Objectives: Wideband acoustic immittance (WAI) measurements are capable of evaluating middle ear performance over a wide range of frequencies relevant to human hearing. It is known that static pressure in the middle ear cavity affects sound transmission to the cochlea, but only a few data sets exist to quantify the relationship between middle ear transmission and pressure level. The purpose of this study is to analyze new WAI measurements of negative middle ear pressure (NMEP), with a focus on the effects of NMEP in individual ears.

Design: In this study, subjects with normal middle ear function were trained to induce consistent NMEPs, quantified by the tympanic peak pressure (TPP) and the WAI. The effects of NMEP on power absorbance are analyzed for 8 individual ears. WAI magnitude and phase quantities at the tympanic membrane (TM) are also studied by removing phase contributions from the residual ear canal (REC).

Results: For the 8 ears presented here, negative TPP has the largest effect from 0.8 to 1.8 [kHz], causing less energy to be absorbed by the middle ear and cochlea. The TPP level is found to be a significant but imperfect predictor of changes in TM acoustic immittance measurements, due to individual variations in the magnitude and frequency range of the effects of NMEP on middle ear transmission. WAI estimates at the TM show pressure effects consistent with an increased stiffness in the middle ear, which could originate from the TM-malleus coupling, annular ligament, or other middle ear structures.

Conclusions: The REC effect is accurately removed from the WAI magnitude and phase, allowing for direct estimation of these quantities at the TM. The effects of NMEP on WAI vary considerably in magnitude and frequency range across individual ears. TPP does not appear to be sufficiently correlated to wideband acoustic changes in the middle ear to be a reliable diagnostic. It is likely that WAI is a better predictor of changes in wideband middle ear transmission than TPP, but more data and modeling are needed to fully utilize WAI for this purpose.
Dear Section Editors, Drs. Gorga and Sanford,

Here is our manuscript, *Effects of Negative Middle Ear Pressure on Wideband Acoustic Impittance in Normal-Hearing Adults*. In this study, eight subjects with normal middle ear function were trained to induce consistent static negative middle ear pressures (NMEPs), quantified by the tympanic peak pressure (TPP) and wideband acoustic immittance (WAI). The effects of NMEP on middle ear power absorbance, along with estimated WAI magnitude and phase quantities at the tympanic membrane (TM-WAI), are analyzed for individual ears. TPP is found to be a significant but imperfect predictor of changes in acoustic immittance measurements, due to individual variations in the magnitude and frequency range of the effects of NMEP on middle ear transmission.

This is an original work that has not been published nor submitted to another journal. A limited preliminary version of this study was presented as a paper for the Mechanics of Hearing meeting, Cape Sounio, Greece, June 23-39, 2014, which is scheduled to be published in the meeting proceedings in 'early 2015' via the American Institute of Physics. This study was approved by the Institutional Review Board of the City University of New York Graduate Center. All authors meet the criteria for authorship outlined in the International Committee of Medical Journal Editors (ICMJE) Uniform Requirements for Manuscripts Submitted to Biomedical Journals.

Suzanne Thompson and Jont Allen may be reached at thompss1@stjohns.edu and jontalle@illinois.edu.

Sincerely,

Sarah R. Robinson
Eight subjects with normal middle ear function were trained to induce consistent static negative middle ear pressures (NMEPs), quantified by the tympanic peak pressure (TPP) and wideband acoustic immittance (WAI). The effects of NMEP on middle ear power absorbance, along with estimated WAI magnitude and phase quantities at the tympanic membrane (TM-WAI), are analyzed for individual ears. TPP is found to be a significant but imperfect predictor of changes in acoustic immittance measurements, due to individual variations in the magnitude and frequency range of the effects of NMEP on middle ear transmission. Thus, it is important to consider the TM-WAI.
Effects of Negative Middle Ear Pressure on Wideband Acoustic Immittance in Normal-Hearing Adults

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ABSTRACT

Objectives: Wideband acoustic immittance (WAI) measurements are capable of evaluating middle ear performance over a wide range of frequencies relevant to human hearing. It is known that static pressure in the middle ear cavity affects sound transmission to the cochlea, but only a few data sets exist to quantify the relationship between middle ear transmission and pressure level. The purpose of this study is to analyze new WAI measurements of negative middle ear pressure (NMEP), with a focus on the effects of NMEP in individual ears.

Design: In this study, subjects with normal middle ear function were trained to induce consistent NMEPs, quantified by the tympanic peak pressure (TPP) and the WAI. The effects of NMEP on power absorbance are analyzed for 8 individual ears. WAI magnitude and phase quantities at the tympanic membrane (TM) are also studied by removing phase contributions from the residual ear canal (REC).

Results: For the 8 ears presented here, negative TPP has the largest effect from 0.8 to 1.8 [kHz], causing less energy to be absorbed by the middle ear and cochlea. The TPP level is found to be a significant but imperfect predictor of changes in TM acoustic immittance measurements, due to individual variations in the magnitude and frequency range of the effects of NMEP on middle ear transmission. WAI estimates at the TM show pressure effects consistent with an increased stiffness in the middle ear, which could originate from the TM-malleus coupling, annular ligament, or other middle ear structures.

Conclusions: The REC effect is accurately removed from the WAI magnitude and phase, allowing for direct estimation of these quantities at the TM. The effects of NMEP on WAI vary considerably in magnitude and frequency range across individual ears. TPP does not appear to be
sufficiently correlated to wideband acoustic changes in the middle ear to be a reliable diagnostic. It is likely that WAI is a better predictor of changes in wideband middle ear transmission than TPP, but more data and modeling are needed to fully utilize WAI for this purpose.

INTRODUCTION

Wideband acoustic immittance (WAI) is a non-invasive diagnostic measurement for the middle ear, made over a range of frequencies relevant to human hearing for speech perception (e.g. 0.2 to 6.0 [kHz]). The term WAI encompasses a large set of related quantities, including the complex (magnitude and phase) impedance, admittance, and reflectance, as well as power-based quantities such as the power reflectance and absorbance, all of which may be derived from ear canal pressure measures in response to an acoustic stimulus (Møller 1960; Allen 1986; Keefe et al. 1993; Voss & Allen 1994; Feeney et al. 2013). WAI is a promising tool for non-invasive differential diagnosis of middle ear pathologies in a clinical setting. Studies have shown systematic changes of the magnitude reflectance in the presence of different pathological conditions of the middle ear, including disarticulation or fixation of middle ear joints, tympanic membrane (TM) perforations, or degrees of fluid in the middle ear cavity (Feeney et al. 2003; Allen et al. 2005; Nakajima et al. 2012; Prieve et al. 2013; Shahnaz et al. 2009). A large amount of data has been collected in human ears over the last two decades, primarily presented as power absorbance or reflectance. However, more normative and pathological data sets, and modeling techniques, are required before WAI can reach its full clinical potential (Feeney et al. 2013). In this report, the effects of middle ear pressure on WAI measurements are studied.

