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Normative wideband reflectance, equivalent admittance at the tympanic membrane, and acoustic stapedius reflex threshold in adults

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Abstract

Objectives—Wideband acoustic immittance (WAI) measures such as pressure reflectance, parameterized by absorbance and group delay, equivalent admittance at the tympanic membrane (TM), and acoustic stapedius reflex threshold (ASRT) describe middle-ear function across a wide frequency range, compared to traditional tests employing a single frequency. The objective of this study was to obtain normative data using these tests for a group of normal hearing adults and investigate test-retest reliability using a longitudinal design.

Design—A longitudinal prospective design was used to obtain normative test and retest data on clinical and WAI measures. Subjects were 13 males and 20 females (mean age = 25 y). Inclusion criteria included normal audiometry and clinical immittance. Subjects were tested on two separate visits approximately one month apart. Reflectance and equivalent admittance at the TM were measured from 0.25 to 8.0 kHz under three conditions: at ambient pressure in the ear canal and with pressure sweeps from positive to negative pressure (downswept) and negative to positive pressure (upswept). Equivalent admittance at the TM was calculated using admittance measurements at the probe tip which were adjusted using a model of sound transmission in the ear canal and acoustic estimates of ear-canal area and length. Wideband ASRTs were measured at tympanometric peak pressure (TPP) derived from the average TPP of downswept and upswept tympanograms. Descriptive statistics were obtained for all WAI responses, and wideband and clinical ASRTs were compared.

Results—Mean absorbance at ambient pressure and TPP demonstrated a broad band-pass pattern typical of previous studies. Test-retest differences were lower for absorbance at TPP for the downswept method compared to ambient pressure at frequencies between 1.0 and 1.26 kHz. Mean

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Conflicts of Interest:
Douglas Keefe has an interest in the commercial development of devices to assess middle-ear function.

tympanometric peak-to-tail differences for absorbance were greatest around 1.0 to 2.0 kHz and similar for positive and negative tails. Mean group delay at ambient pressure and at TPP were greatest between 0.32 and 0.6 kHz at 200 to 300 μs, reduced at frequencies between 0.8 and 1.5 kHz, and increased above 1.5 kHz to around 150 μs. Mean equivalent admittance at the TM had a lower level for the ambient method than at TPP for both sweep directions below 1.2 kHz, but the difference between methods was only statistically significant for the comparison between the ambient method and TPP for the upswept tympanogram. Mean equivalent admittance phase was positive at all frequencies. Test-retest reliability of the equivalent admittance level ranged from 1 to 3 dB at frequencies below 1.0 kHz, but increased to 8 to 9 dB at higher frequencies. The mean wideband ASRT for an ipsilateral broadband noise activator was 12 dB lower than the clinical ASRT, but had poorer reliability.

Conclusions—Normative data for the WAI test battery revealed minor differences for results at ambient pressure compared to tympanometric methods at TPP for reflectance, group delay, and equivalent admittance level at the TM for subjects with middle-ear pressure within ±100 daPa. Test-retest reliability was better for absorbance at TPP for the downswept tympanogram compared to ambient pressure at frequencies around 1.0 kHz. Large peak-to-tail differences in absorbance combined with good reliability at frequencies between about 0.7 and 3.0 kHz suggest that this may be a sensitive frequency range for interpreting absorbance at TPP. The mean wideband ipsilateral ASRT was lower than the clinical ASRT, consistent with previous studies. Results are promising for the use of a wideband test battery to evaluate middle-ear function.

Keywords

wideband acoustic immittance; acoustic stapedius reflex threshold; absorbed sound power; test-retest reliability

I. INTRODUCTION

Wideband acoustic immittance (WAI) refers to a family of middle-ear acoustical measures obtained across a wide frequency range (0.25 to 8.0 kHz) including pressure reflectance, admittance, and the acoustic stapedius-muscle reflex (ASR) (for a review see Feeney et al. 2013). The pressure spectrum $P(f)$ as a function of frequency f at the probe tip is the sum of the forward pressure spectrum $P_F(f)$ moving towards the tympanic membrane (TM) and the reverse pressure spectrum $P_R(f)$ moving back towards the probe. The pressure reflectance $R(f)$ of the ear is defined as a ratio of the reverse pressure to the forward pressure, i.e., $R(f) = P_R(f)/P_F(f)$. The energy reflectance ER is defined as $ER = |R(f)|^2$, and the absorbance is defined as $1 - ER$. The complex pressure reflectance is parameterized in this study in terms of absorbance and group delay, in which the group delay is calculated in terms of the negative phase gradient of the pressure reflectance with respect to 2**π** times the frequency. Wideband absorbance in ears with normal function is large at frequencies for which the middle ear is efficient in collecting sound energy. Sound energy absorbed by the middle ear is partially forward-transmitted and absorbed by the cochlea. In addition, sound energy may be dissipated within the middle ear for some conductive pathologies (e.g., ossicular disarticulation) relative to normal ears. Wideband absorbance may be measured at ambient pressure in the ear canal, and also as a function of varying air pressure in the form of a wideband absorbance tympanogram.

Absorbance is relatively insensitive to probe position within the ear canal (Stinson et al. 1982; Voss et al. 2008), unlike acoustic admittance, which is sensitive to probe position in adults. The result is that no compensation for ear-canal acoustics is required for absorbance as it is for admittance. This is the major reason for the interest in using absorbance as a diagnostic test above approximately 1.5 kHz. A fast technique to measure aural acoustic impedance in cats (Allen 1986) was adapted for non-invasive clinical use in humans, and extended to measure ambient reflectance (Keefe et al. 1992; Keefe et al. 1993). Normative measurements of wideband reflectance or absorbance have been reported for adults at ambient pressure (for a review see Shahnaz et al. 2013) and as tympanograms with varying ear-canal pressures (for a review see Sanford et al. 2013).

The long-term test-retest reliability of WAI at ambient pressure has recently been studied (Abur et al. 2014; Feeney et al. 2014b; Rosowski et al. 2012; Werner et al. 2010). Werner et al. (2010) measured test-retest reliability of energy reflectance at ambient pressure in 210 young adults tested approximately two weeks apart. Mean absolute test-retest differences were around 0.1 from 0.25 kHz to 2.0 kHz increasing to a maximum test-retest difference of around 0.2 at 4.0 kHz. Feeney and colleagues (2014b) measured energy reflectance in 112 adults (187 ears) for up to 5 annual tests. They reported the test-retest variability had a standard deviation around 0.1 at 1.0, 2.0 and 4.0 kHz. Similar results were obtained by Rosowski et al (2012), who made four weekly energy reflectance measurements on 7 adults. The standard deviation for those measurements was around 0.1 at 1.0, 2.0, and 4.0 kHz (their Figure 5). Abur et al. (2014) examined the test-retest reliability of energy reflectance using up to 8 repeated measures on 7 female subjects. They found similar but somewhat lower test-retest variability to that of Rosowski et al. (2012) with the within-subjects variability approximately 50% of the overall standard deviation. The present study is the first to address the test-retest reliability for tympanometric measures of WAI.

Group delay has been calculated from ambient reflectance data in adult ears (Keefe et al. 1993; Voss & Allen 1994; Robinson et al. 2013). For an adult ear canal with rigid walls and negligible wall loss at frequencies in the measurement range (up to 8.0 kHz), the group delay at the probe tip may be expressed as the sum of the round-trip delay from the probe tip to the TM and the group delay at the TM. The latter is affected by the sound-reflection properties of the TM and middle ear. An equivalent middle-ear group delay at the TM is defined by subtracting the estimated round-trip ear-canal delay from the group delay at the probe tip (Keefe et al. 2015). This is the first study to present group data on wideband group delay and its test-retest reliability in adults, which may be a useful measure for evaluating middle-ear status.

The ANSI S3.39 (2012) standard for measuring aural acoustic immittance specifies a method for compensated admittance that pertains to the use of a 226-Hz probe tone. The assumptions associated with this compensation do not hold for high frequencies (>660 Hz) due to standing-wave effects (Shanks & Lilly 1981), and, in fact, do not hold at 226 Hz (Keefe et al. 2015). In the present report, the estimate of the equivalent admittance at the TM refers to an adjustment of the measurement of the acoustic admittance at the probe tip using a transmission-line model to remove the acoustical effects of sound transmission in the ear canal between the probe tip and the TM. This model assumes a cylindrical ear-canal geometry whose length and cross-sectional area are acoustically estimated from the measured reflectance and admittance at the probe tip (Keefe et al. 2015). Hunter et al. (2015) reported that tympanometric absorbance and group delay in a longitudinal cohort of infants revealed developmental effects consistent with anatomical changes (Keefe et al., 2015). The complex equivalent admittance is represented in terms of its magnitude and phase, in which the magnitude is sometimes further expressed as an equivalent admittance level in dB. This equivalent admittance may complement a reflectance test battery in evaluating middle-ear disorders.

A wideband ASR shift may be measured by comparing a reference wideband measurement obtained in quiet with that obtained in the presence of an activator sound presented to the ipsilateral or contralateral ear that elicits the ASR (for a review see Schairer et al. 2013). Wideband ASR threshold (ASRT) tests have been performed in adult ears with normal hearing at ambient pressure (Feeney & Keefe 1999; 2001; Feeney et al. 2003a; Feeney et al. 2004; Schairer et al. 2007; Keefe et al. 2010) and at tympanometric peak pressure (TPP) (Keefe et al. 2010). Keefe et al. (in press) described a new wideband ASRT test, which is based on detecting ASR shifts in the sound power absorbed by the test ear from a reference sound. Using this power-based ASRT test in an ipsilateral mode, the present study describes the first reports on the mean ASRTs at TPP in a group of normal adult ears, and the test-retest reliability of the ASRT. Hunter et al. (in press) presented group data for the ASRT in infants with normal, conductive and sensorineural hearing loss using procedures described in Keefe et al. (in press).

The present study was part of a multi-year investigation evaluating a WAI test battery for the assessment of middle-ear and cochlear function in adults and children. This article describes normative data and test-retest reliability on a battery of WAI tests in adult subjects with normal hearing. The WAI tests included absorbance, group delay, equivalent admittance at the TM, both at ambient pressure in the ear canal and with air pressure sweeps in the ear canal from positive to negative pressure (downswept) and negative to positive pressure (upswept), and an ipsilateral ASRT test at TPP using a broadband noise (BBN) activator. These data in normal ears are expected to be useful for interpreting differences in reflectance and equivalent admittance at the TM between groups of ears with normal hearing and middle-ear dysfunction, as well as ASRT differences in normal ears and in individuals with cochlear, cranial nerve VIII or brainstem dysfunction.

II. METHODS

A. Subjects

All procedures were approved by the Institutional Review Boards at the University of Washington and the Boys Town National Research Hospital. A total of 33 normally hearing adults were recruited from both the University of Washington (N=20) and Boys Town National Research Hospital (N=13) for this study. The combined cohort ranged from 19 to 46 years (mean age=26 y), consisting of 13 males (mean age=26 y) and 20 females (mean age=25 y). Three additional subjects were recruited for the study, but valid data were not obtained due to equipment issues.

To be included in the study, subjects had: 1) normal 226-Hz tympanometry defined as having peak-compensated static acoustic admittance (Y_{tm}) ranging from 0.3 to 1.7 mmho (i.e., 0.001 mho in CGS units) and middle-ear pressure within ±100 daPa (Margolis & Hunter, 1999); 2) normal pure-tone air conduction thresholds ≤ 25 dB HL from 0.25 to 8.0 kHz; and 3) audiometric air-bone-gaps ≤10 dB HL at octave frequencies from 0.25 to 4.0 kHz. All subjects except one had puretone thresholds at ≤ 20 dB HL for all frequencies. That subject met the ≤ 20 dB HL criterion except at 3.0 kHz in both ears with a threshold of 25 dB HL.

B. Instrumentation

1. Clinical measurements—Clinical audiometry and immittance at 226 Hz were conducted at each site using a Grason Stadler Instruments (GSI) 61 audiometer and GSI Tympstar tympanometer calibrated to ANSI standards S3.6 and S3.39, respectively. The BBN reflex activator stimulus for the GSI Tympstar was calibrated in dB SPL in a 2 cm^3 (HA-1) coupler.

2. Experimental measurements—The system hardware used for the WAI research tests was an Interacoustics Wideband Research System consisting of an Interacoustics AT235 tympanometer with modified firmware as described in Liu et al. (2008). This firmware on the pressure controller circuit communicated the current tympanometric pressure at times during a tympanometric sweep to software that controlled data acquisition on a personal computer via an RS-232 serial port, and the software transmitted the desired sweep pressure back to the firmware. The experimental probe assembly contained two receivers: one was a high-bandwidth receiver used to generate wideband clicks (bandwidth 0.2 to 8.0 kHz) as a probe stimulus; and the second had the same bandwidth but allowed higher levels to generate reflex activator signals. The personal computer generated digital stimuli and recorded digital responses from the probe under custom software using a 24-bit sound card (CardDeluxe) that operated at a sample rate of 22.05 kHz per channel. An additional port exiting the probe coupled air pressure changes delivered by a pump and pressure controller in the AT235 tympanometer to achieve the desired pressure under the control of the custom software for measurements at a fixed air pressure or for pressure sweeps during tympanometry. Ambient-pressure measurements were obtained following probe insertion in the ear canal by adjusting the ear-canal pressure with the tympanometric pump to the ambient pressure.

C. Procedure

Clinical and experimental tests were completed in a sound-treated booth while participants were seated comfortably. All procedures were repeated on a second test visit approximately one month later (mean = 30 d, range = 7 to 55 d).

1. Clinical measurements—Following an otoscopic examination, air- and bone-conduction behavioral pure-tone thresholds were obtained using standard techniques with a

5-dB step size, followed by the 226-Hz clinical tympanometry test. Subjects who passed the clinical screening criteria were tested using a 226-Hz probe tone for the ipsilateral ASRT for BBN in both ears using a starting level of 65 dB SPL and a procedure in which the activator level was increased in 5 dB steps until a reflex response was obtained with a reflex-shift criterion of 0.03 mmho. The stimulus level was then reduced by 10 dB and the procedure was repeated with the level increasing in 5 dB steps if an ASR was not observed at a given level. The clinical ASRT was defined as the lowest activator level of the BBN that resulted in a criterion ASR shift on two ascending runs. If the criterion shift was not observed at the maximum activator level of 90 dB SPL, the ASRT test was terminated and recorded as *No Response*. Subjects were provided a break, if desired, prior to completing the wideband experimental measurements.

2. Experimental measurements—The system was calibrated for reflectance measurements by recording the pressure response to a click stimulus with a spectrum of 0.2 to 8.0 kHz in a pair of hard-walled cylindrical tubes (with nominal lengths of 292 and 8.2 cm); each was closed at one end with a cross-sectional diameter of 7.94 mm, similar to that of an average adult ear. The incident pressure spectrum and the source reflectance of the Interacoustics probe were calculated using these measured data and an acoustical model of sound propagation in cylindrical tubes with viscothermal loss (Keefe et al. 1993; Keefe & Simmons 2003). The software determined when a valid calibration was obtained. This calibration was performed daily before measurements in human subjects were obtained.

