate that the change in admittance increased further, which corroborated the presence of the response at threshold. The stimulus was then decreased by ten clinical units and increased, once again, in two-clinical-unit increments until the response was observed again. The lowest stimulation level (in clinical units) in which a change in admittance of ≥0.02 mmho was observed in two ascending trials was recorded as the ESRT (Wiley et al, 1987) (see Figure 1 for a visual depiction of the ESRT as measured with acoustic immittance).

Table 1. Participant Demographic Information

Participant	Age	Duration HL (yr)	Duration Deaf (yr)	Length of CI Use (yr)	Etiology of HL
1	51	30	20	3	Unknown
2	58	26	16	3	Usher's syndrome
3	37	30	10	4	Unknown
4	58	20	7	5	Unknown
5	47	0.5	0.5	1	Sudden SNHL
6	55	40	20	3	NIHL/hereditary
7	22	20	17	7	Hereditary
8	54	45	45	3	Unknown
9	35	20	10	2	Hereditary
10	43	25	15	1.5	Unknown
11	70	25	6	0.5	NIHL/presbyacusis
12	20	18	5	2	Hereditary
Average	40.7	25.5	16.3	2.7	
SD	14.4	10.8	11.0	1.7	

Note: CI = cochlear implant; HL = hearing loss; NIHL = noise-induced hearing loss; SD = standard deviation; SNHL = sensorineural hearing loss.

For WBR measurements, a baseline measure of reflectance was obtained with no stimulus (see Figure 2) for all 12 participants. WBR measurements were made with the Mimosa Acoustics (Champaign, IL) Middle Ear Power Analysis instrument, a system designed for clinical measurement of WAI. As a result, a detailed statistical analysis of WAI across different frequency bands as completed by Feeney and colleagues (2017) was not possible with this clinical instrument. Instead, a clinical analysis similar to what was used to analyze the ESRT with conventional acoustic immittance was used to analyze the ESRT measured with WBR.

Specifically, WBR measurements were made during the presentation of trains of biphasic pulses at a rate of 900 pps with a duration of 3,000 msec. The ESRT was determined by identifying the lowest level of stimulation that resulted in an observable change in reflectance relative to the baseline measure. This was completed via visual confirmation by the experimenter. To ensure that the observed change in reflectance was, indeed, a valid ESRT response, the stimulus was presented an additional time to ensure that the change in the WBR response was repeatable (i.e., the WBR curve was identical; there was no visual separation between the two curves that were obtained in response to stimulation and deviated from the baseline curve) across two measurements completed at the same eliciting level. Also, the examiner confirmed that the curve obtained in response to the stimulus was different from the baseline curve (i.e., there was visual separation corresponding to at least a three percentage-point change in WBR at any frequency between the stimulus curves and the nonstimulus curve). It should be noted that the ESRT-elicited change in WBR typically occurred between 500 and 2000 Hz. Next, a reflectance measure was repeated without stimulation to confirm that the baseline response had not shifted due to artifact (i.e., there was no separation visually observed between the two nonstimulus curves) (see Figure 3). This step was necessary to ensure that the change in WBR relative to the baseline curve was attributed to a change facilitated by the ESRT and not by a drift in the baseline response over time, such as what might occur with minor changes in middle ear pressure related to swallowing, sneezing, etc. If the examiner was unsure whether the ESRT existed (i.e., low amplitude), the level of the stimulus was increased by two clinical units to ensure that the amplitude of the response correspondingly increased (i.e., there was visual separation between the WBR ESR curve obtained at the threshold level relative to the curve obtained at the higher stimulus level) (see Figure 4), consistent with our protocol for verifying ESRT via conventional acoustic immittance.