Middle ear pressure is typically evaluated via tympanometry, the clinical standard for middle ear assessment. The tympanic peak pressure (TPP), an estimator of static middle ear pressure, is
commonly used for middle ear diagnosis. Here we ask, is the TPP a good predictor of physical changes (i.e. acoustic transmission) in the middle ear, as characterized by direct measurements of the WAI? Further, we consider estimates of the WAI at the TM (TM-WAI). This is important because the TM-WAI is directly related to the middle ear’s acoustic transmission over a wide range of frequencies.

**Wideband Acoustic Reflectance**

The complex wideband acoustic reflectance, $\Gamma(f)$, is the primary WAI quantity we will consider in this analysis. WAI measurements were made with a Thévenin-calibrated probe sealed in the ear canal, containing at least one microphone and loudspeaker (Møller 1960; Allen 1986). A wideband acoustic stimulus, such as a steady-state periodic chirp, is played via the loudspeaker; this incident signal is partially reflected and partially absorbed in a frequency-dependent manner by the TM and middle ear. The reflectance is defined as the complex ratio of the reflected to incident pressure as recorded by the probe microphone.

The complex reflectance is related to the complex acoustic admittance $Y(f)$ by

$\Gamma(f) = \frac{1-r_0 Y(f)}{1+r_0 Y(f)}$.

The real quantity $r_0 = \rho_0 c/A_0$ is the 'surge resistance,' where $A_0$ is the assumed area of the ear canal, $\rho_0$ is the density of air, and $c$ is the speed of sound. The squared magnitude, $|\Gamma|^2$, is referred to as the 'power reflectance,' as it is a measure of the relative fraction of the power reflected by the middle ear. A related quantity, the 'power absorbance,' $A(f) = 1 - |\Gamma|^2$, is a measure of the acoustic power absorbed by the middle ear and cochlea (Allen et al. 2005). The power absorbance, when plotted in decibels (the absorbance level), has a very distinctive shape.
for normal middle ears (Allen et al. 2005; Rosowski et al. 2012). Below 1 [kHz], normative data show a rising slope of 15 [dB] per decade. Above this breakpoint, typically at 1 [kHz] in the normal middle ear, the absorbance level is flat with a mean of -2 [dB], and varies over a small decibel range (the ±1 standard deviation range is 2 to 3 [dB]). Rosowski et al. (2012) additionally characterize a falling slope of -23 [dB] per decade above 4 [kHz]. This band pass response of the absorbance level is qualitatively similar to estimates of the middle ear transfer function (Lynch et al. 1982; Puria & Allen 1991; Allen et al. 2005).

The reflectance phase, $\angle \Gamma'$, is a measure of latency. Assuming a lossless uniform ear canal, the probe reflectance may be expressed as the product of the reflectance at the TM and a round-trip delay $\tau_{rec} = 2L_{rec}/c$ due to the residual ear canal (REC) between the probe microphone and TM. Specifically,

\begin{equation}
(2a) \quad \Gamma'(f) = \Gamma_{tm}e^{-j2\pi f \tau_{rec}}
\end{equation}

\begin{equation}
(2b) \quad \angle \Gamma'(f) = \angle \Gamma_{tm}(f) - 2\pi f \tau_{rec}
\end{equation}

\begin{equation}
(2c) \quad \tau(f) = \tau_{tm}(f) + \frac{\tau_{rec}}{2L_{rec}/c}
\end{equation}

where $L_{rec}$ is the length of the REC (Voss & Allen 1994). The delay $\tau(f)$ is defined as the negative slope of the reflectance phase $\angle \Gamma'$ with respect to the radian frequency ($2\pi f$). For a REC of varying area (i.e. a real ear canal), the delay term $\tau_{rec} = 2L_{rec}/c$ can be a function of frequency. When the ear canal has small losses,

\begin{equation}
(3) \quad |\Gamma'(f)| = |\Gamma_{tm}(f)|,
\end{equation}
since $|e^{-j2\pi f \tau_{rec}}| = 1$, which is a reasonable assumption for adult ears (Voss & Allen 1994; Voss et al. 2008). This allows for comparison across different ears and probe insertion depths.

Equation 3 is a standard assumption for WAI analysis, which often only considers the power reflectance $|I'|^2$.

**Middle Ear Pressure**

Chronic negative middle ear pressure (NMEP) is one of the most common middle ear pathologies. It typically occurs when the Eustachian tube is dysfunctional, such that the pressure behind the TM cannot be equalized to the ambient atmospheric pressure. In the case of NMEP, this pressure imbalance can cause a retraction of the eardrum, resulting in compression of the ossicular chain (Shaver & Sun 2013). Eustachian tube dysfunction is extremely common in infants and children (Bluestone & Klein 2007). It often results in a combination of NMEP and fluid in the middle ear cavity, and can lead to chronic infections such as otitis media with effusion, and in severe cases, bacterial biofilm (Nguyen et al. 2012, 2013; Monroy et al. 2015).

Because NMEP is so common, a number of studies have considered the impact of NMEP on otoacoustic emissions (OAEs), including transient evoked OAEs (Marshall et al. 1997; Prieve et al. 2008) and distortion product OAEs (Sun & Shaver 2009). OAE testing is widely used for infant hearing screening, because it is an objective test which does not require a behavioral response. However, middle ear pathologies (e.g. middle ear fluid and NMEP) can confound the results of OAE tests, which depend on the round trip of a signal to and from the cochlea via the middle ear. Even small NMEPs (e.g. less negative than -100 [daPa]), which are considered to fall in the ‘normal’ range, can compromise OAE test results (Sun & Shaver 2009).
The TPP varies when the Eustachian tube is functioning normally. Typically it is slightly negative during waking hours, and slightly positive when the subject is recumbent or sleeping (Tideholm et al. 1998). When a subject with normal middle ear function swallows or yawns, the Eustachian tube briefly opens, causing a pressure equalization; this leads to a time-varying TPP. This natural variation, or lack thereof, may be used to diagnose Eustachian tube dysfunction. By having subjects attempt to alter their middle ear pressure by swallowing, yawning, or performing the Valsalva and Toynbee maneuvers, the Eustachian tube function may be assessed (Holmquist & Olen 1980; Honjo et al. 1981). In the case of extreme dysfunction (e.g. otitis media with effusion), it may not be possible to assess the middle ear pressure via tympanometry, due to extreme changes in the TM admittance function resulting in no measurable TPP. As we will show, even in normal ears modest changes around zero TPP (e.g. -65 [daPa]) can cause significant and easily observed changes in the TM-WAI.

Two recent studies have been conducted to investigate the effects of middle ear pressure on WAI measurements, specifically the effects on the power reflectance and absorbance. Voss et al. (2012) performed WAI measurements in 8 cadaver preparations with controlled MEPs over a ±300 [daPa] range. Their results showed there was a systematic increase in the power reflectance (decrease in the absorbance) below 2 [kHz] as the middle ear pressure magnitudes increased. For individual ears, this increase was monotonic. Above 2.6 [kHz], negative pressures caused a decrease in the power reflectance (increase in the power absorbance). Voss et al. (2012) model these acoustic changes according to Kringlebotn (1988), assuming NMEP reduces the compliance of all middle ear structures.