For measurements in the ear of a human subject, the probe was placed into the ear canal with a leak-free insertion using a soft plastic impedance probe tip. The challenge of obtaining a seal for these measurements was similar to that posed by clinical 226-Hz tympanometry. A repetitive sequence of clicks was generated by the probe to which the pressure response in the ear canal was measured using the microphone. All WAI measurements were calculated in terms of these measured data along with the incident pressure and source reflectance stored from the calibration for that day.

a. Wideband Reflectance: The ear-canal data for the ambient reflectance test consisted of 32 click responses collected over 2 s. The clicks were delivered to the receiver at a rate of 1024 samples every 46 ms. Artifacts were classified and rejected using a median absolute deviation test (Liu et al., 2008; Keefe et al. 2015). This procedure identified and excluded outliers from the set of 32 click responses. Such artifact rejection was useful for recording responses in human ear canals, because it detected and excluded data that were contaminated by transient noise, whether generated in the test environment, the measurement system, or by the test subject. Each click response was either judged valid or an outlier. The remaining click responses that were valid, i.e., that were not excluded as outliers, were then averaged to obtain a mean waveform. The standard error (SE) of the mean was also calculated to provide a real-time measure of noise in the time-domain estimate of the mean waveform. The reflectance at the probe tip was calculated in terms of this mean measured pressure waveform in the test ear and the calibration outputs described above. The resulting absorbance and group delay spectra were averaged into 1/6th octave frequency bands between 0.25 and 8.0 kHz. This amount of frequency averaging was sufficiently large to average out noise effects and contributions from otoacoustic emissions, and sufficiently small to resolve many of the frequency variations related to ear-canal and middle-ear function.

As discussed in Keefe et al. (2015) there is interest in exploring the difference in the group delay between ears with normal auditory function and age-matched ears with a conductive disorder. Assuming a random variation in ear-canal length across test ears with a mean difference of zero between normal and conductive-impaired ears, the group delay at the probe tip would be sufficient to explore such differences without the need to convert to an equivalent group delay at the TM, which would also require estimation of the ear-canal length. This article presents group-delay data measured at the probe tip. Because the mean ear-canal length data are also presented in this article, it is straightforward to evaluate the equivalent group delay at the TM, with the following proviso. The procedure to estimate this length involved additional assumptions that the cross-sectional area of the ear canal was constant or at least slowly varying between the probe and the TM, and the TM was represented as located at a single location in an acoustic transmission line describing sound propagation between the probe and TM. These procedures and related assumptions are described in Keefe et al. (2015).

The tympanometric reflectance test was similar to the ambient reflectance test in that responses were recorded to a sequence of wideband clicks. The additional variable was that the tympanometric pressure was swept over the desired range during the presentation of the clicks, so that each click response was recorded at a slightly different ear-canal pressure (Keefe et al. 2015). At the nominal sweep rate of 100 daPa/s, the static pressure varied by about 4.6 daPa between adjacent click responses. As with the ambient reflectance data, the absorbance and group delay spectra for each sweep direction were averaged into 1/6th octave frequency bands between 0.25 and 8.0 kHz. Two reflectance tympanograms were measured using an ear-canal pressure that was either downswept starting at +200 daPa down to −300 daPa, or upswept starting from −300 daPa up to +200 daPa. The TPP was calculated for each sweep direction by calculating the pressure at which the maximum of the low-frequency averaged absorbance occurred over the frequency range from 0.376 to 2.0 kHz. This frequency range was used based on Liu et al. (2008), which excluded the somewhat noisier data below 0.376 kHz related to the absence of averaging across click responses during the tympanometric sweep.

Recordings were monitored by a researcher during data collection to ensure that the probe insertion was maintained. Movement of the probe with the tympanometry tips used with this system is typically not an issue. The researcher was alerted by the software to the possibility of a leaky probe fit. If this occurred, then the measurement was repeated after reseating the probe. If the probe tip moved but not enough to produce a leak, the artifact rejection procedure might identify outliers as described above. Click responses were not analyzed in this present report when they occurred in the early part of the sweep as the pressure changed from ambient (0 daPa) to the desired start pressure of the sweep, and in the final part of the sweep as the pressure changed from the desired end pressure of the sweep back to ambient pressure.

b. Wideband Equivalent Admittance at the TM: A transmission-line model of sound propagation in a cylindrical ear canal may be used with measurements of the admittance at the probe tip to calculate the equivalent admittance at the TM (Rabinowitz 1981). This study used the method described by Keefe et al. (2015) to calculate the equivalent admittance at the TM. This was based on acoustical estimates of the ear-canal area at the probe tip and the ear-canal length between the probe tip and the eardrum at a mid-TM location 4 mm from the innermost point of the ear canal. This method assumed a constant ear-canal area between the probe and TM.

c. Wideband ASRT: The wideband ASRT test as described in Keefe et al. (in press) was used for this study. This section contains a summary description of these test procedures. Following Keefe et al. (2010), a pulsed stimulus set was used in which the BBN activator was pulsed on and off four times, and click (i.e., probe) stimuli were presented before the first activator pulse and after each subsequent activator pulse for a total of five clicks. The click-stimulus waveform had a bandwidth from 0.2 to 8.0 kHz, and was identical to that used to measure the reflectance and equivalent admittance at the TM.

The BBN activator was selected from a sampled white-noise signal that was low-pass filtered at 8.0 kHz. The duration of each BBN pulse (116 ms) was longer than the onset latency of the ASR. The overall waveform duration was 1.58 s with the clicks and BBN pulses presented in the initial 0.79 s. This was followed by a 0.79 s period of silence to allow recovery from the reflex. The stimulus set was presented twice at each activator level, and 10 different activator levels were used in increasing level in 5 dB steps for a total test duration of 31.6 seconds. BBN activator levels were calibrated for the clinical and wideband experimental systems based on the sound pressure level (SPL) measured in a 2-cm^3 (HA-1) coupler. Activator stimulus levels ranged from 45 to 90 dB SPL for the experimental ASR test. The wideband ASR data were analyzed up to 8.0 kHz, although the ASR shift was used to define the ASR threshold over a low-frequency range from 0.2 to 2.4 kHz. This comprised the frequency range of the ASR shifts of largest amplitude and is similar to the bandwidth over which ASR effects have previously been studied (Rabinowitz 1977; Pang & Peake 1986). The wideband ASR was recorded ipsilaterally at TPP, which was obtained by averaging the TPP values for the downswept and upswept absorbance tympanograms as described by Keefe et al. (2015).

The ASR was detected based on the method of Keefe et al. (in press) by assessing the difference in absorbed sound power between the initial click and any of the other four clicks that followed each BBN activator pulse in each pulse-stimulus set. In contrast, Keefe et al. (2010) detected the ASR in terms of the response difference in acoustic pressure between the initial and later clicks. An artifact rejection procedure to identify noisy buffers displayed messages to the operator during data acquisition.

For each measured response using the pulsed stimulus set, the reflectance and absorbed sound power were measured at the probe tip from each click response. The initial click was used to measure the baseline absorbed power in the ear, and the clicks following the activator pulses were used to measure the absorbed power including the effects of any ASR shifts elicited by the activator pulse. For each activator level, an ASR shift was classified as present if both the following conditions were satisfied for at least one of the two trials at the same activator level: (1) the shift was sufficiently large, that is, if a shift in weighted absorbed power level $|\Delta L_{W1}|$ (which was calculated in terms of a frequency-weighted cumulative sum of absorbed sound power) for the low frequencies was ≥0.7 dB, and had an expected spectral shape of a reduction in absorbed power at low frequencies when the ASR was present, and (2) if the shifts in absorbed power level ΔL_W as a function of frequency relative to the baseline click were sufficiently similar to one another for the four later clicks based on pair-wise correlations between their measured power spectra at frequencies within the ASR passband. That is, an ASR shift at a single activator level had to be sufficiently large and sufficiently similar to those of several of the later clicks. Otherwise, the ASR shift was classified as absent at the given activator level. After discarding the initial results measured at the lowest activator level, the ASRT was estimated using the ASR shifts classified in the remaining nine activator levels (Keefe et al. in press).

It should be noted that the shift in absorbed power level ΔL_W is defined at each test frequency whereas the shift in weighted absorbed power level $|\Delta L_{W1}|$ is defined as a weighted power sum over all frequencies, which preferentially weights lower frequencies up to about 2 kHz. The ASRT was classified as *No Response* if the ASR shift was absent in all activator levels, or if there were no valid tests at any activator level due to artifact (the latter was much more likely to occur in an infant test than an adult test). For tests with an ASR shift present at any of the nine remaining activator levels, the ASRT was determined using a maximum-likelihood procedure refined from that in Keefe et al. (2010).

When the ASR shift was present at more than one activator level, an additional criterion was used to compare responses across levels. This was to ensure that the shift in absorbed power ΔL_W measured at one activator level was sufficiently similar across frequencies in the ASR passband to ΔL_W measured at another activator level. The top panel of Figure 1 shows shifts in absorbed power level ΔL_W for each activator level for one subject in this study. The spectral shape of the shift in power was similar across activator levels, and higher activator levels resulted in greater shifts in absorbed power in the low frequencies (below 2.0 kHz) compared to lower activator levels. A weighted, across-level correlation between these power responses was calculated, which varied between −1 and 1. If this correlation value was 0.5 or less, the ASRT was recorded as no response. The bottom panel of Figure 1 shows the shift in weighted absorbed power level $|\Delta L_{W1}|$ for each activator level. The criterion power shift level (≥0.7 dB) was observed for a BBN activator level of 65 dB SPL. The ASRT was calculated using the maximum-likelihood procedure over the final range of activator levels.

E. Data Analysis

The first goal of this analysis was to provide normative data in adult ears for 1/6th octave absorbance, group delay, and equivalent admittance at the TM for the ambient, upswept- and downswept-TPP conditions, and positive and negative tympanometric tails. The second goal was to provide normative data on the test-retest reliability for each measure. The means and test-retest differences for the ear-canal length and area estimates used in the calculation of the equivalent admittance at the TM were also obtained. These normative baseline data were from the first test for which the subject-inclusion criteria were satisfied; data from 12 ears were included although their data were not part of the test-retest reliability analyses. The absolute test-retest differences were calculated for those 45 ears with a valid baseline test and a valid retest according to the inclusion criteria. A repeated-measures analysis of variance (ANOVA) was used to explore the mean differences across test conditions for some measures.

The goals for the ASRT analyses were to provide normative data for the ipsilateral clinical and wideband tests for a BBN activator, including test-retest reliability, and to test the difference between the mean ipsilateral ASRTs for the two methods. A statistical modelling approach was used for these comparisons that took into consideration some of the unique properties of these data. First of all, there are several correlation features of the data that should be considered: there were up to two sessions of measurement per ear and one to two ears per subject with usable data. Furthermore, both wideband and clinical tests were used to measure the ASRT, and these were also likely correlated.

In light of these features, these ASRT data were analyzed using a hierarchical model with correlated random effects. More specifically, measurement y_{iejk} was modeled with mean μ_{iejk} given by the e^{th} ear of the i^{th} subject on the j^{th} measurement occasion using the k^{th} method (k=1 for wideband ASRT, 2 for clinical ASRT) as $\mu_{iejk} = \theta_k + \delta_i + \varphi_{ie}$. The δ and φ terms described within-subject random effects for subject and ear, respectively. The parameter θ_1 was the population mean reflex threshold using the wideband ASRT, and θ_2 was the population mean reflex threshold using the standard method. Independent residual variances σ_1^2 for the wideband ASRT method and clinical ASRT method σ_2^2 were assumed. The model test-retest reliability was defined as the average absolute difference between test and retest for a single ear using the k^{th} metric, which is $2\sqrt{\frac{\sigma_k^2}{\pi}}$ (Bland & Altman 2003; McMillan 2014). With this definition of reliability, larger values indicated larger test-retest differences, which represented poorer reliability than did smaller values. The reliability of a test variable had the same units as the test variable. The mean and 95% confidence interval (CI) of the absolute difference between test and retest in each test ear were compared across all test ears for the two ASRT methods. The SE of the test-retest reliability was estimated across subjects, and was used to compute CIs for the test-retest reliability.

Measurements that did not achieve a reflex threshold at 90 dB (or lower) were said to be ‘censored’ at 90 dB. This designation was used to distinguish observations that had a known reflex threshold from those that were greater than 90 dB. This nomenclature was taken from survival data analysis where this kind of data structure is common. This feature affected the likelihood function, from which all of the parameter estimates were derived, such that the contribution of an observation to the likelihood was $f(y)^{I(y \le 90)} \cdot F(y)^{(1-I(y \le 90))}$. Here, $I(y \le 90)$ is an indicator function for y observed at or below 90 dB SPL. The functions f and F are the Gaussian probability density and cumulative distribution functions, respectively.

III. RESULTS

Averaged adult data for wideband absorbance, group delay, equivalent admittance at the TM and equivalent admittance phase at the TM are first presented followed by test and retest data for these measures from a single subject (additional individual adult data obtained with the same methods are presented in Keefe et al. 2015). This is followed by averaged adult data for the wideband acoustic reflex threshold test for which individual data are shown in Figure 1.

A. Wideband Absorbance

For the first session with usable data from 57 ears, the mean 1/6th octave absorbance at ambient pressure A_a and the tympanometric absorbance at TPP for upswept A_tU and downswept A_tD tympanograms are shown in the top panel of Figure 2. The pattern of absorbance across frequency was similar for these three measures. The mean absorbance had a minimum around 0.1 at 0.25 kHz, increased with frequency to a broad maximum centered around 1.0–1.4 kHz, decreased slightly at frequencies centered around 2.0 kHz, and increased to a second maximum around 4.0 kHz before dropping to 0.4 and below at 8.0 kHz. A two-factor repeated measures ANOVA on the three methods of absorbance measurement with a lower-bound correction showed a significant effect of method ($F_{1, 56}$ =119.6, p<0.001) and frequency ($F_{1, 56}$ =128.4, p<0.001), as well as significant method by frequency interaction ($F_{1, 56}$ =44.5, p<0.001). An ANOVA for pairwise comparisons of absorbance methods with a Bonferroni adjustment for multiple comparisons showed that the overall mean differences among the three methods were significant (p<0.001). Paired-sample t-tests were obtained for mean differences in absorbance between methods at each frequency using a Bonferroni correction for multiple comparisons for an alpha level of 0.05. Both A_tD and A_tU at TPP were greater than A_a at frequencies ≤2.5 kHz and ≤2.2 kHz, respectively. A_a was greater than A_tD at frequencies from 3.6 to 5.7 kHz, and greater than A_tU at frequencies ≥3.6 kHz. A_tU was significantly greater than A_tD at frequencies from 0.25 to 1.41 kHz, but less than A_tD at frequencies ≥4.0 kHz.

Also shown in the top panel of Figure 2 are the mean values of A_tD and A_tU at +200 daPa, the tympanometric positive tail (PT), and −300 daPa, the tympanometric negative tail (NT). These pressure extremes caused a reduction in absorbance compared to TPP and ambient absorbance at frequencies below about 4.0 kHz for NT conditions, and below about 3.0 kHz for PT conditions. Maxima occurred for the PTs at frequencies between 4.0 and 4.5 kHz and for the NTs at 5.0 kHz. These maximum tail absorbances slightly exceeded the absorbance for A_t at TPP.

The middle panel of Figure 2 shows the mean absolute test-retest differences for A_a, and A_tD and A_tU at TPP at each 1/6th octave frequency for the 45 ears with data meeting the inclusion criteria for both baseline and one-month tests. Test-retest differences for all three measures increased with frequency from a low of around 0.04 at 0.25 kHz to a high of around 0.1 at frequencies between 4.0 and 8.0 kHz. A two-factor repeated measures ANOVA on the test-retest differences for the three methods showed a significant effect of method ($F_{1, 44}$ =8.8, p=0.005) and significant method by frequency interaction ($F_{1, 44}$ =4.9, p=0.03). An ANOVA for pairwise comparisons of absorbance methods with a Bonferroni adjustment for multiple comparisons showed that the overall mean test-retest difference between A_a and A_tD of 0.017 was significant (p=.002), but the mean difference between A_a and A_tU of 0.011 was not significant (p=0.062). A paired-samples t-test with Bonferroni correction for multiple comparisons revealed that better absorbance test-retest reliability was shown for A_tD compared to A_a at the frequencies between 1.0 and 1.26 kHz.