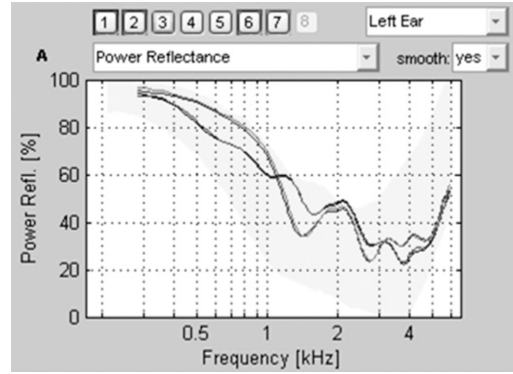

Figure 3. ESRT measured with WBR. Two measures were made without stimulation (one at the onset of testing and another at the outset) to confirm the validity and repeatability of the baseline and two measures were made during electrical stimulation to confirm the validity and repeatability of the response.

RESULTS

Figures 3 and 4A–C show typical ESRT responses measured with WBR. In most cases, the contraction of the stapedial muscle resulted in an increase in reflectance <1000 Hz and a decrease between 1000 and 2000 Hz. In some instances, a decrease in reflectance was also observed in the high frequencies as well (2000–6000 Hz). Of note, the magnitude of the WBR response increases as the stimulus level increases.

The ESRT was measured with WBR in all cases in which it was measured with acoustic immittance. For one participant, the ESRT was not present with stimulation to the basal electrode when using the acoustic immittance measure, but the ESRT was present with WBR. For data analysis, the acoustic immittance ESRT of this participant was taken as the highest presented level (i.e., 230 clinical units) at which there was no recordable response but the participant's loudness discomfort level was encountered because the examiners predicted that the actual response would be measurable near 230 clinical units (additional information provided in the "Discussion" section). Figure 5 shows mean ESRTs for the ESRT measured with the two techniques at the three different electrodes.

To examine and compare levels obtained with the traditional ESRT and WBR test techniques at the three different electrode contact locations (apical, middle, and basal), two-factor repeated-measures analysis of variance (RM ANOVA) was conducted. The independent variables in the analysis were test technique and electrode contact location. According to the analysis, there was a main effect of test measure [$F_{(1,72)} = 17.6$, $p < 0.001$] with WBR resulting in significantly lower levels than the traditional ESRT test technique with the conventional acoustic immittance measurement. The mean differences in ESRT between the conventional acoustic immittance and WBR measurements were 1.2, 3.6, and 3.7 clinical units for electrodes 22, 11, and 3, respectively. There was no main effect of electrode contact location [$F_{(2,72)} = 1.2$, $p = 0.33$] and no interaction effect between test measure and electrode contact location [$F_{(2,72)} = 2.9$, $p = 0.07$].