Similar results were obtained from 35 human subjects by Shaver and Sun (2013), who trained the subjects to self-induce NMEPs. They show averaged data with standard deviation regions from
4 NMEP ranges, but do not show data from individual ears. They found that the power reflectance increased for low- to mid-frequencies and decreased above 3 [kHz], with the largest changes occurring in the 1.0 to 1.5 [kHz] and 4.5 to 5.5 [kHz] ranges, respectively. They observed that, on average, the magnitude of these changes increased with TPP magnitude. Shaver and Sun also used wideband tympanometry to compensate for NMEP by measuring WAI at the TPP. They found, on average, that measuring at the TPP restored the power reflectance to near-baseline values. Considering Figures 1 and 3 from Shaver and Sun (2013), on average, the absorbance level will be about 2 [dB] higher at TPP than at ambient middle ear pressure (AMEP) around 200 [Hz], and about 0.5 [dB] higher around 1 [kHz]. Sun and Shaver (2009) show that there is also no significant difference between TPP and AMEP measurements of DPOAEs. These studies indicate that WAI measurements made at TPP and ambient ear canal pressure are similar in normal ears.

For the measurements presented here, the probe was sealed in the ear canal with ambient atmospheric pressure. As in the Shaver and Sun (2013) study, subjects were trained to induce consistent TPP levels using the Toynbee maneuver. Though it was not possible to simultaneously measure the TPP and WAI in the current study (these measurements were taken a few minutes apart), the subjects were able to perform this task consistently, and then hold the NMEP for the duration of each test, as discussed in the Methods section. Under the limitations of this noninvasive procedure, mechanisms for acoustic changes due to middle ear pressure, including the TM, ossicle joints, and annular ligament stiffness are considered and discussed.

**Tympanometry**
For assessment of the middle ear status, tympanometry is the clinical standard. In this procedure, the ear canal admittance $Y$ (related to the impedance by $Z = 1/Y$) is measured at single frequency, typically 226 [Hz], using a probe that is hermetically sealed in the ear canal. The static pressure in the canal is varied (e.g. typically from +200 to −400 [daPa]). It is assumed that the TM is maximally compliant (has a peak admittance magnitude) when the pressures in the ear canal and middle ear cavity are equal; the pressure where the peak occurs is called the tympanic peak pressure (TPP). As mentioned in the previous section, in the normal middle ear the TPP changes when the Eustachian tube opens, thus the TPP is time-varying in normal ears (e.g. it changes several times per minute). When a defined peak is present, as in the case of normal ears and mild pathologies, the TPP is taken to be equal to the middle ear pressure (Eliachar & Northern 1974). A TPP ranging from -400 to -100 [daPa] is considered to be abnormal.

When using tympanometry, it is assumed that (1) at 226 [Hz] the probe admittance is purely compliant (no friction losses) and is modeled as the sum of two compliances ($|Y_{tm}| \approx 2\pi f(C_{tm} + C_{rec})$), where $C_{rec}$ is the compliance (volume) of the REC and $C_{tm}$ is the compliance at the TM, and (2) for extreme canal pressures the low frequency compliance of the TM ($C_{tm}$) approaches 0 (Shanks et al. 1988). Based on these assumptions, the high pressure ‘tails’ of the tympanogram represent the REC compliance $C_{rec}$. Thus, the REC volume compliance is subtracted from the compliance at tympanic peak pressure (TPP) to obtain the estimated compliance of the TM ($C_{tm} = C_{probe}\big|_{TPP} - C_{probe}\big|_{+200\text{[daPa]}}$).

Assumption (2) has been questioned by numerous investigators (Rabinowitz 1981; Shanks & Lilly 1981; Shanks et al. 1988). Here we also show using WAI that assumption (2) is incorrect; the compliance of the REC is overestimated, thus the compliance of the eardrum is
underestimated, at +200 [daPa]. Rabinowitz (1981) models this error by relating changes in canal pressure to changes in hearing thresholds. Shanks and Lilly (1981) compare tympanometric volume estimates with measured volumes to assess this error. They showed that while both methods have high errors (>20%), the negative tail of the tympanogram is a better estimator of REC volume than the positive. However, this may not be the case for extreme negative TPPs (e.g. if the tympanogram peak is close to −400 [daPa]).

Pressurizing the ear canal to eliminate the REC is not a generally valid method above 500 or 600 [Hz], because the TM admittance is not a simple compliance. At higher frequencies, it is necessary to account for the conductance ‘G’ and susceptance ‘B’ tympanograms, representing the real (G) and imaginary (B) parts of the admittance, respectively (i.e. \( Y = G + jB \)) (Shanks et al. 1988; Vanhuyse et al. 1975).

In this article, we will not only study the relationship between TPP and WAI measurements, but also relate WAI and tympanometry by directly estimating the REC volume and the equivalent compliance at the TM from complex (magnitude and phase) WAI measurements. In this way we can define a relationship between WAI and the 3 parameters derived from the tympanogram: TPP, peak compliance, and REC volume. Note that the estimated TM-WAI is determined at all the measured frequencies (i.e. 0.2-6.0 [kHz]).

MATERIALS AND METHODS

Subjects

Twenty-six adult subjects were recruited for the study, which was approved by the IRB of the City University of New York Graduate Center. All subjects had normal hearing and normal
middle ear function, confirmed by a test battery including otoscopic examination, pure-tone
treshold testing, tympanometry, and acoustic reflex testing. Subjects had little to no cerumen
accumulation, healthy intact TMs, pure-tone air-conduction thresholds above 15 [dB-HL] (in
octaves from 125 to 8000 [Hz]), normal tympanograms (GSI 33 Middle Ear Analyzer, Grason-
Stadler), and acoustic reflex thresholds below 95 [dB].

Out of the 26 subjects trained to induce consistent NMEP, 8 completed the study. NMEPs more
negative than -50 [daPa] were desirable, as NMEPs in this range have been shown to affect

Data Collection

Subjects were trained to perform the Toynbee maneuver, in which NMEP is induced by pinching
the nose while swallowing, thus sucking air from the middle ear cavity via the Eustachian tube.
To assess subjects’ ability to induce and maintain consistent NMEPs, tympanometry was
performed separately from reflectance measurement, during the same session. A total of 16
admittance tympanograms ($|Y_{em}|_{f=226\,[Hz]}$) were taken for each subject at a sweep rate of -50
[daPa/s], alternating 8 trials at NMEP and 8 trials at AMEP, such that each NMEP measurement
was made from a separate attempt of the Toynbee maneuver. Subjects were asked to swallow or
yawn between trials to equalize the pressure in the middle ear. For each admittance
tympanogram, the REC volume was estimated based on the positive tail pressure at +200 [daPa].

Figure 1 shows that these 8 subjects induced consistent NMEPs, with a range from -60 to -350
[daPa]. Both the AMEP and NMEP values for each subject are shown. The gray box plots show
the AMEPs, while the black box plots show the NMEPs. Each box plot represents 8 TPPs,
collected from separate performances of the Toynbee maneuver, alternated with pressure
equalizations. The measurements are divided into quartiles, with the median measurements shown as a horizontal line, the first and third quartiles as the bottom and top of the thin box, and outliers as circles. While there is larger variability of NMEPs than AMEPs for a given individual, these 8 subjects were able to perform the task with a small intrasubject variability.