The mean absorbance test-retest differences for the positive and negative tympanometric tail conditions for A_tD and A_tU are shown in the bottom panel of Figure 2. At frequencies above 1.0 kHz, the results were similar for all test-retest differences rising from around 0.04 at 1.0 kHz to a peak around 0.15 near 3.6 kHz, and then decreasing at higher frequencies. At frequencies below 1.0 kHz, the PT conditions had lower test-retest differences than for the NT conditions.

An effect of ear-canal pressurization on any WAI variable may be obtained by comparing the magnitude or phase of the variable at TPP to that obtained at extreme ear-canal pressures (at the positive or negative tympanometric tails). The difference between these values, or peak-to-tail differences, may be useful for comparison with ears with middle-ear disorders. This is similar to Y_{tm} for 226 Hz tympanometry, which is the admittance magnitude at the TPP minus the admittance magnitude at the PT or NT. For 57 ears at baseline, the mean differences between the A_t at TPP and A_t at the tympanometric tails are shown in Figure 3 for the PT differences and NT differences (top panel). Results were similar for the TPP minus PT conditions for A_tD and A_tU as were results for the TPP minus NT conditions. The TPP minus PT conditions were generally greater than the TPP minus NT conditions at frequencies below 0.8 kHz and less than TPP minus PT conditions for higher frequencies. A minimum in the peak-to-tail absorbance difference occurred near 4.0 kHz for the PT differences and 6.0 kHz for the NT differences. A two-factor repeated measures ANOVA showed that there was a significant effect of condition ($F_{1,56}$ =82.0, p<0.001). An ANOVA for pairwise comparisons of conditions with a Bonferroni adjustment for multiple comparisons showed that the TPP minus NT conditions were significantly different for A_tD and A_tU (p<0.001), but the TPP minus PT conditions were not significantly different (p=0.85). Since the NT conditions were obtained with a greater pressure change with respect to the TPP than the PT conditions, 300 vs 200 daPa, respectively, an analysis was not conducted of the difference between peak-to-tail differences for the two pressure conditions.

The mean test-retest reliabilities for peak-to-tail differences for A_tD and A_tU are shown in the bottom panel of Figure 3. The PT condition for A_tD had the lowest test-retest differences at frequencies from 0.25 to 0.9 kHz. Otherwise, the test-retest differences were similar for the four measures across all frequencies from a low of 0.03 at 0.25 kHz to a high of 0.12 at 3.6 kHz. A two-factor repeated measures ANOVA revealed that there was a significant effect of condition for these peak-to-tail test-retest differences ($F_{1, 44}$ =4.4, p=0.043) and a significant effect of frequency ($F_{1, 44}$ =5.2, p=0.028). An ANOVA for pairwise comparisons of conditions with a Bonferroni adjustment for multiple comparisons showed that the overall mean test-retest difference for the TPP-PT A_tD condition was significantly greater than for the A_tU conditions for both tails, but not greater than the TPP-NT A_tD condition. The combination of a large peak-to-tail difference in absorbance (top panel of Figure 3) with low test-retest differences (bottom panel of Figure 3) occurred at frequencies between about 0.7

and 3.0 kHz. This may lie in a clinically sensitive frequency range for interpreting A_t measurements.

The difference between A_t at TPP and A_t at each of the tympanometric tails may be averaged across a range of frequencies to provide a summary description of the absorbance tympanogram (Keefe et al. 2015). This reduces the large number of frequency variables involved in a wideband tympanogram at the expense of frequency specificity. The negative and positive peak-to-tail differences in A_t were calculated for the subjects in this study averaged over a low-pass (0.376 to 2.0 kHz) or high-pass (2.0 to 8.0 kHz) band. Table 1 shows the mean low-pass and high-pass-filtered peak-to-tail difference for A_t and the positive-tail (+200 daPa) or negative-tail (−300 daPa) pressure for A_tD and A_tU. The mean peak-to-tail absorbance difference for the low-frequency band for both A_tD and A_tU exceeded 0.4 for each condition, while the mean peak-to-tail difference for the high-pass band was less than 0.1 for each condition. The small average peak-to-tail difference for the high-frequency band reflects the pattern across frequency shown in the 1/6th octave high-frequency data of Figure 3, which changed from a positive peak-to-tail difference starting at frequencies near 2.0 kHz to a negative peak-to-tail difference at frequencies above 3.0 to 4.0 kHz. This accounts for the average being close to zero across the high-frequency band. Table 1 also shows mean test-retest reliability for peak-to-tail differences for both the low-pass and high-pass bands for ears with test and retest (N=45). These absorbance differences are within 0.04 for both A_tD and A_tU for both the low-pass and high-pass conditions.

The mean absorbance tympanometric widths for both A_tD and A_tU are shown in Table 2 for 57 ears. These are calculated as the width in daPa between the 50% amplitude points on the positive and negative slopes of the low-pass averaged absorbance tympanogram, as defined in Keefe et al. (2015). The mean tympanometric widths and test-retest differences were similar for the downswept and upswept conditions. The mean test-retest differences for tympanometric width were around 10 daPa for both pressure-sweep conditions. Also shown in Table 2 for comparison is the mean 226 Hz tympanometric width and test-retest differences for the same subjects. This was defined as the pressure interval in daPa that bisects the 226 Hz tympanogram slopes at an admittance magnitude of 50% of the peak-to-positive tail difference. Because the tympanometric width is defined differently for the clinical and research tests, it is not meaningful to compare their test values in absolute terms. What would be meaningful is to evaluate the degree to which either tympanometric width is accurate in diagnosing a particular type of middle-ear disorder, although this is outside the scope of the present study.

B. Wideband Group Delay

The mean group delay as a function of frequency for the ambient method D_a and tympanometric methods at TPP for the downswept D_tD and upswept D_tU tympanograms is shown in the top panel of Figure 4. These are trimmed means with outliers greater than the 5th and 95th percentiles deleted. The means were trimmed to eliminate positive and negative outliers that may occur in the 0.8 to 4.0 kHz range (Keefe et al. 1993; Voss & Allen 1994). The greatest outliers were −1850 μs and + 2833 μs at 1.59 kHz for D_a, −1438 μs at 1.12 kHz and +1404 μs at 3.60 kHz for D_tU at TPP, and −1106.10 μs at 0.79 kHz and +1659 μs at 1.0 kHz for D_tD at TPP.

The mean group delay for all three methods was less than 100 μs at 0.25 kHz, attained maxima with values in the range of 200–300 μs between 0.32 and 0.6 kHz, decreased to minima in the range of 15–100 μs between 0.8 and 1.5 kHz, and were less variable across frequency from 2.0 to 8.0 kHz with values ranging from 100 to 175 μs. At frequencies below about 0.7 kHz, D_t was around 50 μs larger for both sweep directions than D_a, while this was reversed in the octave around 1.0 kHz with greater group delay for D_a. Above 2.0 kHz, the mean group delay was similar for the three methods. A repeated-measures ANOVA failed to show a significant effect of method on group delay ($F_{1,44}$ =3.8, p=0.58).

The mean D_tD and D_tU for PT and NT is shown in the middle panel of Figure 4, with all data included in the calculation of the mean. The mean D_t showed maxima and minima at about the same frequencies as for the conditions in the top panel especially at frequencies below 2.0 kHz, but the differences between maxima and minima were comparatively reduced for the tail conditions especially in the low frequencies. The standard errors of the mean group delay were generally smaller below 1.8 kHz at the tail pressures than at the TPP or in the ambient condition. A repeated-measures ANOVA on these tail data failed to show a significant effect of condition on group delay ($F_{1,56}$ =0.45, p=0.50).

The mean 1/6th octave peak-to-tail differences in D_t are shown in the bottom panel of Figure 4 for downswept and upswept tympanograms for the PT and NT conditions. The plots were similar for the four conditions with the mean peak-to-tail difference around 25 μs at 0.25 kHz, increasing to around 100 μs at frequencies from 0.28 to 0.56 kHz, and then dropping to negative values from around 0.8 kHz to 3.0 kHz. The mean peak-to-tail differences were positive for all four conditions at frequencies above 4.0 kHz. A repeated-measures ANOVA on these peak-to-tail differences failed to show a significant effect of condition on group delay ($F_{1,56}$ =1.60, p=0.21).

Mean test-retest differences in group delay are shown in the top panel of Figure 5 for D_a, D_tD and D_tU at TPP. For all three methods, the test-retest differences were greatest at one or more 1/6 octave frequencies between about 0.75 and 1.5 kHz with another peak near 4.0 kHz. Test-retest differences were smallest at and above 6.0 kHz and at 0.25 kHz. A repeated-measures ANOVA on these test-retest differences failed to show a significant effect of method on group delay ($F_{1,44}$ =1.65, p=0.21).

The middle panel of Figure 5 shows the test-retest differences for D_tD and D_tU at PT and NT. These were similar for all four conditions at around 50 μs between 0.25 and 2.0 kHz. The D_t near 4.0 kHz was greater for the PT conditions than the NT conditions. However, a two factor repeated-measures ANOVA failed to show a significant effect of condition on test-retest differences for group delay at the tympanometric tails ($F_{1,44}$ =3.49, p=0.07). The mean test-retest differences for the peak-to-tail differences for D_tD and D_tU are shown in the bottom panel of Figure 5. These test-retest differences combine features from the TPP and tail reliability plots in the upper two panels of Figure 5 with maxima around 1.0 and 4.0 kHz and the best reliability at frequencies below 0.75 kHz and above 5.0 kHz. A two factor repeated-measures ANOVA failed to show a significant effect of condition on test-retest differences for peak-to-tail differences for group delay ($F_{1,44}$ =3.73, p=0.06).

C. Wideband Equivalent Admittance at the TM

The equivalent admittance at the TM, a complex variable, is denoted as Y_a for ambient data and Y_t for tympanometric data. The magnitude of the ambient equivalent admittance at the TM is $|Y_a|$, and its phase is ϕ_a. The group results for $|Y_a|$ and $|Y_t|$ are plotted as admittance levels in dB, with 0 dB corresponding to a magnitude of 1 mmho. Estimates of the ear-canal area just in front of the probe and the ear-canal length between the probe and the mid-TM location were used to estimate Y_a and Y_t from the admittance measured at the probe tip from 0.25 to 8.0 kHz as described above.

Table 3 shows the mean ear-canal area of 44.4 mm^2 and the mean ear-canal length of 18.3 mm based on the data from the present study. Also presented are the data on the mean test-retest differences for these measures which were approximately 25% of the mean value for both measures.

The mean $|Y_a|$ level and SE across the 57 test ears is shown in the top panel of Figure 6. The mean $|Y_t|$ level at TPP is plotted in a similar manner for both downswept $|Y_t|D$ and upswept $|Y_t|U$ tympanograms. All three measures increased from near 0 dB at 0.25 kHz to around 10 to 12 dB at 1.0 kHz at a slope of 6 dB per octave, but the $|Y_a|$ level was lower than the $|Y_t|$ levels at TPP for both pressure-sweep directions across this frequency range. $|Y_t|$ level at TPP plateaued for both sweep directions at around 10 to 12 dB from 1.0 kHz to 2.0 kHz, while $|Y_a|$ level gradually increased to 10 dB from 1.0 kHz to 1.5 kHz. All three measures had similar values from about 1.5 to 8.0 kHz, as they increased around 5 dB from 1.5 to 8.0 kHz with a maximum around 15 dB. A repeated-measures ANOVA revealed a significant overall effect of method ($F_{1, 56}$=4.79, p=0.033), and there was a significant method by frequency interaction ($F_{1,56}$=12.35, p=0.001). An ANOVA for pairwise comparisons of methods with a Bonferroni adjustment for multiple comparisons showed that $|Y_a|$ was significantly different from $|Y_t|U$, but not from $|Y_t|D$. Paired-samples t-tests with Bonferroni correction showed that $|Y_a|$ was significantly lower than $|Y_t|U$ at frequencies 0.25 to 1.12 kHz.

The mean and SE of ϕ_a and ϕ_t at TPP for the downswept $\phi_t D$ and upswept $\phi_t U$ tympanograms are shown in the bottom panel of Figure 6. The mean phase of the equivalent admittance at the TM was similar for all three methods at around 68° at 0.25 kHz and decreased to a minimum between 10° and 20° at 1.5 kHz. The phase then increased to a maximum near 30° at 3.0 kHz such that $\phi_t D$ at TPP was lower than ϕ_a and $\phi_t U$ at TPP at frequencies between 1.5 and 3.0 kHz. The mean phase ranged between 10° and 30° at all frequencies above 1.0 kHz for all three methods. A repeated-measures ANOVA failed to show a significant effect of method on admittance phase ($F_{1,56}$ =2.51, p=0.12), or method by frequency interaction ($F_{1,56}$ = 3.41, p=0.07). The fact that the mean phase remained positive across all frequencies implies that the mean equivalent admittance at the TM was stiffness dominated for all three conditions.

The mean test-retest differences for the equivalent admittance level at the TM were slightly higher for the $|Y_a|$ level compared to the $|Y_t|$ level at TPP for both pressure-sweep conditions as shown in the top panel of Figure 7. However, the general pattern across frequency was similar for the three measures. The mean test-retest differences across the three methods were within 2 dB of one another across the frequency range. At higher frequencies the test-retest differences increased for all three measures from a minimum of around 2 dB at 1.0 kHz to a maximum of around 8 to 9 dB between 6.0 and 8.0 kHz. A repeated-measures ANOVA failed to show a significant overall effect of method on the equivalent admittance level at the TM ($F_{1,44}$ =2.99, p=0.09), and the method by frequency interaction was also not significant ($F_{1,44}$ =0.43, p=0.52).

The mean test-retest differences for the equivalent admittance phase at the TM were similar for ϕ_a, and both $\phi_t D$ and $\phi_t U$ at TPP for the upswept and downswept tympanograms across the frequency range as shown in the bottom panel of Figure 7. Overall for the three methods, the test-retest differences gradually increased from around 10 to 15° in the low frequencies to around 20° at 1.8 kHz, plateaued from 1.8 to 3.2 kHz, and then sharply increased to around 30° at 3.6 kHz and continued to increase with frequency at a rate of about 30° per octave. A repeated-measures ANOVA failed to show a significant effect of method on test-retest difference for equivalent admittance phase ($F_{1,44}$ =1.11, p=0.30), and the method by frequency interaction was not significant ($F_{1,44}$ =1.47, p=0.23).

The mean and SE of the $|Y_t|$ level at the tympanometric tails are shown for $|Y_t|D$ and $|Y_t|U$ in the top panel of Figure 8. The mean $|Y_t|$ level was similar for the four tail conditions from 0.25 to 0.8 kHz. At higher frequencies the NT conditions resulted in lower mean admittance level than the PT conditions by several dB. The $|Y_t|$ levels at the NT were slowly varying with frequency from 0.8 to 1.5 kHz, increased at higher frequencies with a maximum at 5.0 kHz, and had slightly lower values at higher frequencies within 2 dB of the maximum. The $|Y_t|$ levels at the PT generally increased from −8 dB at 0.25 kHz to a maximum of 18 dB at 4.0 kHz, and the levels were relatively constant above 4.0 kHz. Although the overall differences between conditions were small, a repeated-measures ANOVA revealed a significant overall effect of condition for $|Y_t|$ level at the tympanometric tails ($F_{1, 56}$=19.0, p<0.001). Compared to the $|Y_t|D$ and $|Y_t|U$ level at TPP (top panel, Figure 6), the $|Y_t|$ level at the tympanogram tails was about 8 dB lower at frequencies between 0.25 and 1.0 kHz decreasing to 0.6 dB at 2 kHz, and was less than for the tails by about 3 dB at higher frequencies.