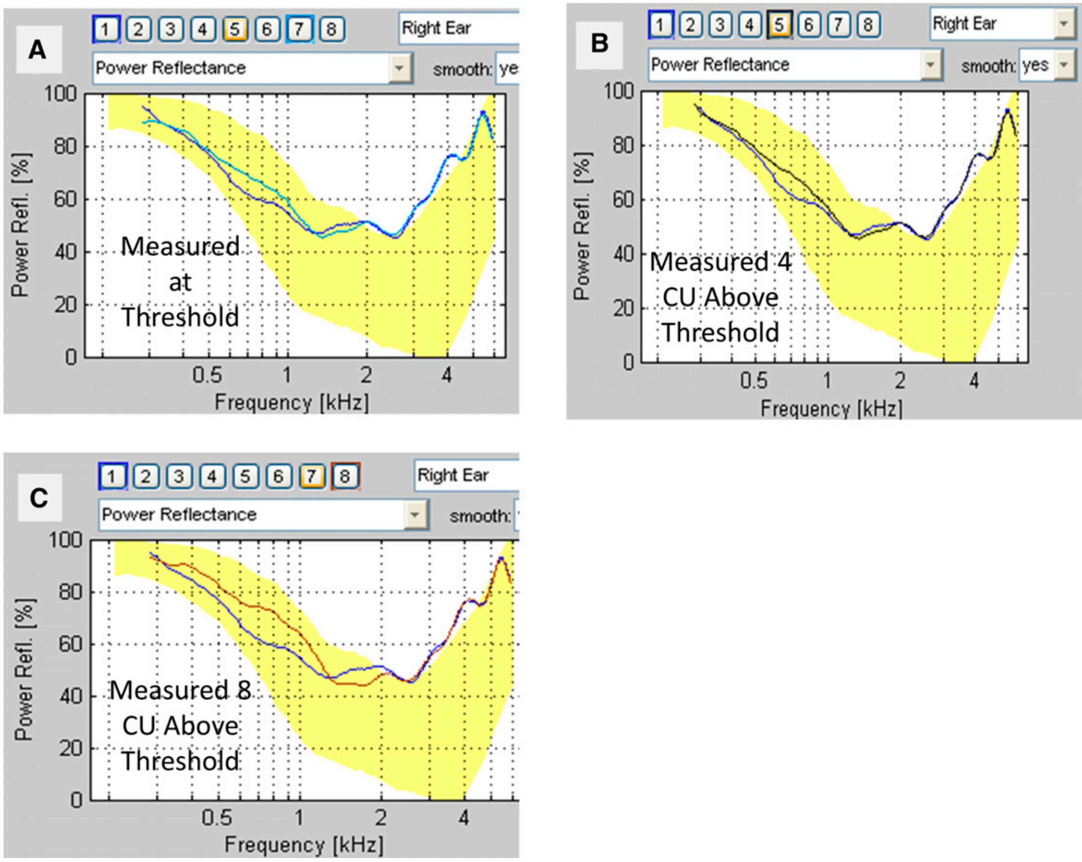

Figure 4. Electrically evoked stapedial reflex responses measured at (A) threshold, (B) four clinical units (CLs) above threshold, and (C) eight CLs above threshold. (This figure appears in color in the online version of this article.)

DISCUSSION

The results of this study have demonstrated the feasibility of successfully recording the ESRT with the use of WBR measurement. In fact, the results of this study suggest that there may be several advantages to using WBR/WAI measurement to measure the ESRT rather than the conventional acoustic immittance technique. It is important to note that the ESRT could not be measured for one of the three channels for one participant in this study and that the response recorded for this channel was a predicted rather than actual response. A predicted value was used (a) because the examiners believed a response would be measureable near the loudness discomfort level and (b) to avoid a missing value in the dataset, which should be avoided when conducting RM ANOVA. To ensure that this predicted response had no impact on the statistical analysis, the data were reanalyzed with an RM ANOVA after all data from this particular participant were deleted. The outcomes of this new analysis yielded identical results to the original analysis.

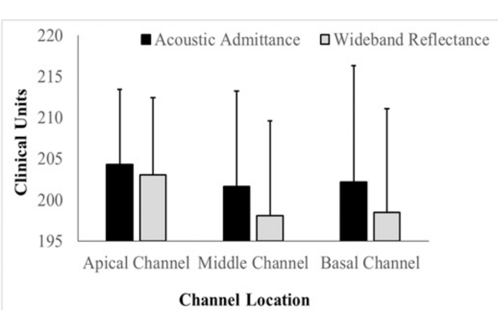

Figure 5. Mean ESRTs obtained with acoustic immittance and WBR on an apical, middle, and basal electrode for ten participants using the Cochlear Corporation Nucleus Freedom cochlear implant.

Based on the results of this study, potential advantages of the use of WBR/WAI to measure the ESRT include the following:

1. The ESRT may be recorded at lower stimulation levels with WBR relative to acoustic immittance.
2. WBR may be a more sensitive measure to record the ESRT, so it may be possible to observe the ESRT in some participants for whom no response was obtained with the acoustic immittance approach. The primary reason that WBR may be more sensitive than acoustic immittance is the fact that changes in middle ear compliance are observed across a much wider frequency range as compared to a single frequency with acoustic immittance.