WAI was measured using Mimosa Acoustics’ Hear ID Middle-Ear Power Analyzer (MEPA3). The system was calibrated according to the manufacturer’s guidelines once daily before collecting measurements. Eight trials each at AMEP and NMEP conditions were interleaved as in the tympanometry trials. During each trial, up to 8 test-retest measurements were attempted, for a total of 64 measurements per condition (AMEP or NMEP) in each ear.

WAI measurements presented here are from sets of test-retest measurements having the least measurement noise. The probe was not re-inserted between trials, such that the residual ear canal (REC) volume remained approximately constant for all measurements for a given subject.

Subject S1 is notable in that the probe appears to have 'drifted,' as discussed in the Results section. The REC effect was removed from each measurement using our 'reflectance factorization' algorithm (Robinson et al. 2013) to isolate the REC contribution from the complex TM reflectance (i.e. beginning at or near the TM). This allowed for direct comparison of TM-WAI magnitude and phase data across subjects, as well as accurate estimates of the REC volume and length for each measurement.

These data were taken as part of a larger study investigating the effects of middle ear pressure on DPOAE measurements. Results of the DPOAE study are currently under review (Thompson et al. 2015).

Data Analysis
Initially the reflectance magnitude is analyzed, since $|Γ|$ is nearly the same at the probe and the TM (Eq. 3). This is similar to the analyses presented by Shaver and Sun (2013) and Voss et al. (2012). In practice, we consider the absorbance level $A(f) = 1 - |Γ|^2$ [dB], because it has a distinctive and well-characterized pattern for normal middle ears (Allen et al. 2005; Rosowski et al. 2012), as described in the Introduction. The REC contribution to the complex reflectance, $Γ_{rec}(f) \approx e^{-j4πfL_{rec}/c}$ (Eq. 2a), is estimated using a factorization of the complex reflectance (Robinson et al. 2013) to separate the reflectance into middle ear and REC responses. This method allows the REC contribution to the 'group' delay (Eq. 2c) to be frequency dependent, which accounts for lossless delay of a REC of non-uniform area. Note that any lossless TM delay, as described by Puria and Allen (1998) and modeled by Parent and Allen (2010), may be included in this component. The second factor, $Γ_{tm}(f)$, defines the complex reflectance of the middle ear near the TM. The wideband TM admittance is calculated using Equation 1 (i.e., $n_0 Y_{tm} = (1 - Γ_{tm})/(1 + Γ_{tm})$). From these estimates, an analogy to tympanometry is formed, via the middle ear network compliance $C_{tm}$ at the TM, and the REC volume $V_{rec}$.

For a lossless REC of uniform area, the REC volume $V_{rec}$ is given by the product of the canal length $L_{rec} = τ_{rec} c/2$ and the canal area $A_0$. When the group delay $τ_{rec}$ is a function of frequency, $L_{rec}$ is a function of frequency, and this simple relationship breaks down. The REC volume may be estimated if the equivalent network compliance, which is proportional to the volume, is known (Shanks et al., 1988). In terms of the compliance $C_{rec}$, the canal volume is $V_{rec} = C_{rec} ρ_0 c^2$.

Based on the model established by tympanometry, $C_{tm}$ and $C_{rec}$ may also be estimated from frequency-dependent (rather than pressure-dependent) data, given $Yn_0 \approx j2πf(C_{tm} + C_{rec})$ and
\[ Y_{tm} r_0 \approx j2\pi f C_{tm} \] below 500 to 600 [Hz]. Thus \( V_{rec} \propto C_{rec} \) can be directly estimated from these quantities. It will be shown in the Results section that \( Y \) and \( Y_{tm} \) are not purely imaginary as assumed by tympanometry, even at low frequencies. Using a WAI measurement rather than a single frequency, it is possible to accurately model the frequency-dependent conductance \( G \) (the real part of the admittance). The low frequency conductance \( (G, G_{tm}) \) has a functional form consistent with a resistance in the middle ear, which is known to be primarily due to the cochlear load resistance (Zwislocki 1962; Lynch et al. 1982; Puria & Allen 1991). This is more easily seen by considering the impedance \( Z = 1/Y = R + jX \), where \( R \) and \( X \) are the resistance and reactance, as described in the Results section.

The reflectance factorization algorithm was experimentally verified using controlled volumes in a syringe. Figure 2 shows measurements made over a volume range of 0.2 to 1.7 [mL], corresponding to a length range of about 3 to 25 [mm]. For each of two calibrated probe tips, 32 measurements were made, for a total of 64 measurements. The syringe had a slightly peaked rubber stopper, which appeared to have a very small non-zero compliance and a slight influence on the cavity volume. There is some jitter in these data \( (r^2 = 0.98) \) due in part to the visual estimation of the syringe lengths.

RESULTS

Power Absorbance

Figure 3 shows individual absorbance level \( (A(f) = 1 - |\Gamma|^2) \) results for all 8 ears from the study, sorted by average TPP in the NMEP state. For comparison, the gray solid lines show the absorbance at AMEP, while the black dashed lines show NMEP. The light gray region \( (\pm 1 \text{ standard deviation}) \) and thin dotted line (mean) show normative data from Rosowski et al.
For these ears, the magnitude of the NMEP effect is typically between 1 and 5 [dB], and is 2 to 3 [dB] on average; the affected frequency range varies considerably across ears. The effects of middle ear pressure on absorbance do not seem to change in a strict way with TPP.

Most ears show a depression of the absorbance level for some range of frequencies below 2 [kHz]. This depression has a frequency range width of at least 1 [kHz] for all ears. The ears with the most severe TPP values, S8 and S7, have the widest frequency ranges of separation between the AMEP and NMEP states, extending from at least 0.5 to 4.0 [kHz]. Above 2 to 3 [kHz], at least half of the ears (e.g. S2, S5, S7 S8) show a slight increase in absorbance due to NMEP at higher frequencies, consistent with the results of Shaver and Sun (2013) and Voss et al. (2012).

For most ears, the AMEP and NMEP absorbances across trials (e.g. separate pressure manipulations) remain fairly consistent. Ear S3 shows the largest variation across measurements for a given pressure state, and the most overlap between the pressure states (particularly below 1 [kHz]). Ears S4 and S8 appear to have an in-between pressure state, likely caused by inconsistencies in the Toynbee induced NMEP.

These responses may be grouped according to similarity. The first group, ears S1, S2 and S7, is characterized by a mid-frequency depression in the absorbance beginning around 0.5 to 1.0 [kHz]. In Figure 3 we denote these ears as group A. The group B ears, S4, S5, and S8, show a large separation due to NMEP, extending all the way down to the lowest measurement frequency of 0.2 [kHz]. For group B, NMEP appears to cause not only a depression of the absorbance level over this frequency range, but a large shift of its low frequency rising slope upward in frequency.