The $\phi_t D$ and $\phi_t U$ values for PT and NT are shown in the bottom panel of Figure 8. At frequencies from 0.25 to 3.0 kHz, the downswept PT and NT conditions generally had lower phase than for the corresponding upswept conditions. At frequencies from 0.5 to 3.0 kHz, the upswept NT condition had generally greater phase than for ϕ_t at TPP for either sweep direction (bottom panel, Figure 6). The lowest mean phase was for $\phi_t D$ at the PT condition from 0.25 to 2.0 kHz at around 35° to 40°, and $\phi_t D$ at the NT condition at frequencies between 0.5 and 1.0 kHz. At frequencies above 3.0 kHz the phase values for all four conditions were similar, decreasing from about 50° to 20° at 4.0 kHz and plateauing at higher frequencies. As was the case with the ambient and TPP conditions, the mean equivalent admittance phase at the TM for the tympanometric tails was stiffness dominated at all frequencies. There was greater variability across subjects for phase at the tympanometric tails at frequencies from 0.25 to 3.0 kHz (bottom panel, Figure 8) than for ϕ_t at TPP for either sweep direction (bottom panel, Figure 6). A repeated-measures ANOVA revealed a significant overall effect of condition for phase at the tympanometric tails ($F_{1, 56}$ =8.6, p<0.01). An ANOVA for pairwise comparisons of conditions with a Bonferroni adjustment for multiple comparisons showed that $\phi_t D$ for the PT was significantly lower than for the other three conditions and that $\phi_t U$ for the PT was significantly lower than for $\phi_t U$ for the NT.

The top panel of Figure 9 shows the mean and SE of the test-retest differences for $|Y_t|D$ and $|Y_t|U$ levels at the tympanometric tails. These were about 4 dB or less at frequencies below 1.0 kHz, and increased to values in the range of 6–8 dB between 4.0 and 8.0 kHz. A repeated-measures ANOVA failed to show a significant effect of condition on test-retest differences for equivalent admittance at the tympanometric tails ($F_{1,44}$ =0.47, p=0.50). In general, the mean test-retest differences in the $|Y_t|$ level at the tympanometric tails were slightly greater than those for the $|Y_t|$ level at TPP from 0.25 to 2.0 kHz, but were similar at higher frequencies (top panel of Figure 7).

The mean and SE of the test-retest differences of the equivalent admittance phase for the tympanometric tails are shown in the bottom panel of Figure 9. These were roughly constant between 20° and 30° at frequencies from 0.25 to 3.0 kHz for the PT and NT conditions for both $\phi_t D$ and $\phi_t U$. The mean test-retest differences increased at frequencies above 4.0 kHz with a maximum between 50° and 60° at 8.0 kHz. A repeated-measures ANOVA failed to show a significant effect of condition on test-retest difference for equivalent admittance phase at the tympanometric tails ($F_{1,44}$ =0.20, p=0.66).

The mean and SE of the differences in the $|Y_t|$ level at TPP minus the $|Y_t|$ level at the tail values are plotted in the top panel of Figure 10 for the PT and NT differences. The mean results were similar for the two sweep directions for both tail conditions. For the PT conditions, the peak-to-tail differences in $|Y_t|$ level were constant at around 7 to 8 dB from 0.25 to around 0.9 kHz. Above 0.9 kHz, the level difference decreased with a slope of around −6 dB per octave to a minimum value of −7 dB at 4.0 kHz and increased at higher frequencies. For the NT conditions, the $|Y_t|$ peak-to-tail level difference increased slightly from 0.25 kHz to a maximum of 8 dB around 1.0 kHz, and then dropped to a minimum of −3 dB at 4.0 kHz. Thus, the responses for the PT and NT conditions were similar for both sweep directions, but different from each other. This is a measure of asymmetry in the $|Y_t|$ tympanogram consistent with the asymmetry in the pressure extremes of +200 and −300 daPa. A repeated-measures ANOVA revealed a significant overall effect of condition for the peak-to-tail differences ($F_{1,56}$=21.08, p<0.001). An ANOVA for pairwise comparisons of conditions with a Bonferroni adjustment for multiple comparisons showed that the PT conditions were different from the NT conditions (p<0.01).

The bottom panel of Figure 10 shows the mean and SE of the test-retest differences of the $|Y_t|$ level peak-to-tail difference for $|Y_t|D$ and $|Y_t|U$ at PT and NT. At frequencies from 0.25 to 1.0 kHz, the PT conditions tended to have slightly higher mean test-retest differences than the NT conditions, averaging about 3.0 dB. At frequencies from 1.0 to 4.0 kHz the negative-tail conditions tended to have higher mean test-retest differences of around 4.0 dB. At frequencies above about 4.0 kHz, the mean test-retest differences generally decreased to a minimum of 2 dB at 8.0 kHz, with the exception of $|Y_t|D$ for the NT condition that increased to over 3 dB at 8.0 kHz. A repeated-measures ANOVA failed to show a significant effect of condition on peak-to-tail test-retest differences ($F_{1,44}$ =0.68, p=0.42).

D. Individual ear data

Reflectance and admittance data from the right ear of one subject for the baseline test and retest one week later are shown in Figure 11 (ASR data from the same test ear are shown in Figure 1 for the initial test). The data for this subject were chosen because this 27 year-old female had a difference in tympanometric peak pressure in that ear on the two test visits while meeting all inclusion criteria. The TPP for the wideband DS tympanogram was +5 daPa for test one and −40 daPa for test two. TPP for the wideband test is the pressure at which the maximum of the low-frequency averaged absorbance occurred over the frequency range from 0.376 to 2.0 kHz. The left column in Figure 11 shows data obtained for the test and retest obtained at ambient pressure and the right column shows the data for the two tests obtained at TPP.

The top left panel shows that A_a for test two is lower than test one by 10% or more from 0.79 kHz to 1.41 kHz with a maximum difference of 14% at 1.0 kHz. A_a for test two is higher than test one at frequencies from 2.2 to 5 kHz and at 6.3 kHz with the greatest difference of 10% at 2.5 and 2.8 kHz. For A_tD at TPP in the upper right panel the results for the two tests are more similar, exceeding a 10% difference at only one frequency; 13% lower for test two at 5.7 kHz.

D_a for the two tests is shown in the second row, left panel. At frequencies between 0.25 and 1.26 kHz the difference between the two tests does not exceed 50 μs. However, the group delay is greater for test two than test one by 85 μs at 1.41 kHz, 72 μs at 2.2 kHz and 230 μs at 4.0 kHz. The group delay for test one is greater than test two by 278 μs at 2.8 kHz and 206 μs at 3.2 kHz. For D_tD at TPP the greatest difference between tests is found at 1.2 kHz where the group delay for test two exceeds that of test one by 40 μs. $|Y_a|$ for test one and test two are shown in the third row of Figure 11, left panel. The greatest difference between these measures is at 2.2, 2.5 and 2.8 kHz with test two exceeding test one by 2.7, 3.2 and 2.4 dB, respectively. The results for $|Y_t|$ at TPP for test one and test two are shown for $|Y_t|D$ in the third row, right panel. The difference between these measures is 2 dB or greater at 7.1 and 8.0 kHz at 2.0 and 2.4 dB, respectively.

Equivalent admittance phase at the TM for test one and test two are shown in the bottom row of Figure 11 for ϕ_a (left panel) and ϕ_tD at TPP (right panel). Both panels show admittance phase around 80 degrees at 0.25 kHz and gradually decreasing with frequency with a zero crossing between 4.0 and 4.5 kHz. ϕ_a for test two exceeded that of test one by 10 to 15 degrees from 0.89 to 1.41 kHz, and ϕ_a for test one exceeded that of test two by 15 degrees or more from 2.8 to 3.6 kHz with a maximum difference of 22 degrees at 3.2 kHz. The difference between ϕ_tD for test one and test two only exceeded 5 degrees in the frequency range between 4.0 and 5.7 kHz with a maximum of 12.4 degrees at 4.5 kHz.

E. Wideband and Clinical ASRT

Figure 12 shows the clinical ASRT plotted against the wideband ASRT for 57 ears. The diagonal line represents equality in the ASRT for the two methods and the dashed lines show the upper limit of the BBN activator stimuli at 90 dB SPL. Given this upper stimulus level, the data points at 95 dB SPL for both measures represent a no-response outcome at the highest stimulus level of 90 dB SPL. Each bubble radius is proportional to the number of measurements at a given clinical ASRT/wideband ASRT combination. The data in the figure lie predominantly above the diagonal indicating lower ASRTs for the wideband method. The model-based estimates are listed in Table 4 for the mean and the 95% CIs of the wideband and clinical ASRTs in 57 ears. The mean wideband ASRT was 12.3 dB lower than the mean clinical ASRT, which was a statistically significant difference ($p<.0001$). The estimated reliability of the wideband ASRT was 6.2 dB greater than for the clinical ASRT, which was also a statistically significant difference ($p<.0001$).

IV. DISCUSSION

A. Wideband Absorbance

The wideband absorbance by frequency plots for the subjects in this study were similar to previously published data for ambient absorbance or energy reflectance (Keefe et al. 1993; Voss & Allen 1994; Farmer-Fedor & Rabbitt 2002; Feeney & Sanford 2004; Shahnaz & Bork 2006, Werner et al. 2010, Rosowski et al. 2012; Abur et al. 2014; Feeney et al. 2014b), and similar to absorbance tympanograms in adults measured over a set of static pressures (Keefe & Simmons 2003; Margolis et al. 1999; Sanford & Feeney 2008) or using a pressure sweep (Liu et al. 2008). The mean absorbance data (top panel of Figure 2) showed that A_a was lower than A_t for either pressure sweep direction at frequencies below 2.0 kHz. One reason for this finding may be that measurements at TPP successfully compensated for middle ear over- or under-pressure that might result in increased middle-ear stiffness and thus reduced low-frequency absorbance (Shaver & Sun 2013, Voss et al. 2012). This suggests that measuring A_t at TPP would allow for a determination of the functional status of the middle-ear in adults that would not be complicated by middle-ear pressure effects, as was proposed by Margolis et al. (1999). Since negative middle-ear pressure has been shown to reduce low-frequency absorbance (Feeney et al. 2003b; Shaver & Sun 2013), this suggests that testing A_t at TPP may increase the potential for obtaining more reliable data on repeated testing with varying middle-ear pressures.

The suggestion of better reliability at TPP was supported by the absorbance data of one subject from the present study who had TPP of +5 daPa on test one and −40 daPa on test two. (top panels of Figure 11). When tested at ambient pressure this subject’s absorbance on test one was greater than for test two at frequencies below 1.5 kHz and less than test two at frequencies between 2.2 and 5 kHz. The test-retest differences for A_tD were greatly reduced compared to A_a for this subject suggesting that test reliability would be improved by using A_t at TPP to correct for middle-ear pressure in the evaluation of changes in middle-ear function unrelated to middle-ear pressure changes for adults, and possibly for identifying middle-ear disorders as suggested by Margolis et al. (1999).

As recently reported in infants from this same multi-year study, Hunter et al. (2015) found that tympanometric absorbance measures obtained at TPP were more adult-like than ambient pressure measures due to attenuation of ear-canal wall effects and thus had good properties for analysis of middle-ear problems in infants. This is analogous to the current clinical practice of testing 226 Hz admittance using tympanograms rather than measuring the admittance at ambient pressure.

The mean test-retest differences for A_a (middle panel, Figure 2) were greatest for the mid and high frequencies, exceeding 10%, but were similar across frequency to that reported in previous studies in adults (Werner et al. 2010; Rosowski et al. 2012; Abur et al. 2014; Feeney et al. 2014b). Test-retest differences for tympanometric absorbance have not been reported previously. In the frequency range of 0.5 to 2.0 kHz, the mean test-retest differences for A_t at TPP for both pressure-sweep directions was as much as one half that for A_a, although the differences between the means for these methods was only significant between A_a and A_tD. This improvement in test reliability may be related to the ability to correct for middle-ear pressure with A_t at TPP. The middle-ear pressure may vary from test to test in a given ear and increase the variability in absorbance when measured at ambient pressure, especially at frequencies below 3.0 kHz (Feeney et al. 2003b; Shaver & Sun 2013). The improvement in test-retest reliability obtained by using the A_t at TPP would be expected to increase in cases of greater middle-ear pressure than was allowed by the inclusion criterion for the present study (TPP within ±100 daPa).

At frequencies below 1.0 kHz, the mean test-retest difference for A_t at the PT (bottom panel of Figure 2) was lower than at the NT, and lower than the test-retest difference for A_t at TPP for both pressure-sweep directions (middle panel of Figure 2). At frequencies between 1.5 and 3.6 kHz, the test-retest differences for both tail conditions were greater than the test-retest difference for A_t at TPP for both sweep directions. This was likely due to the sharp peak in the mean tympanometric tail absorbance for both pressure sweeps as shown in the mean data in the top panel of Figure 2. Test-retest differences were similar for the tail conditions and A_t at TPP at frequencies above 4.0 kHz.

The 1/6th octave peak-to-tail differences in the absorbance tympanograms (upper panel of Figure 3) showed maxima at frequencies around 1.0 to 2.0 kHz, with negative minima at 4.0 to 6.0 kHz. It will be of interest in future studies to compare this peak-to-tail pattern with those for various middle-ear disorders, where, for example, more shallow peak-to-tail differences might be found in the low frequencies for ears with increased stiffness such as with otosclerosis, and conversely greater peak-to-tail differences in absorbance for ears with hypermobility.

Similarly, the peak-to-tail difference in absorbance averaged over a lower frequency band (0.376 to 2.0 kHz) and a higher frequency band (2.0 to 8.0 kHz) is a measure of the effect of tympanometric pressure on absorbance in the two frequency bands. These differences will also be interesting to compare in normal ears and in ears with various middle-ear disorders. The mean lower frequency average of peak-to-tail differences in absorbance ranged from about 0.41 to 0.46 (see Table 1). These mean differences were about 3 to 5% greater at the NT than at the PT for both downswept and upswept conditions.

The relatively small change in absorbance with ear-canal pressure for the higher frequency band average in Table 1 was consistent with previous studies showing a greater effect of ear-canal pressure and middle-ear pressure on frequencies below 3.0 kHz in adults (e.g., Feeney et al. 2014a; Shaver & Sun 2013). The mean test-retest differences in absorbance for both high-pass and low-pass peak-to-tail differences was on the order of 0.03 to 0.04, respectively, which suggests this measure may have good repeatability for clinical applications.

B. Wideband Group Delay

Keefe et al. (1993) presented group delay data at ambient pressure for two adults with normal hearing. The group delay was fairly constant in the low frequencies with marked fluctuations from 2.0 to 4.0 kHz and then fairly constant at higher frequencies similar to the group delay for subjects in the present study. The group delay from 0.25 to 1.0 kHz was around 55 μs for one subject and 100 μs for the other subject, which was below the mean ambient-pressure group delay of 161 μs from 0.25 to 1.0 kHz in the present study (top panel Figure 4). Voss and Allen (1994) presented group delay data for 10 adult ears. The average low-frequency group delay (≤0.5 kHz) was fairly constant for each subject and averaged around 130 μs, similar to the mean for the present study. At frequencies higher than 0.5 kHz in that study some subjects had a steep decrease in group delay (similar to the outliers in the present study), and thus higher frequencies from that study were not used to estimate the average group delay. Data from one subject in the present study (Figure 11, second row), who had TPP of +5 daPa on test one compared to −40 daPa on test two, had larger differences between test and retest for D_a compared to D_tD, especially around 2.8 to 4 kHz. This variability was greatly reduced by testing for group delay at TPP.