The results of this study align relatively well with previous studies examining the ASRT using WAI and conventional acoustic immittance. Schairer and colleagues (2007) found no difference in ASRT measured with WAI versus conventional acoustic immittance. In contrast, Feeney et al (2003) reported that the contralateral ASRT measured with WAI was 12 dB lower than the ASRT measured with conventional acoustic immittance. Also, Feeney et al (2004) found ipsilateral ASRT to be 3 dB lower when measured with WAI relative to conventional acoustic immittance. More recently, Keefe and colleagues found ipsilateral ASR to be 12 dB lower when measured with WAI compared to the ASRT obtained with conventional acoustic immittance. The modest reduction in ESRT obtained with WBR relative to conventional acoustic immittance in the current study is in line with the results obtained in studies examining the ASRT measured with the two techniques.

Additional research is necessary to evaluate the benefits of using WAI to measure the ESRT for persons with cochlear implants. Specifically, the following issues must be addressed:

1. The ESRT should be measured with a larger number of cochlear implant recipients using both the conventional acoustic immittance and WAI approaches. Though we demonstrated that an ESRT was measured with WBR in all 12 patients for whom ESRTs were also obtained via conventional acoustic immittance, the incidence of obtaining present ESRT should be established for each technique in a larger clinical population. Also, the difference in ESRT needs to be clarified between the two techniques—recognized as a limitation of the current study given that the raw WBR data were not available from the clinical WAI equipment. Additionally, the WAI ESRT should be compared to the ESRT measured with conventional acoustic immittance with multiple probe tones (e.g., 226, 678, and 1000 Hz).
2. Research should be conducted to explore the potential difference in the incidence of successful ESRT measurement with the probe in an implanted ear versus a nonimplanted ear.
3. WAI should be used to characterize differences in middle ear function of implanted and nonimplanted ears to better understand the influence of cochlear implantation on middle ear function as well as the impact of cochlear implant surgery on the incidence of successful measurement of the ESRT. This is particularly of interest for a comparison of ESRT obtained via acoustic immittance and WAI/WBR for CI recipients with different surgical approaches (round window versus cochleostomy), given the possibility for differences in resultant middle ear mechanics.
4. It is necessary to further elucidate the relationship between ESRTs measured with WAI and with acoustic immittance with various probe tone frequencies (e.g., 226, 678, and 1000 Hz) and upper stimulation levels for children and adults with cochlear implants of different manufacturers and with different electrode arrays. Ideally, a program should be created to estimate ideal upper stimulation levels for ESRTs obtained from recipients of a variety of ages and with a variety of different cochlear implant technologies.
5. Hunter et al (2017) recently showed the ASRT measured with WAI was lower when the measurement was made at tympanometric peak pressure. Additional research is needed to explore the effects of pressurized WAI ESRT in cochlear implant users.
6. A potential limitation of this research is the fact that a detailed statistical analysis similar to what was used in other WAI stapedial reflex threshold studies (Keefe et al, 2017; Schairer et al, 2007) was not employed in the current study. The clinical instrumentation used for WAI measurement in the current study did not allow for the detailed statistical analysis used by Keefe and colleagues (2017). As a result, it is possible that different ESRT results would have been obtained if alternative analysis methods had been used in the current study. However, it should also be noted that the lower ESRTs obtained with WBR in the current study were consistent with the lower ASRT findings obtained with WAI in the Feeney and Keefe studies (Feeney et al, 2003; 2004; Keefe et al, 2017). Additionally, it should be noted that the primary motivation of this study was to evaluate the feasibility of measuring the ESRT with WAI, and the study findings do indicate that WAI possesses good potential as a measure to obtain the ESRT in cochlear implant recipients.

CONCLUSION

The results of the current study demonstrate that ESRTs can be obtained using WAI/WBR as a means of measuring a visual threshold with repeatable changes in reflectance relative to baseline. Indeed, WBR-mediated ESRTs were obtained for all 12 participants who also exhibited ESRT with conventional acoustic immittance (226-Hz probe tone). Further we demonstrated that ESRTs confirmed via visually observed change in reflectance were obtained at lower CI stimulation levels with a mean difference of 2.8 clinical units, collapsed across the electrode array.

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