Ears S3 and S6 are less easily grouped. For ear S6 the NMEP curves fall most significantly below the AMEP curves from 0.8 to 1.5 [kHz], while for S3 the AMEP and NMEP states overlap, except from 1.5 to 2.5 [kHz] and above 4 [kHz]. Ear S3 is most similar to group A,
showing a mid-frequency band of separation, while S6 is most similar to group B, showing slight
separation of the states down to the lowest measurement frequencies (these tentative groupings
are denoted with parenthesis).

These suggested groupings appear to be highly related to similarities in the baseline AMEP
measurements across ears. Ears S3 and S6 have more noticeable small resonances (fine-structure
minima and maxima) in the mid-frequency region from 1.0 to 4.0 [kHz], and these resonances
are altered by the NMEP in a systematic way. Disparities in the effect of NMEP at low
frequencies between groups A and B appear to be related to differences in the compliance
(stiffness) characteristics of the middle ear, which dominate below about 1 [kHz].

Figure 4 shows statistics for the results across all ears, as compared to a study of normal ears by
Rosowski et al. (2012). Normative data from Rosowski et al. are displayed using a solid line for
the mean curve and error bars showing ±1 standard deviation. Mean curves for the current
experiment are shown as dashed lines for the AMEP (open circles) and NMEP (solid squares)
states, along with regions of ±1 standard deviation (light gray and dark gray, respectively). This
plot has been derived using 6 measurements for each ear, which was the minimum number of
successful tests taken for each ear in each condition, so that the distributions favor each ear
equally. The AMEP distribution from this study shows excellent agreement with normative data
from Rosowski et al. The mean AMEP curve is within 1 [dB] of the Rosowski et al. mean, below
4.0 [kHz].

The maximum separation of the AMEP and NMEP distributions occurs from about 0.8 to 1.8
[kHz]. The largest separation of the AMEP and NMEP means occurs at 1.50 [kHz], while the
largest separation of the ±1 standard deviation regions occurs at 1.13 [kHz]. Comparing the
NMEP distribution to the Rosowski et al. (2012) study, the optimum separations of the mean curves and standard deviation regions both occur higher in frequency, at 1.59 [kHz].

**Residual Ear Canal Contributions to WAI**

Residual ear canal delays $\tau_{rec}$ (Eq. 2c) are shown in Figure 5, ordered by increasing negative TPP. These frequency-dependent group delays were calculated via reflectance factorization (Robinson et al. 2013). AMEP and NMEP states are shown as gray solid and black dashed lines, respectively. Though probe insertions were not modified between measurements, a few ears show changes in $\tau_{rec}$ that are independent of pressure state. These are likely due to ‘drift’ in the probe insertion. Such drifts could be caused by small movements of a subject’s head between measurements.

For example, ear S1 (top left plot) shows a drifting $\tau_{rec}$ function across measurements. This effect is nearly independent of middle ear pressure, thus we assume that the configuration of the REC must be changing. For this ear, the estimated REC length changed systematically with time during data collection. The largest change in $\tau_{rec}(f)$ occurred in the increasing peak between 2 and 3 [kHz]. Such a peak is functionally consistent with an area constriction in the REC, which could be due to the angle of the probe in the ear canal, for instance, a drooping probe insertion.

Upon closer inspection of the TM group delay $\tau_{em}(f)$ and the total delay $\tau(f)$ (not shown), when the REC delay $\tau_{rec}(f)$ is removed from $\tau(f)$, the resulting TM delay ($\tau_{em}(f) = \tau(f) - \tau_{rec}(f)$) shows an increased separation of AMEP and NMEP states (the variances of the AMEP and NMEP distributions are decreased). Thus, factoring out the REC response is highly effective in improving the utility of complex TM-WAI estimates.
Estimated TM-WAI

Figures 6 and 7 show the estimated complex TM impedance $Z_{tm} = R_{tm} + jX_{tm}$. Specifically, the resistance ($R_{tm}$, the real part of the impedance) and magnitude impedance ($|Z_{tm}|$) are shown. Consistent with the absorbance level displays of Figure 3, these TM-WAI impedance estimates show related separations of the AMEP and NMEP states. Both could be used for detection and modeling of pathologies.

Figure 6 gives the estimated wideband TM resistance $R_{tm}(f)$ for each of the 8 ears, shown in order of increasingly negative mean TPP, for the AMEP (gray solid) and NMEP (black dashed) states. For most of the ears the resistance remains between 2 and 6 normalized units, especially in the AMEP state. Below 1 [kHz], the resistance is much smaller than the reactance, making these $R_{tm}$ estimates sensitive to noise in the measurements and fitting procedure. Though the very low frequency (200 to 300 [Hz]) curves appear smooth due to the parametric fitting procedure, large variations occur due to measurement noise. For example, NMEP data for S8 visibly approaches the noise floor in Figure 3 (bottom right) below 400 [Hz]. For all ears, $R_{tm}$ depends on the middle ear pressure for some range of frequencies. This effect is likely related to acoustic power dissipation in the middle ear due to compression of the ossicle joints with NMEP. Note this effect is most severe for ears S7 and S8, which have the largest TPP values.

Figure 7 gives the estimated wideband TM impedance magnitudes $|Z_{tm}(f)|$ for each of the 8 ears, shown in order of increasingly negative mean TPP, for the AMEP (gray solid) and NMEP (black dashed) states. Below about 0.7 to 1.0 [kHz], the magnitude impedance $|Z_{tm}|$ is dominated by the compliance at the TM ($|Z_{tm}|/r_0 \approx |X_{tm}|/r_0 \approx 1/2\pi f C_{tm}$), which on a log-log
scale appears as a straight line with a negative slope of 1. In the mid-frequency range from 1 to 4 kHz, where the reactance $X_{tm}$ (not shown) becomes small, the resistance dominates.

Comparing Figures 6 and 7, the largest systematic effect of NMEP is a decreased compliance (increased stiffness) at low frequencies, characterized by the upward shift of the low frequency ramp of the magnitude impedance. NMEP also shifts various local resonant behaviors of the middle ear. For example, ear S5 (bottom left) has a small 3 to 6 [dB] minimum in $|Z_{tm}|$ at 1.5 kHz. In the NMEP state, this local minimum shifts to 2.5 kHz, corresponding to a shifted response in the NMEP absorbance (Fig. 3). This seems consistent with increased stiffness of the middle ear structures, possibly including the TM, ossicle joints, and annular ligament (Voss et al. 2012). Most of the ears show some degree of such local ‘shifted resonance’ behavior.

It is important to note that the term resonance is typically defined for a second order system, such as a spring-mass system (e.g. a simple harmonic oscillator). The ‘middle ear resonance,’ ignoring small individually varying minima and maxima, is better characterized as a resistor in series with a spring, namely a damped first order system, as described next.