A comparison of the top and middle panels of Figure 4 shows that compared to the mean group delay observed at lower frequencies (0.32 to 0.6 kHz) at TPP for both sweep directions, measurements of D_t at the tympanometric tails resulted in lower group delay. The mean peak-to-tail difference in this frequency region was around 100 μs (bottom panel of Figure 4). This suggests that pathologies that reduce middle-ear stiffness, such as disarticulation or hyper-mobile TM compliance, may have greater low-frequency group delay than normal. Moreover, pathologies that increase middle-ear stiffness, such as otosclerosis and otitis media, may have a reduced group delay at low frequencies. Further research is needed to study these cases: the peak-to-tail values of group delay may be a relevant feature.

It should be noted that the top panel of Figure 4 was constructed using trimmed means with outliers greater than the 5^{th} and 95^{th} percentile of the data removed, while the second panel in Figure 4 for the tympanometric tails included all the data. Thus, the effect of ear-canal pressure on group delay is likely understated by these plots. These large mid-frequency variations in group delay have been reported previously for ambient-pressure measures of group delay (Keefe et al 1993; Voss & Allen 1994), and may be related to some unknown noise effect or any isolated, narrow resonance in individual ears. On the other hand, the high-frequency group delay (above 2.0 kHz) was little affected by positive or negative pressure in the ear canal and had a similar range of values for the ambient and TPP conditions (see also bottom panel of Figure 4 for peak-tail differences). This suggests that group delay in this frequency region may not be strongly affected by middle-ear disorders in ears with a normal ear canal and intact TM. More research is needed to address this issue. The group delay data above 2.0 kHz were used to estimate the ear-canal length, which was then used to estimate the equivalent admittance at the TM (Keefe et al. 2015).

The effect of ear-canal pressure on group delay for the mid-to-low frequencies was also apparent in the difference between the mean test-retest differences. These were greater for D_t at TPP (top panel of Figure 5) than for D_t at PT and NT for downswept and upswept tympanograms at frequencies below 1.5 kHz (middle panel of Figure 5). However, the group delay test-retest differences were the same or slightly higher for the tail conditions compared to D_t at TPP at frequencies above 1.5 kHz, as shown by comparing the top and middle panels of Figure 5. These concepts suggest that group delay test-retest differences in normal ears are more affected by the state of the middle ear at frequencies below 1.5 kHz than at higher frequencies. The mean test-retest reliability for peak-to-tail differences (bottom panel of Figure 5) shows the combined effects of poorer test-retest reliability around 1.0 kHz for the TPP conditions (top panel of Figure 5) and poorer test-retest reliability around 4.0 kHz for both the TPP conditions and the tail conditions (top and middle panels of Figure 5).

C. Wideband Equivalent Admittance at the TM

Estimates of ear-canal dimensions were used to derive the equivalent admittance at the TM. The mean area of the ear canal obtained for the present study using an acoustic estimate was 44.4 mm^2. This compares to an acoustic estimate of the cross-sectional area in adults of 58 mm^2 in Keefe and Abdala (2007). The present measurement of 44.4 mm^2 is within the inter-quartile range of the Keefe and Abdala data. This mean also compares well with human temporal bone measurements of the ear-canal area of 49 mm^2 (Voss et al. 2008).

The acoustic estimate of ear-canal length resulted in a mean length of 18.3 mm with a SE of 0.9 mm (Table 3). Given that the probe was inserted in the ear canal to obtain an hermetic seal and that the rigid probe could not be inserted more deeply than the location of the initial bend of the ear canal, the estimated insertion depth was 7 mm. In the present procedures, the ear-canal length was estimated from the probe tip to a mid-TM location, which was defined to be 4 mm less than the distance to the innermost point of the canal (Keefe et al. 2015). Thus, the estimated length data in Table 3 was 11 mm less than the total length of the ear canal from entrance to its innermost point.

The geometric length of the ear canal was longer when measured along the curved center axis of the canal, and its measured lengths in adult ear canals were between 27 and 35 mm in castings from ten males and five females (Stinson & Lawton 1989). This length was measured between the entrance into the ear canal and its innermost point. The surface of intersection of the concha and ear canal in which the lateral dimension was rapidly changing was taken to define the entrance point. From these geometrical length measurements, the expected acoustic estimate of length in the present study would be approximately 16 to 24 mm. Salvinelli et al. (1991) made 280 earmold castings from 140 cadaver temporal bones (160 male and 120 female ears) and made linear measurements of ear-canal length using a caliper rather than measuring length along the curved center of axis as in Stinson and

Lawton (1989). Salvinelli et al. measured the canal from the bottom of the concha to the umbo. They reported an overall mean ear-canal length of 23.5 mm (standard deviation=2.5 mm); a mean length of 25.2 mm for males and 22.5 mm for females. The mean value of 18.3 mm from the present study with the addition of an estimated 7 mm insertion depth takes the mean length to 25.3 mm, which is within the range of both previous studies. The test-retest difference of the estimated length in the present study was 4.5 mm (see Table 3). This variability is related to variability in probe insertion, systematic or random errors in the method used to acoustically estimate the length, and any other physiological differences between test and retest.

The level of the equivalent admittance at the TM was similar for $|Y_a|$ and $|Y_t|$ for both pressure-sweep directions, except that the mean $|Y_a|$ level was lower than for the TPP measures at frequencies from 0.25 to 1.5 kHz. The difference was statistically significant between $|Y_a|$ and $|Y_t|$U at frequencies from 0.25 to 1.12 kHz (Figure 6, top panel). This difference would be expected to become greater in clinical practice, which would include ears with TPPs outside the range of the ±100 daPa inclusion criterion for the present study. The data from one subject in the present study with TPP at +5 daPa on test one and −40 daPa on test two are consistent with this expectation (Figure 11, third row). For only a small difference in middle-ear pressure between tests, there was a greater difference in equivalent admittance between tests for the ambient method compared to TPP. This resulted in lower equivalent admittance at frequencies below 1.0 kHz for test two suggesting that greater middle-ear pressure results in increased middle-ear stiffness when tested at ambient pressure, even for a relatively small TPP difference between tests. The equivalent admittance peak-to-tail measures will be of interest in examining middle-ear disorders as these will provide an opportunity to extend the examination of the effect of disorders on static acoustic admittance at the TM across the traditional audiometric frequency range.

The results for the equivalent admittance at the TM, including test-retest results, in Figures 6 and 7 were sensitive to the estimated values in the ear-canal length and area in Table 1, inasmuch as these were used in the transmission line model to calculate this admittance based on measurements at the probe tip. The effect of varying the length and area estimates on the calculation of the equivalent admittance at the TM were analyzed in Keefe et al. (2015) for a single adult ear with normal function. The test results in this ear were generally similar to the mean ambient results in the current study, except that this ear had a phase that was mainly above 60 degrees, whereas the mean phase in the present study (Figure 6, bottom panel) was as low as 11 degrees. It is likely that the increased test-retest difference in phase, as well as level, at frequencies above 4.0 kHz in Figure 9 is related to a greater sensitivity on the estimated length at high frequencies.

The present study extends that of Keefe et al. (2015) in the finding that mean equivalent admittance at the TM in normal adult ears was stiffness controlled over the frequency range up to 8.0 kHz. This differs from the results in Rabinowitz (1981), in which the mean phase was positive (i.e., stiffness controlled) at low frequencies, but was within one standard deviation of zero degrees from 1.2 kHz up to the highest test frequency of 4.0 kHz. The procedural differences between these studies are further described in Keefe et al. (2015).

In contrast with the mean phase data from Figure 6, bottom panel, the data from one subject from the present study showed a stiffness-dominated phase from 0.25 to 4.0 kHz and mass-dominated phase at higher frequencies when tested at both ambient pressure and TPP (Figure 11, row 4). Note that the variability in phase across subjects was greater for the high frequencies as reflected in the standard error of the mean (Figure 6 bottom panel). Thus, although the mean data suggest equivalent admittance at the TM that is stiffness dominated from 0.25 to 8.0 kHz, this is not without exception in normal ears.

D. Wideband and Clinical ASRT

The finding of a 12.3 dB lower mean ipsilateral ASRT for the wideband method compared with the clinical method is in good agreement with Keefe et al. (2010). This article reported an 11 dB lower median ASRT for the wideband ipsilateral test using a similar method with BBN activator compared to a clinical ipsilateral ASRT test with a 226-Hz probe tone. A comparison between clinical and wideband ASRTs depends on the exact algorithm used to detect the change in middle-ear function. If the goal is to detect an ASRT at a lower level, it appears that the parameters of the wideband test used in this study may be used to achieve that goal. It should be noted that the improvement in reflex-threshold detection was achieved at the expense of higher test-retest variability (see Table 4), which may be due in part to the reduced ASRT ceiling effect for the wideband test. The clinical method employed repeated testing with ascending activator levels to obtain the ASRT, which differed from the wideband algorithm that used one repetition of the series of activator levels to determine the ASRT. A more direct comparison of the variability of the methods might be obtained by using similar methods of threshold determination.

Another way to think about the problem of absent reflexes at 90 dB SPL is to consider which reflex threshold method resulted in more cases of these absent reflexes. There were 15 of 102 valid ear sessions with absent reflexes with the clinical system, and 8 of the 15 had wideband ASRTs in the measurable range. In contrast, there were only 9 ear sessions with absent wideband ASRTs. Four of these 9 sessions had present clinical ASRTs. This outcome is expected given the overall lower reflex thresholds obtained with the wideband system. The ability to obtain reflex thresholds in more ears compared to current methods may enhance the clinical applicability of the wideband method. Lower ASRTs may prove useful in distinguishing between ears with sensory dysfunction and cranial nerve VIII or brainstem dysfunction by allowing an ASRT to be measured in ears with greater sensory loss. This may increase the sensitivity of the test to retrocochlear disorders with absent reflexes due to neural dysfunction.

There was no attempt to equate the spectrum of the BBN stimulus for the experimental and clinical systems. The experimental BBN activator was low-pass filtered at 8.0 kHz, whereas the BBN activator on the GSI-Tympstar device employed a 3-dB bandwidth of 0.125 to 4.0 kHz. These signals were equated for overall SPL but the experimental system would have contained greater high-frequency content. Thus, the lower reflex thresholds in the wideband test may have been in part related to this difference. Day and Feeney (2008) reported the level of the 226-Hz probe tone used for clinic ASR testing can affect the ASRT by facilitating reflex activation for a 1.0 kHz activator stimulus. Lower level probe tones led to higher ASRTs. A similar phenomenon could be occurring for some conditions of wideband ASRT determination. Of interest is that ipsilateral wideband ASRTs for BBN activators produced a greater reduction in ASRT in adults compared to a clinical method than when ipsilateral tonal activators were employed (Keefe et al. 2010; Schairer et al. 2007). There may be an interaction between the wideband probe stimulus and the activator stimulus similar to the effect reported by Day and Feeney (2008), which may have a greater effect for a BBN activator than a tonal activator.

V. CONCLUSION

Normative data were presented for a battery of WAI tests including wideband ambient absorbance and absorbance tympanometry, reflectance group delay, equivalent admittance at the TM and wideband ASRTs. Mean absolute test-retest differences for tests obtained one month apart were obtained on all measures. Absorbance at TPP, especially with a downswept tympanogram, appears to provide a more reliable measure of middle-ear function than wideband absorbance at ambient pressure. This is likely related in part to the compensation for middle-ear pressure, which may vary from test to re-test; in this case one month later. Normative data for peak-to-tail differences in absorbance, group delay and equivalent admittance had sufficiently good reliability that they may prove useful in future studies to evaluate middle-ear disorders. The wideband ipsilateral ASRT test for a BBN activator provided a 12 dB lower ASRT than a clinical test with a 226-Hz probe tone, but with greater test-retest variability. Taken together, these normative data will serve as a useful comparison with data from subjects with various middle-ear or cochlear disorders.

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LIST OF ABBREVIATIONS

A_a	absorbance at ambient pressure
ANOVA	analysis of variance
ASR	acoustic stapedius-muscle reflex
ASRT	acoustic stapedius reflex threshold
A_t	absorbance during a tympanometric pressure sweep
A_tD	absorbance during a downswept tympanogram
A_tU	absorbance during an upswept tympanogram

BBN	broadband noise
CI	confidence interval
D_a	group delay at ambient pressure
daPa	dekaPascals
D_t	group delay during a tympanometric pressure sweep
D_tD	group delay during a downswept tympanogram
D_tU	group delay during a upswept tympanogram
ER	energy reflectance
GSI	Grason Stadler Instruments
NT	negative tail of the tympanogram at −300 daPa
PT	positive tail of the tympanogram +200 daPa
SE	standard error
SPL	sound pressure level
TPP	tympanometric peak pressure
TM	tympanic membrane
WAI	wideband acoustic immittance
Y_a	equivalent admittance at the TM at ambient pressure
$\|Y_a\|$	equivalent admittance magnitude at the TM at ambient pressure
Y_t	equivalent admittance at the TM during a tympanometric pressure sweep
$\|Y_t\|$	equivalent admittance magnitude at the TM during a tympanogram
$\|Y_t\|D$	equivalent admittance magnitude at the TM during a downswept tympanogram
$\|Y_t\|U$	equivalent admittance magnitude at the TM during an upswept tympanogram
Y_{tm}	226 Hz peak-compensated static acoustic admittance
ΔL_W	shift in absorbed power level
$\|\Delta L_{W1}\|$	shift in absorbed power level weighted across frequency
ϕ_a	equivalent admittance phase at the TM at ambient pressure
ϕ_t	equivalent admittance phase at the TM during a tympanometric pressure sweep

$\phi_t D$	equivalent admittance phase at the TM during a downswept tympanogram
$\phi_t U$	equivalent admittance phase at the TM during an upswept tympanogram

References

Abur D, Horton NJ, Voss SE. Intrasubject variability in power reflectance. J Am Acad Audiol. 2014; 25:441–448. [PubMed: 25257718]

Allen, JB. Measurement of eardrum acoustic impedance. In: Allen, J.Hall, J.Hubbard, A., et al., editors. Peripheral Auditory Mechanisms. New York: Springer-Verlag; 1986. p. 44-51.

ANSI. Specifications for Audiometers. New York: American National Standards Institute; 2010. ANSI S3.6–2010

ANSI. Specifications for instruments to measure aural acoustic impedance and admittance (aural acoustic immittance) (ANSI S3.39-1987, R2012). New York: American National Standards Institute; 2012.

Bland JM, Altman DG. Applying the right statistics: analyses of measurement studies. Ultrasound Obstet Gynecol. 2003; 22:85–93. [PubMed: 12858311]

Day JE, Feeney MP. The effect of the 226-Hz probe level on contralateral acoustic stapedius reflex thresholds. J Speech Lang Hear Res. 2008; 51(4):1016–1025. [PubMed: 18658068]

Farmer-Fedor BL, Rabbitt RD. Acoustic intensity, impedance and reflection coefficient in the human ear canal. J Acoust Soc Am. 2002; 112:600–620. [PubMed: 12186041]

Feeney MP, Grant IL, Marryott LP. Wideband energy reflectance measurements in adults with middle-ear disorders. J Speech Lang Hear Res. 2003b; 46:901–911. [PubMed: 12959468]

Feeney MP, Hunter LL, Kei J, et al. Consensus statement: Eriksholm workshop on wideband absorbance measures of the middle ear. Ear Hear. 2013; 34(7 Suppl 1):78s–79s. [PubMed: 23900186]

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 reflectance and admittance measurements. J Speech Lang Hear Res. 2003a; 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. Age effects in the human middle ear: wideband acoustical measures. J Acoust Soc Am. 2004; 116:3546–3558. [PubMed: 15658706]

Feeney MP, Sanford CA, Putterman DB. Effects of ear-canal static pressure on puretone thresholds and wideband acoustic immittance. J Am Acad Audiol. 2014a; 25:462–470. [PubMed: 25257720]

Feeney MP, Stover B, Keefe DH, et al. Sources of variability in wideband energy reflectance measurements in adults. J Am Acad Audiol. 2014b; 25:449–46. [PubMed: 25257719]

Hunter LL, Keefe DH, Feeney MP, et al. Longitudinal development of wideband reflectance tympanometry in normal and at-risk infants. Hear Res. 2015 Dec 19. pii: S0378-5955(15)30163-5 Epub ahead of print. doi: 10.1016/j.heares.2015.12.014

Hunter LL, Keefe DH, Feeney MP, et al. Pressurized wideband acoustic stapedial reflex thresholds: Normal development and relationships to auditory function in infants. J Assoc Res Otolaryngol, Under Review. in press.

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. [PubMed: 17348521]

Keefe DH, Bulen JC, Arehart KH, et al. Ear-canal impedance and reflection coefficient in human infants and adults. J Acoust Soc Am. 1993; 94:2617–2638. [PubMed: 8270739]

Keefe, DH., Feeney, MP. Principles of acoustic immittance and acoustic transfer functions. In: Katz, J.Medwetsky, L.Burkard, R., et al., editors. Handbook of Clinical Audiology. 6. Baltimore: Lippincott, Williams, & Wilkins; 2009. p. 125-156.

Keefe DH, Feeney MP, Hunter LL, et al. Aural acoustic stapedius-muscle reflex threshold procedures to test human infants and adults. J Assoc Res Otolaryngol, Under Review. in press.

Keefe DH, Fitzpatrick DF, Liu YW, et al. Wideband acoustic reflex test in a test battery to predict middle-ear dysfunction. Hear Res. 2010; 263:52–65. [PubMed: 19772907]

Keefe DH, Hunter LL, Feeney MP, et al. Procedures for ambient-pressure and tympanometric tests of aural acoustic reflectance and admittance in human infants and adults. J Acoust Soc Am. 2015; 138:3625–3653. [PubMed: 26723319]

Keefe DH, Ling R, Bulen JC. Method to measure acoustic impedance and reflection coefficient. J Acoust Soc Am. 1992; 91:470–485. [PubMed: 1737890]

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]

Liu YW, Sanford CA, Ellison JC, et al. Wideband absorbance tympanometry using pressure sweeps: system development and results on adults with normal hearing. J Acoust Soc Am. 2008; 124:3708–19. [PubMed: 19206798]

Margolis, RH., Hunter, LL. Tympanometry: basic principles and clinical applications. In: Musiek, FE., Rintelmann, WF., editors. Contemporary Perspectives in Hearing Assessment. Needham Heights, MA: Allyn & Bacon; 1999. p. 89-130.

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

McMillan GP. On reliability. Ear Hear. 2014; 35:589–590. [PubMed: 24722511]

Pang, XD., Peake, WT. How do contractions of the stapedius muscle alter the acoustic properties of the ear?. In: Allen, J.Hall, J.Hubbard, A., et al., editors. Peripheral Auditory Mechanisms. New York: Springer-Verglag; 1986. p. 36-43.

Rabinowitz, WM. Doctoral Dissertation. Massachusetts Institute of Technology; Boston, MA: 1977. Acoustic-reflex effects on the input admittance and transfer characteristics of the human middle-ear.

Rabinowitz WM. Measurement of the acoustic input immittance of the human ear. J Acoust Soc Am. 1981; 70(4):1025–35. [PubMed: 7288039]

Robinson SR, Nguyen CT, Allen JB. Characterizing the ear canal acoustic reflectance and impedance by pole-zero fitting. Hear Res. 2013; 301:168–182. [PubMed: 23524141]

Rososwski JJ, Nakajima HH, Hamade MA, et al. Ear-canal reflectance, umbo velocity, and tympanometry in normal-hearing adults. Ear Hear. 2012; 33:19–34. [PubMed: 21857517]

Salvinelli F, Maurizi M, Calamita S, et al. The external ear and the tympanic membrane. A three-dimensional study. Scand Audiol. 1991; 20:253–256. [PubMed: 1842299]

Sanford CA, Feeney MP. Effects of maturation on tympanometric wideband acoustic transfer functions in human infants. J Acoust Soc Am. 2008; 124:2106–2122. [PubMed: 19062852]

Sanford CA, Hunter LL, Feeney MP, et al. Wideband acoustic immittance: tympanometric measures. Ear Hear. 2013; 34(7 Suppl 1):65s–71s. [PubMed: 23900184]

Schairer KS, Ellison JC, Fitzpatrick D, et al. Wideband ipsilateral measurements of middle-ear muscle reflex thresholds in children and adults. J Acoust Soc Am. 2007; 121:3607–3616. [PubMed: 17552712]

Schairer KS, Feeney MP, Sanford CA. Acoustic reflex measurement. Ear Hear. 2013; 34(7 Suppl 1): 43s–47s. [PubMed: 23900179]

Shahnaz N, Bork K. Wideband reflectance norms for Caucasian and Chinese young adults. Ear Hear. 2006; 27:774–788. [PubMed: 17086086]

Shahnaz N, Feeney MP, Schairer KS. Wideband acoustic immittance normative data: ethnicity, gender, aging, and instrumentation. Ear Hear. 2013; 34(7 Suppl 1):27s–35s. [PubMed: 23900176]

Shanks JE, Lilly DJ. An evaluation of tympanometric estimates of ear canal volume. J Speech Hear Res. 1981; 24(4):557–66. [PubMed: 7329051]

Shaver MD, Sun XM. Wideband energy reflectance measurements: effects of negative middle ear pressure and application of a pressure compensation procedure. J Acoust Soc Am. 2013; 134:332–341. [PubMed: 23862811]

Stinson MR, Lawton BW. Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution. J Acoust Soc Am. 1989; 85:2492–2503. [PubMed: 2745874]

Stinson MR, Shaw EAG, Lawton BW. Estimation of acoustical energy reflectance at the eardrum from measurements of pressure distribution in the human ear canal. J Acoust Soc Am. 1982; 72:766–773. [PubMed: 7130535]

Voss SE, Allen JB. Measurement of acoustic impedance and reflectance in the human ear canal. J Acoust Soc Am. 1994; 95:372–384. [PubMed: 8120248]

Voss SE, Horton NJ, Woodbury RR, et al. Sources of variability in reflectance measurements on normal cadaver ears. Ear Hear. 2008; 29:651–665. [PubMed: 18600136]

Voss SE, Merchant GR, Horton NJ. Effects of middle-ear disorders on power reflectance measured in cadaveric ear canals. Ear Hear. 2012; 33:195–208. [PubMed: 22037477]

Werner LA, Levi EC, Keefe DH. Ear-canal wideband acoustic transfer functions of adults and two-to nine-month-old infants. Ear Hear. 2010; 31:587–598. [PubMed: 20517155]

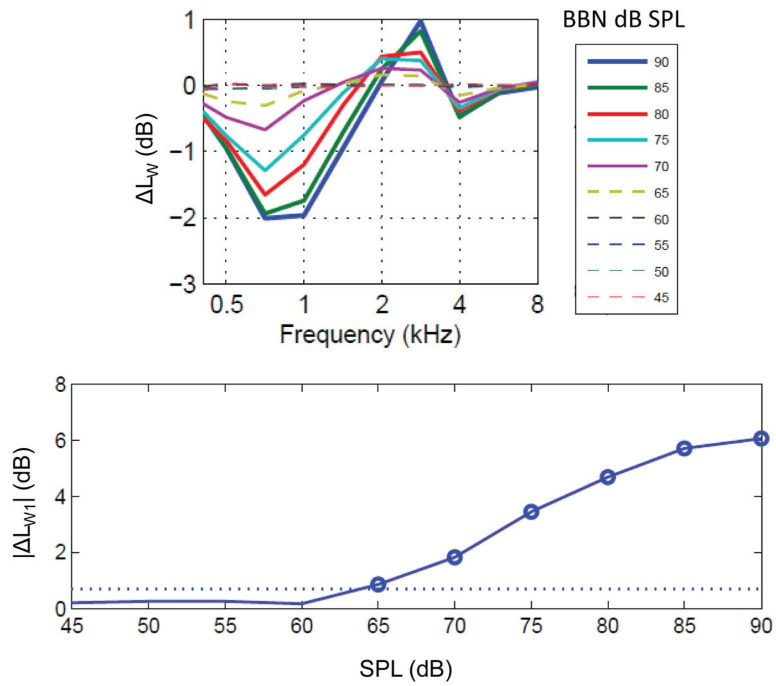

Figure 1.

Top panel shows the shift in power level ΔL_W across frequency for 10 levels of the BBN activator stimulus for the wideband ipsilateral acoustic reflex test. Bottom panel shows the shift in weighted absorbed power level $|\Delta L_{W1}|$ for each activator level. The circles indicate BBN activator levels for which there was a criterion shift in $|\Delta L_{W1}|$ with the minimum significant level for an activator level of 65 dB SPL.

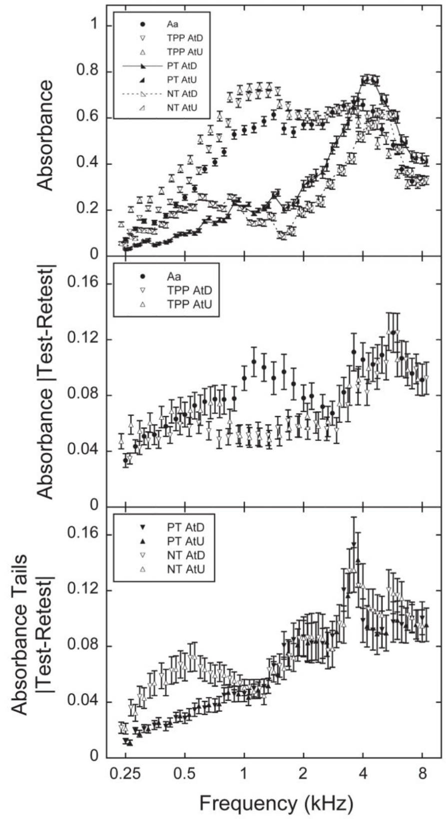

Figure 2.

Top panel shows the mean 1/6th octave absorbance for A_a and for A_t at TPP for the downswept (A_tD) and upswept (A_tU) methods (N=57 ears). Also shown are the mean 1/6th octave absorbance for A_t at the +200 daPa tympanometric tail (PT) and −300 daPa tail (NT) for the A_tD and A_tU methods. Error bars in this and all panels represent ±1 SE. Middle panel shows the mean absolute value of the test-retest difference for A_a and A_t at TPP for the upswept and downswept methods (N=45 ears). Bottom panel shows the mean absolute value of the test-retest difference for the tympanometric tails (N=45 ears). Symbols are jittered on the frequency axis for all three panels for clarity.

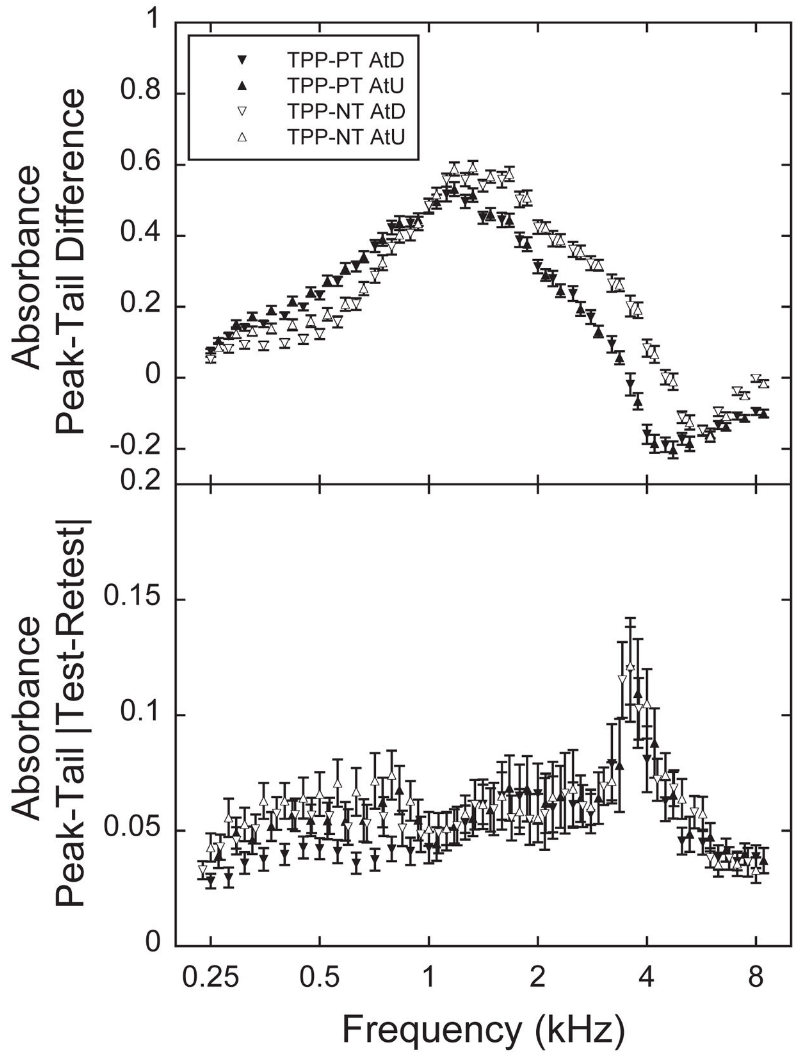

Figure 3.

Top panel shows the mean TPP-minus-tail differences for absorbance tympanograms for positive-tail (PT) and negative-tail (NT) differences for downswept (A_tD) and upswept (A_tU) tympanograms (N=57 ears). Error bars for both panels represent ±1 SE. Bottom panel shows the mean absolute value of the test-retest difference for absorbance TPP-minus-tail differences for PT and NT for A_tD and A_tU tympanograms. Symbols are jittered on the frequency axis in both panels for clarity.

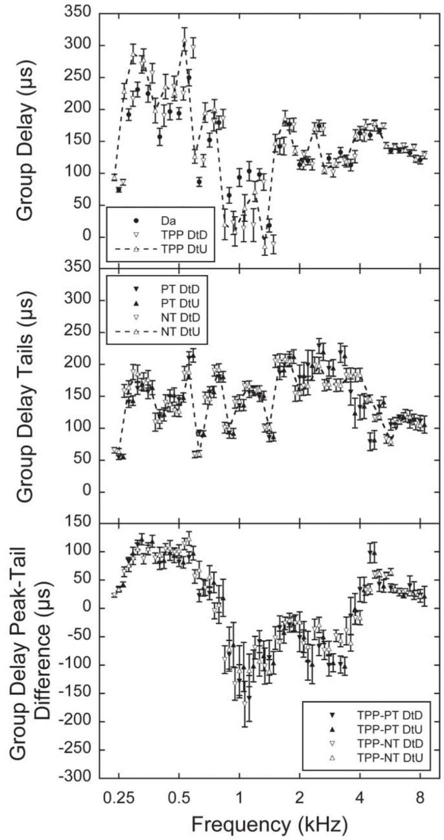

Figure 4.

Top panel shows the 5th and 95th percentile trimmed-mean group delay in µs as a function of frequency for D_a and D_t at TPP for the downswept (D_tD) and upswept (D_tU) methods (N=57 ears). The remaining panels of the figure show standard means. Error bars represent ±1 SE of the mean for all panels. Middle panel shows the mean group delay in µs at the +200 daPa positive tail (PT) and −300 daPa negative tail (NT) conditions for D_tD and D_tU (N=57 ears). Bottom panel shows the mean TPP-minus-tail differences for group delay in µs for PT and NT conditions for D_tD and D_tU (N=57 ears). Symbols are jittered on the frequency axis for all panels for clarity.