**A Simple Model**

Figure 8A shows a simplified model of the middle ear. Included are a tube transmission line of length $L_{rec}$ representing the ear canal, $C_{tm}$ representing the aggregate compliance of the middle ear, and a cochlear load resistance $r_c$, required to match the transmission lines of the middle ear and cochlea (Møller 1960; Zwislocki 1962; Lynch et al. 1982). Model 8A qualitatively captures the behavior of the human middle ear up to 4 to 5 [kHz]. Figure 8B shows a low frequency network equivalent of Figure 8A, where the ear canal is represented by a lumped compliance $C_{rec} = A_0 L_{rec}/\rho_0 c^2$. 
For tympanometry, the input impedance of the middle ear is typically modeled by Figure 8B, but without the cochlear resistor \( r_c = 0 \). Adding a resistor to this model improves the fit to WAI data. Note that the reflectance factorization algorithm is used to analyze the WAI over the entire measured range of frequencies, according to Figure 8A, while tympanometry typically considers the model in Figure 8B at a single low frequency (e.g. 226 [Hz]), assuming \( r_c = 0 \).

From both models, we predict a TM-WAI having an impedance

\[
Z_{tm}(f) = \frac{1}{Y_{tm}(f)} = R_{tm}(f) + jX_{tm}(f)
\]

\[
R_{tm}(f) = r_c
\]

\[
X_{tm}(f) = \frac{-1}{2\pi f_c_{tm}}
\]

where the resistance \( R_{tm} \) and reactance \( X_{tm} \) of the middle ear are simply related to the parameters \( r_c \) and \( c_{tm} \). Equation 4 is consistent with the functional behavior of these data, and will be used to estimate the lumped middle ear compliance at the TM and the REC volume. We consider the complex impedance \( Z_{tm} \) instead of the admittance \( Y_{tm} = 1/Z_{tm} = G_{tm} + jB_{tm} \) described in the Introduction (e.g. \( B \) and \( G \) tympanograms), because the dependence of \( G_{tm} \) and \( B_{tm} \) on \( r_c \) and \( c_{tm} \) is more complicated.

From the model in Figure 8 (Eq. 4), the resistance \( R_{tm} \) is expected to be approximately independent of frequency. The reactance \( X_{tm} \) dominates the magnitude TM impedance below about 1.0 [kHz], and the resistance dominates in the mid-frequency region (about 1 to 4 [kHz], where the reactance becomes small). This model prediction is consistent with the TM-WAI results in Figures 6 and 7. For most ears in Figure 6, the resistance varies over a small range, in
reasonable agreement with the model. Magnitude impedance data given in Figure 7 are in agreement with the model as well.

Values of $C_{rec}$ and $C_{tm}$ estimated from WAI data using the model in Figure 8 are given in Figure 9. Figure 9A shows the REC volumes (proportional to $C_{rec}$) estimated for each of the 8 ears in this study, in order of increasing average TPP magnitude for the NMEP state. These volumes are only significantly different (e.g. 0.1 to 0.2 [mL] difference, $p < 0.05$ using an unpaired t test) between the AMEP and NMEP states for ears S3, S6 and S5 only. Thus, REC volume estimates are approximately independent of pressure state. Estimated REC lengths (assuming a constant canal area) are given on the right-side axis.

Figure 9B shows the estimated middle ear compliances ($C_{tm}$) in milliliter units for each of the 8 ears in this study, in order of increasing average TPP magnitude for the NMEP state. Except for S3, the compliance values at the TM are significantly lower in the NMEP state ($p < 0.01$, and in many cases is much smaller, using an unpaired t test). Thus, NMEP is associated with a decreased compliance at the TM. The group B ears (S4, S5, S8), which showed greater separation at low frequencies due to NMEP, have larger changes in the middle ear compliance $C_{tm}$ than group A.

Figure 10 shows peak admittance $|Y_{tm}|_{f=226\,[Hz]}$ values estimated via tympanometry at 226 [Hz] compared with $|Y_{tm}|_{f=226\,[Hz]}$ estimated from the WAI at AMEP via reflectance factorization. These WAI estimates are based on fits to the model in Figure 8, using the AMEP $C_{tm}$ values given in Figure 9B. For both WAI and tympanometry, mean values are given for 8 estimates from each ear, and error bars show ±1 standard deviation. There is a significant, positive
correlation ($r^2 = 0.67$, $p = 0.01$ using an unpaired $t$ test) between the WAI estimates and the
tympanometric measurements.

DISCUSSION

Network Equivalent Compliance at the TM: WAI vs. Tympanometry

The uncertainty over a set of repeated measurements is approximately equal (standard deviations
are on the order of 1 [mL]) for both the tympanometric and WAI estimates of the 226 [Hz]
middle ear admittance at the TM. Though there is a correlation between these estimates in Figure
10, the TM admittance values are consistently lower when estimated via tympanometry. This is
an anticipated result (Rabinowitz 1981; Shanks & Lilly 1981; Shanks et al. 1988); tympanometry
assumes, incorrectly, that the compliance at the TM is zero at static ear canal pressure extremes
(e.g. +200 [daPa]). A reduction by 30% is a large error, and this error may be avoided by directly
measuring the TM admittance using WAI.

Errors in the tympanometric estimates may arise because TM compliance estimates tend to be
lower (REC volume estimates tend to be higher) when the positive tail of the tympanogram is
used to compensate for the REC volume (Shanks & Lilly, 1981). Shanks and Lilly showed that
the error in REC volume estimated at 220 [Hz] was 39% using the positive tail, and 24% using
the negative tail. However, it was prudent to compensate for the REC using the +200 [daPa]
value in this study, because negative shifts in the peak due to NMEP can artificially raise the
compliance of the negative tympanogram tail if the TPP is close to -400 [daPa].

Errors in the WAI estimates may arise if the ear is not equalized properly. For instance, if the
subject does not completely release the pressure, or sniffs after yawning, then the tympanogram
peak may be shifted slightly from 0 [daPa]. Considering Figure 1, the AMEP across all 8 ears
has a mean value of -1 [daPa] with a standard deviation of 10 [daPa]. Under these circumstances,
the $C_{em}$ estimated from a WAI measurement made at AMEP might be slightly below the peak
value. However, Figure 10 suggests that any errors of this nature must be quite small compared
to errors due to poor REC volume estimates by tympanometry.

**Dependence of WAI Changes on Middle Ear Pressure**

Figure 4 indicates that the mid-frequency region around 1.0 to 1.5 [kHz] is optimal for detecting
the effect of NMEP. This is in agreement with the results of Shaver and Sun (2013), who also
found that the largest change in the power reflectance occurred from 1.0 to 1.5 [kHz]. Based on
this result, we selectively averaged the absorbance level over the 0.8 to 1.8 [kHz] range to study
its relationship to TPP; Figure 11 shows this comparison. A TPP magnitude greater than 50
[daPa] causes a decrease in the mean 0.8 to 1.8 [kHz] absorbance for all ears except S3. In
addition to the significant separation of the average NMEP from AMEP absorbance over the 0.8
to 1.8 [kHz] range, there is a significant correlation of these quantities with magnitude TPP
($p < 0.001$). However, there is enough variability in this relationship ($r^2 = 0.74$) such that it
does not allow for perfect detection of an abnormal negative TPP using the absorbance level (e.g.
S3 appears normal when there is an induced NMEP).

Considering the raw measurements (Fig. 3), the frequency ranges and magnitudes of the NMEP
effects are highly variable across ears. Thus the relationship between TPP and WAI is not
straightforward, though there is a correlation over a population of ears. For instance, for subject
S3 NMEP causes a mean depression of the absorbance level of -2 [dB] at 2 [kHz], above the
range of most common separation (0.8 to 1.8 [kHz]). This is a similar magnitude change to those
observed for the other ears in Figure 11, but occurs outside of the 0.8 to 1.8 [kHz] frequency range over which the absorbance was averaged. This variability is also apparent in the raw measurements. Consider ears S5 and S6 in Figure 3, which have similar TPPs but show disparate effects at low frequencies.

General changes in the absorbance level with NMEP, characterized by a depression below about 2 [kHz] followed by an elevation at higher frequencies, such as those seen in Figure 3 and the cadaver ears of Voss et al. (2012), are consistent with previous experimental data on middle ear transmission. Murakami et al. (1997) showed that both negative and positive pressures caused a decrease in stapes and umbo vibrational displacement at low frequencies, and an increase at high frequencies, with the change in direction of the effect occurring near 2 [kHz]. This is related to the depression of the absorbance level below about 2 [kHz] and elevation at higher frequencies seen here. This effect is also present in the magnitude TM impedance in Figure 7. Murakami et al. found that, while the effect was similar at low frequencies, the high frequency increase in displacement was greater for negative than for positive pressure. This agrees with the results of Voss et al. (2012), who find that both positive and negative MEPs have a similar effect below 2 [kHz], but only the NMEP condition causes an increase in the absorbed power at high frequencies.

**Mechanisms for Pressure-Dependent Changes in WAI**

As discussed with regard to Figures 3, 7 and 9B, the effect of NMEP on WAI may be primarily described as an increased stiffness in the middle ear system. A stiffness measured at the TM could in fact be due to many middle ear structures behind the TM, including the ossicle joints,
muscles, and ligaments. However, it is unclear which middle ear structures contribute to WAI changes due to NMEP, and to what extent.

It is commonly assumed that the TM is the largest contributor to nonlinear (NMEP-dependent) stiffness characteristics in such data. For example, the common assumption of tympanometry is that the TM is analogous to a rigid wall when pressurized. However, it has been shown that the TM functions primarily as a delay line (Puria & Allen 1998). This suggests that the nonlinear effect is primarily due to the stiffness of its coupling to the malleus, particularly when the middle ear pressure is within the range of normal variation.

Retraction of the TM under NMEP is likely similar to TM displacement due to contraction of the tensor tympani muscle. However, unlike the stapedius muscle, the tensor tympani is not activated as part of the acoustic reflex in humans (Møller 1983); how it functions and what causes it to contract are not well understood (Mukerji et al. 2010; Aron et al. 2015). Thus, its effects on the acoustic impedance have been difficult to isolate. Studies in cats and rabbits (Møller 1983) and humans (Bance et al. 2013; Aron et al. 2015) indicate that the effects of tensor tympani contraction on the acoustic impedance measured in the ear canal are similar to the effects of stapedius muscle contraction, which applies a force to the annular ligament, but does not displace the TM.

In vivo measurements in human ears of the acoustic stapedius reflex, which applies a force on the annular ligament and changes the motion of the stapes footplate (Møller 1983), show similar changes in the WAI to those found here (Feeney & Keefe 1999; Feeney et al. 2004; Schairer et al. 2007). The ‘shifted resonance’ effect due to an increased stiffness, seen here as an increase in
impedance below 1 to 2 [kHz], followed by a small decrease in impedance for high frequencies, is described via a simple harmonic oscillator model by Feeney and Keefe (1999).

The nonlinear characteristics of the annular ligament have been measured and modeled (Lynch et al. 1982; Pang & Peake 1986; Murakami et al. 1997; Lauxmann et al. 2014). The effects of NMEP on WAI found here are consistent with changes in the stapes response due to a pressure differential across the annular ligament, in animal and mathematical models (Lynch et al. 1982; Lauxmann et al. 2014). According to measurements of Lynch et al. (1982) in cat, a partial middle ear system consisting of the stapes, annular ligament and cochlea gives an impedance change due to middle ear pressure that is qualitatively similar to the impedance results in Figure 7. Thus a pressure differential between the middle ear and inner ears can cause a change in stiffness of the annular ligament. In human cadaver ears, Murakami et al. (1997) found a similar effect in the stapes displacement given a decrease in middle ear pressure, but the same research team found only a decrease in stapes velocity (no high-frequency increase) when the pressure in the cochlea was increased instead (Myers et al. 1998).

Clinical Implications

For diagnostic purposes, one might wish to determine the relationship between the measured TPPs and the effects of NMEP on WAI measurements, as analyzed in Figure 11. However, due to the variability of the TPP measurement itself, and the large individual variability of the effects of TPP on WAI, a strong, predictive relationship seems unlikely. Namely, some ears with ‘normal’ MEPs (e.g. $|TPP| < 100$ [daPa]) will have significant changes due to pressure, while some ears with ‘abnormal’ MEPs show less severe effects. Thus, it seems that better modeling tools for characterizing the WAI of individual ears are required, rather than delineating the
affected ears based on a TPP threshold. An improved understanding of the physical sources of WAI change due to NMEP will improve the clinical utility of WAI measurements for detecting those NMEPs that significantly affect sound transmission through the middle ear.

Given the variability in the frequency range of the pressure effects, it will be unproductive to try to infer the NMEP via averaging frequency bands across a large set of measurements. Considering Figure 11, even the average power absorbance over the best frequency range of WAI separation (Fig. 4) is only modestly correlated with TPP. Because of this variability, it would be more direct to study the relationship between WAI and other multi-frequency diagnostic measurements of concern, such as DPOAEs.

We suspect, based on the evidence, that a NMEP that significantly impacts other measures, such as OAEs, is detectable using WAI measurements made at ambient pressure. Under the assumption that the variability in WAI measurements is meaningful and directly related to middle ear transmission, WAI is a more informative measurement than TPP. In their WAI experiment, Shaver and Sun (2013) show that there are average trends as a function of TPP for power reflectance measurements, but there is a large variability across individual ears, also found here. In Figure 5 of Sun and Shaver (2009), they also find large intersubject variability of DPOAE levels for a given TPP, even though there is a trend in the effect over many ears. It is likely that these variabilities are at least partially linked. In this case, WAI could be a better predictor of wideband DPOAE change than TPP. This is a complicated problem which requires further investigation, as WAI is related to, but does not completely describe the forward and reverse transfer functions of the middle ear.
One method to circumvent the NMEP is to apply a compensatory pressure in the ear canal, and measure WAI and DPOAEs at the TPP (Sun & Shaver 2009; Shaver & Sun 2013). However, a compensated measurement does not precisely simulate the normal (ambient) listening conditions for the patient, as the normal middle ear system typically has a small negative pressure during waking hours (Tideholm et al. 1998). In fact, a small amount of tension or stiffness in the system may be necessary to aid sound transmission to the cochlea. Additionally, the results of Lynch et al. (1982), Lauxmann et al. (2014), Myers et al. (1998) indicate that the difference between the middle and inner ear pressures has an effect, in addition to the different between the canal and middle ear pressures. Finally, note that the compensation technique was studied for normal ears.