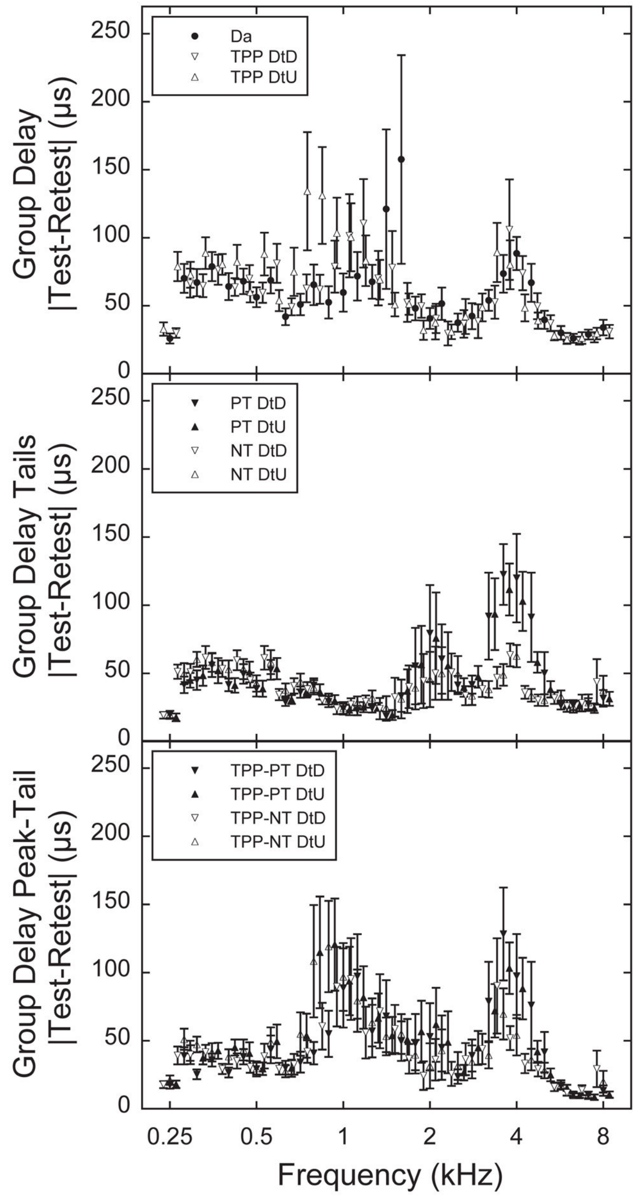

Figure 5.

Top panel shows the mean absolute value of the test-retest differences in group delay for D_a, and D_t at TPP for the downswept (D_tD) and upswept (D_tU) methods (N=45 ears). Error bars represent ±1 SE of the mean for all panels. Middle panel shows the mean group delay absolute value of the test-retest differences for the positive tails (PT) and negative tails (NT) for D_tD and D_tU (N=45 ears). Bottom panel shows the mean group delay absolute value of the test-retest differences for TPP-minus-tail differences for the PT and NT for D_tD and D_tU (N=45 ears). Symbols are jittered on the frequency axis for all panels for clarity.

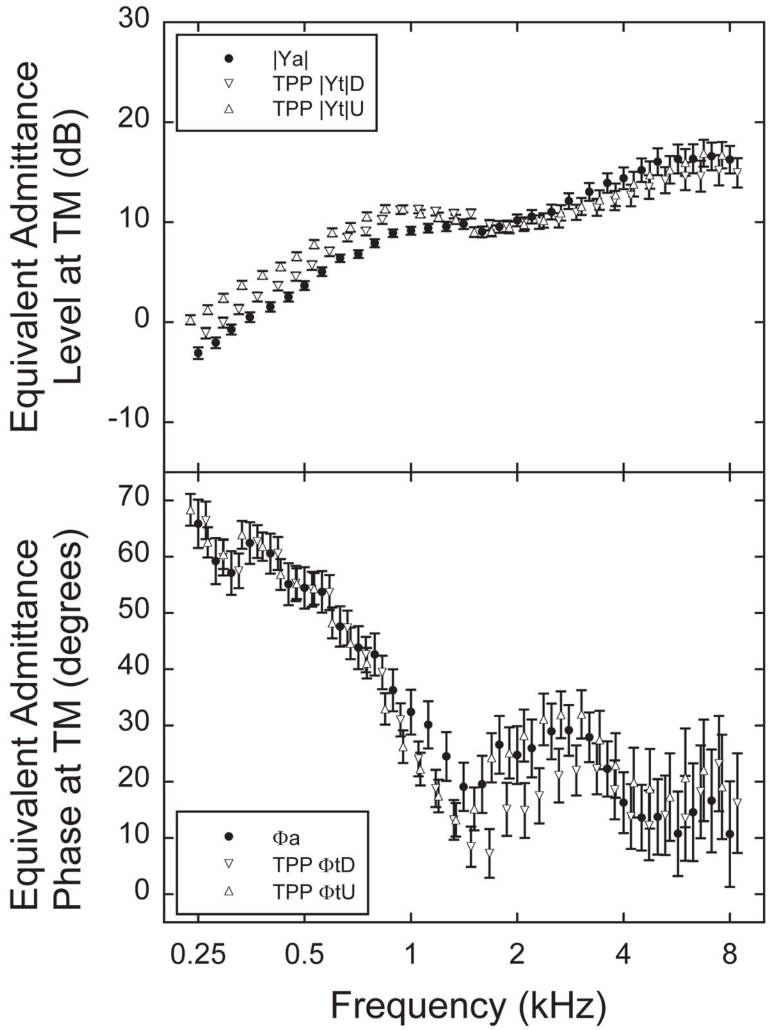

Figure 6.

Top panel shows the mean equivalent admittance level at ambient pressure $|Y_a|$ and at TPP for the downswept ($|Y_t|$D) and upswept ($|Y_t|$U) tympanograms (N=57 ears). Admittance level is normalized to 0 dB for an admittance magnitude of 1 mmho. Error bars represent ±1 SE of the mean for both panels. Bottom panel shows the mean equivalent admittance phase as a function of frequency at ambient pressure ϕ_a and at TPP ϕ_t for downswept (ϕtD) and upswept (ϕtU) tympanograms (N=57 ears).

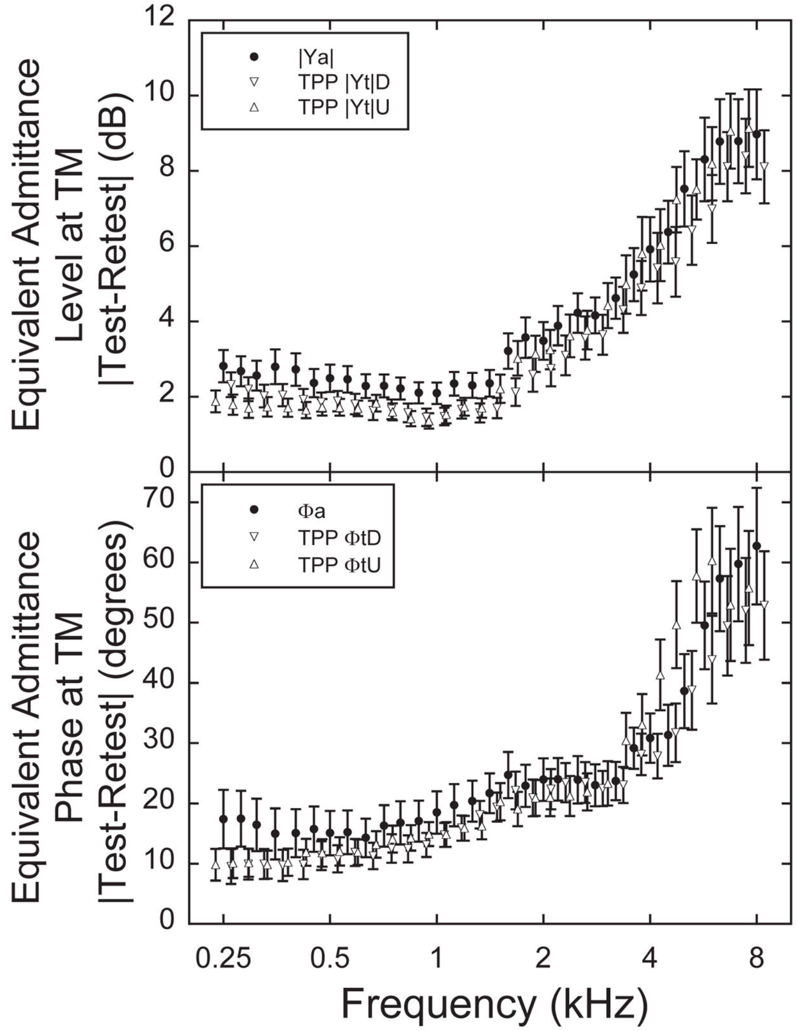

Figure 7.

Top panel shows the mean absolute value of the test-retest differences in equivalent admittance level at ambient pressure $|Y_a|$ and at TPP for the downswept ($|Y_t|$D) and upswept ($|Y_t|$U) tympanograms (N=45 ears). Bottom panel shows the mean absolute value of the test-retest differences for equivalent admittance phase at ambient pressure ϕ_a and at TPP ϕ_t for the upswept (ϕ_tD) and downswept (ϕ_tU) tympanograms. Error bars for both panels represent ±1 SE. Symbols are jittered on the frequency axis for both panels for clarity.

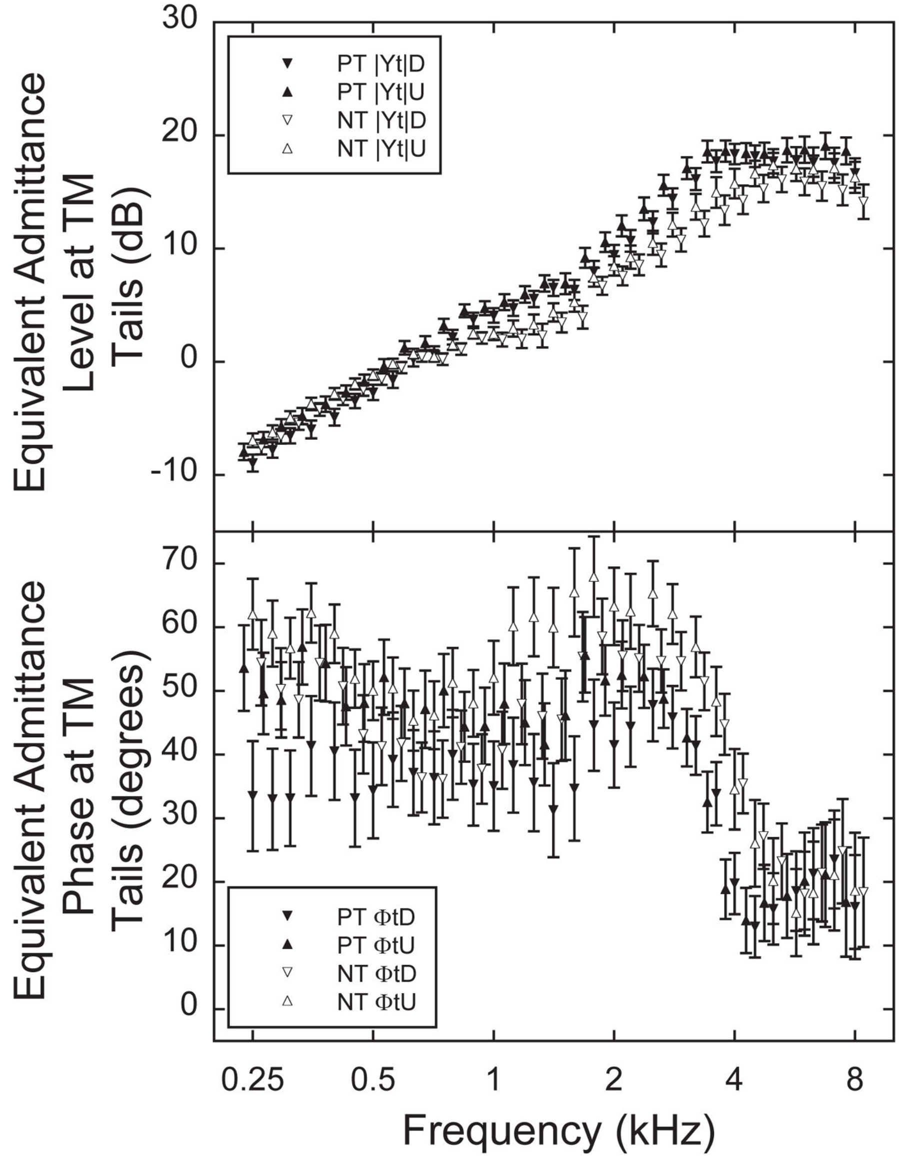

Figure 8.

Top panel shows the mean equivalent admittance level at the tympanometric tails for the downswept ($|Y_t|$D) and upswept ($|Y_t|$U) tympanograms for the positive tail (PT) and negative tail (NT) conditions. Admittance level is normalized to 0 dB for an admittance magnitude of 1 mmho. Bottom panel shows the mean equivalent admittance phase for PT and NT conditions as a function of frequency for the downswept (ϕtD) and upswept (ϕtU) tympanograms (N=57 ears). Error bars for both panels represent ±1 SE. Symbols are jittered on the frequency axis for both panels for clarity.

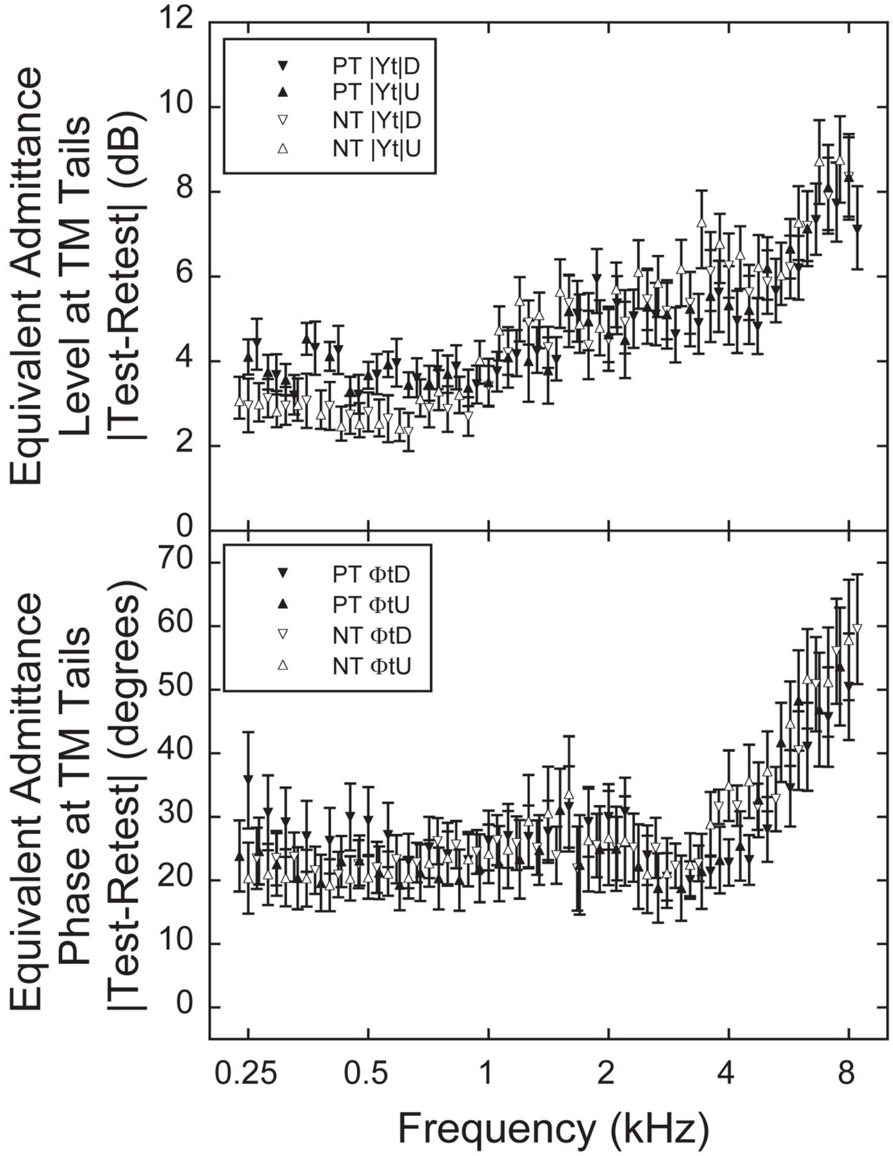

Figure 9.

Top panel shows the mean absolute value of the test-retest differences for the equivalent admittance level at the tympanometric tails for the positive tail (PT) and negative tail (NT) conditions for the downswept ($|Y_t|$D) and upswept ($|Y_t|$U) tympanograms (N=45 ears). Bottom panel shows the mean absolute value of the test-retest differences for the equivalent admittance phase at the PT and NT conditions as a function of frequency for the downswept (ϕtD) and upswept (ϕtU) tympanograms (N=45 ears). Error bars for both panels represent ± 1 SE. Symbols are jittered on the frequency axis for both panels for clarity.

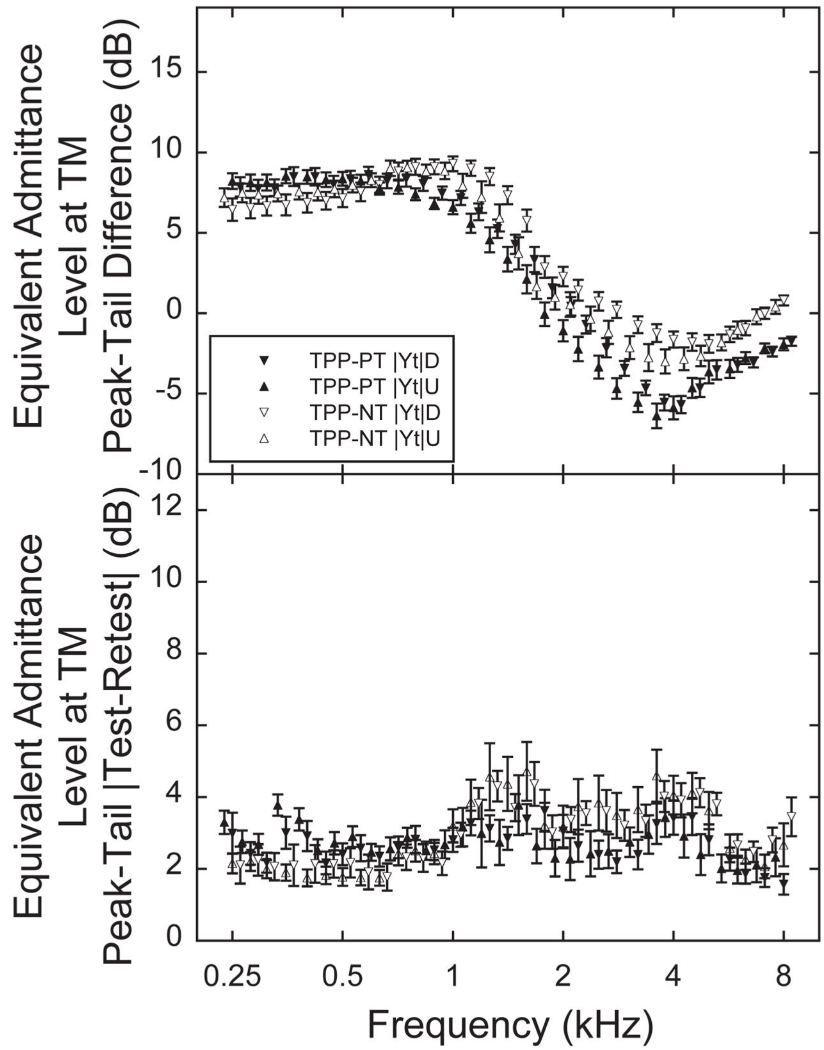

Figure 10.

Top panel shows the mean equivalent admittance level at TPP minus the positive tail (PT) and negative tails (NT) for the for the downswept (|Y_t|D) and upswept (|Y_t|U) tympanograms (N=57 ears). Bottom panel shows the mean absolute value of the test-retest differences for TPP minus PT and NT for |Y_t|D and |Y_t|U tympanograms (N=45 ears). Error bars for both panels represent ±1 SE. Symbols are jittered on the frequency axis for the three panels for clarity.

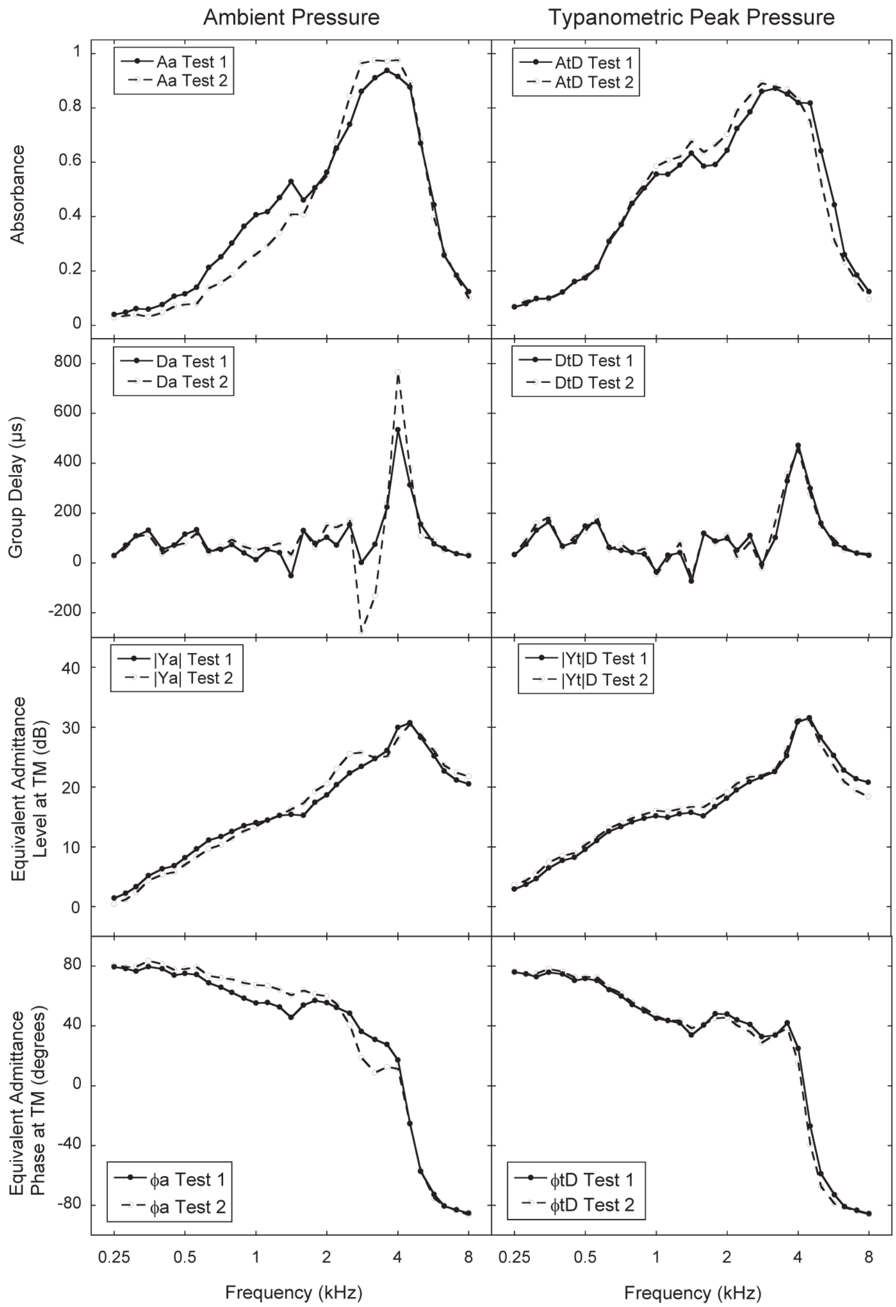

Figure 11.

Individual data for one subject in this study for both study visits. The left column shows data obtained for test one and test two (one week later) obtained at ambient pressure in the ear canal, and the right column shows data for the two tests obtained at tympanometric peak pressure for the downswept tympanogram, the pressure at which the maximum of the low-frequency averaged absorbance occurred over the frequency range from 0.376 to 2.0 kHz. This was +5 daPa for test one and −40 daPa for test two. The top panels show data for the wideband absorbance at ambient pressure (A_a) and TPP for the downswept tympanogram (A_tD), the second row of panels shows data for group delay at ambient pressure (D_a) and

TPP for the downswept tympanogram (D_tD, the third row shows data for equivalent admittance magnitude at the TM at ambient pressure ($|Y_a|$) and TPP for the downswept tympanogram ($|Y_t|$D); and the bottom row shows equivalent phase at the TM at ambient pressure (ϕ_a) and at TPP for the downswept tympanogram (ϕtD).

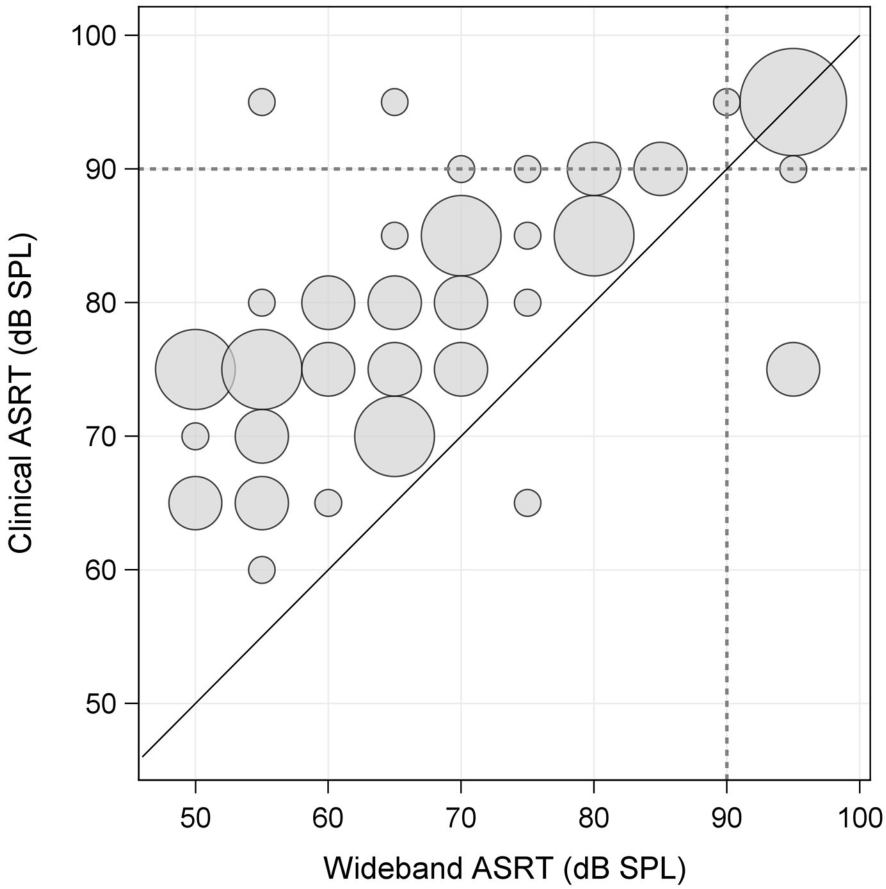

Figure 12.
Plot of wideband ASRT on the X axis versus the clinical ASRT on the Y axis for 57 ears. Each bubble radius is proportional to the number of measurements at that WB ASRT/ Clinical ASRT threshold method combination for each ear. The diagonal line corresponds to equivalence between the two methods, and the dashed lines indicate the test limit of 90 dB SPL. Data plotted as 95 dB SPL for either method represent *No Response* at 90 dB SPL.

Table 1

Mean peak-to-tail tympanometric absorbance differences for either the positive tail (+200 daPa) or the negative tail (−300 daPa) pressure conditions for downswept (A_tD) and upswept (A_tU) tympanograms.

Condition			Absorbance Measure			
Frequency Band	Sweep Condition	Tail Pressure (daPa)	Mean Peak-to-Tail Difference	SE	Mean Peak -to-Tail Difference Test-retest	SE
Low Pass						
	A_tD	+200	0.41	0.01	0.04	0.01
	A_tU	+200	0.41	0.01	0.04	0.01
	A_tD	−300	0.44	0.01	0.04	0.01
	A_tU	−300	0.46	0.01	0.04	0.01
High pass						
	A_tD	+200	−0.06	0.01	0.03	0.00
	A_tU	+200	−0.08	0.01	0.03	0.01
	A_tD	−300	0.05	0.01	0.04	0.00
	A_tU	−300	0.04	0.01	0.04	0.00

Results are shown for downswept and upswept tympanograms averaged over a low-frequency pass band (0.376 to 2.0 kHz) or high-frequency pass band (2.0 to 8.0 kHz). The data were averaged over single sessions for 57 ears. A positive value indicates that the peak of the frequency-averaged absorbance tympanogram was greater than the tail. Also shown are the mean absolute value of the test-retest differences for peak-to-tail-differences and SEs for 45 ears with two tests performed about one month apart.

Table 2

Mean and SE of the wideband tympanometric width in daPa from the downswept and upswept A_t, and the mean and SE of the clinical tympanometric width from the downswept 226 Hz tympanogram.

	Wideband Tympanogram		Wideband Test-retest		Clinical 226-Hz Tympanogram		Clinical 226-Hz Test-retest	
Condition	**Mean TW (daPa)**	**SE (daPa)**	**Mean TW (daPa)**	**SE (daPa)**	**Mean TW (daPa)**	**SE (daPa)**	**Mean TW (daPa)**	**SE (daPa)**
Downswept	119	4.9	10.4	1.8	79.7	5.8	16.9	4.6
Upswept	123	5.2	10.3	2.0	--	--	--	--

The data are averaged over single sessions for 57 ears. Also shown are the mean and SE of the absolute value of the test-retest differences for wideband TW for 45 ears with two tests one month apart. The right half of the table shows the mean and SE of the clinical admittance TW for downswept tympanograms over the same pressure range as the wideband tympanogram. Also shown are the mean and SE of the absolute value of the test-retest differences for the clinical TW.

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Table 3

Mean and SE for the ear-canal cross-sectional area at the probe tip and an ear-canal length between the probe tip and TM.

	Mean N= 57 ears	SE	Mean test-retest N= 45 ears	SE
Area (mm^2)	44.4	3.2	11.6	1.6
Length (mm)	18.3	0.9	4.5	0.6

A mid-TM location is assumed to be 4 mm from the innermost point of the ear canal. Also shown are the mean and SE of the absolute value of the test-retest differences in the area and length.

Table 4

Model-based estimates of the mean ipsilateral ASRT for broadband noise and test-retest reliability for the WB ASRT and clinical ASRT methods.

			95% Confidence Interval	
ASRT (dB SPL)	**Estimate**	**SE**	**Lower**	**Upper**
Mean WB	68.4	1.9	64.6	72.2
Mean Clinical	80.7	1.7	77.2	84.1
Reliability WB	10.2	0.9	8.4	12.0
Reliability Clinical	4.0	0.5	3.1	5.0

The SE is given for each estimate along with the 95% confidence intervals.