If a NMEP is present and the patient cannot release it voluntarily (e.g. by yawning, which can be assessed in real-time at ambient pressure), then it is likely that middle ear transmission is compromised by some related pathology, such as otitis media. In such a case, the compensation procedure would not yield the desired DPOAE results. Pressure compensation might be needed for a young child or infant who cannot attempt to alter their NMEP on command; still, if a large NMEP is present, it is likely that middle ear transmission may be compromised by a coexisting pathological change.

**Summary**

Our methods accurately estimate the REC by removing its contribution to the complex WAI, thus allowing for a direct estimation of the complex TM-WAI (magnitude and phase). For the 8 subjects presented here, NMEP has the largest and most significant effect (a mean change of 2 to 3 [dB]) between 0.8 and 1.8 [kHz], causing a reduction in energy absorbed by the middle ear and cochlea. However, WAI results vary considerably in magnitude and frequency range across individual ears. General changes in the TM-WAI due to NMEP, characterized by an increase in
the TM impedance (decrease in the absorbance level) below 2 [kHz], and a decrease at higher frequencies, appear consistent with previous results, and may be related to a stiffening of the TM-malleus coupling, annular ligament and other middle ear structures in the presence of middle ear pressure.

Tympanometry, specifically the measurement of TPP (and tympanogram shape, not addressed here) has been the clinical gold standard for identifying ears compromised by MEP. However, when compared to WAI quantities, including the power absorbance and estimated TM-WAI, TPP does not appear to be sufficiently correlated to wideband acoustic changes in the middle ear to be a reliable diagnostic. Though MEP is of concern for other diagnostic measures such as DPOAEs, it is likely that variability in these measures as a function of TPP is linked to that found here for WAI. WAI could be a better predictor than TPP of changes in wideband middle ear transmission due to NMEP, but further modeling is needed to fully utilize WAI in this way.

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REFERENCES


**FIGURES**

Figure 1: Subjects were able to induce consistent negative middle ear pressures (NMEPs) using the Toynbee maneuver. Middle ear pressures were measured via tympanometry; the tympanic peak pressure (TPP) value is taken as the NMEP. Box plots show the measured TPPs in ambient middle ear pressure (AMEP, gray) and NMEP (black) states. Each box plot divides the measurements into quartiles, showing the median measurement as a horizontal line, and the first and third quartiles as the bottom and top of the thin box. Outliers are shown as circles. The TPPs have lower variability for the AMEP state, as expected.

Figure 2: Volumes in a syringe, calculated using the reflectance factorization method (Robinson et al. 2013).
Figure 3: Absorbance level [dB] for each of the 8 ears ordered by average TPP for the ambient middle ear pressure (AMEP, gray solid) and negative middle ear pressure (NMEP, black dashed) states. For each ear, 8 measurements are shown, each selected to have the lowest noise from a pool of up to 8 retest measurements. For the majority of the ears there is a decrease in the absorbance below 2 [kHz] due to NMEP, and a slight increase in the absorbance level above 3 [kHz]. Note the individual variation of the severity and frequency range of the absorbance change due to NMEP. The light gray region (± 1 standard deviation) and thin dotted line (mean) show normative data from Rosowski et al. (2012).

Figure 4: Absorbance distributions for the ambient middle ear pressure (AMEP, light gray) and negative middle ear pressure (NMEP, dark gray) states. Mean curves for each state are shown as dashed lines (AMEP, open circles; NMEP, solid squares). Normative data from Rosowski et al. (2012) are shown as a solid line (mean curve) with error bars showing ± 1 standard deviation. The AMEP mean from this study is in close agreement with the Rosowski et al. (2012) normal mean.

Figure 5: The estimated group delay due to the residual ear canal (REC, $\tau_{rec}$, Eq. 2c) is shown for all 8 ears. Ambient middle ear pressure (AMEP, gray) and negative middle ear pressure (NMEP, black dashed) states are shown. Some ears, particularly ear S1, show differing responses across measurements which do not depend on the pressure state. This is likely due to a 'drifting' probe insertion.

Figure 6: Wideband tympanic membrane (TM) resistance estimates ($R_{tm}$) for each of the 8 ears are shown in order of increasingly negative mean tympanic peak pressure (TPP), for the ambient middle ear pressure (AMEP, gray solid) and negative middle ear pressure (NMEP, black dashed)
The real part of the TM impedance is approximately independent of frequency. For most states, the resistance remains between 2 and 6 normalized units. At the lowest frequencies (200 to 300 [Hz]), the resistance is artificially smoothed due to the parametric fitting procedure; variations at these frequencies are present due to measurement noise.

Figure 7: Estimated wideband tympanic membrane (TM) impedance magnitudes ($|Z_{tm}|$) for each of the 8 ears are shown in order of increasingly negative mean tympanic peak pressure (TPP), for the ambient middle ear pressure (AMEP, gray solid) and negative middle ear pressure (NMEP, black dashed) states. The impedance is compliance dominated at low frequencies, and resistance dominated at mid-frequencies.

Figure 8: A, A simplified wideband model showing the residual ear canal (REC) as a tube transmission line and the lumped middle ear compliance $C_{tm}$ and resistance $r_c$ at the tympanic membrane (TM). This model is qualitatively descriptive of the middle ear behavior up to about 4 to 5 [kHz], at least. B, A low-frequency approximation of panel (A). For tympanometry, $r_c$ is assumed to be 0. Adding a resistor to the model of tympanometry better represents the true behavior of these wideband acoustic immittance (WAI) data. This resistor is primarily due to the cochlear load, and is necessary to match the transmission lines of the middle ear and cochlea (Zwislocki 1962; Lynch et al. 1982).

Figure 9: A, Residual ear canal (REC) volumes estimated via reflectance factorization, proportional to $C_{rec}$. The right-side axis gives corresponding estimated REC lengths, assuming a uniform canal area. B, Lumped middle ear compliances $C_{tm}$ at the tympanic membrane (TM) in milliliters, estimated from the TM wideband acoustic immittance (TM-WAI). Black box plots show the negative middle ear pressure (NMEP) results, while gray box plots show the ambient
middle ear pressure (AMEP) results. For most ears, the $V_{rec}$ estimates are not significantly different between the pressure states, whereas for all ears (other than the high variance subject S3) the TM compliance is significantly lower in the NMEP state, using an unpaired $t$ test individually for each subject.

Figure 10: Comparison of mean 226 [Hz] $|V_{tm}|$ values estimated by tympanometry at tympanic peak pressure (TPP) and those estimated from wideband acoustic immittance (WAI) at ambient middle ear pressure (AMEP) using 'reflectance factorization' (Robinson et al. 2013). Error bars show ±1 standard deviation for each quantity. There is a correlation between these quantities ($r^2 = 0.67, p = 0.01$ using an unpaired $t$ test), but tympanometry significantly underestimates the tympanic membrane (TM) compliance to be about 2/3 of the true value. This effect was observed by Rabinowitz (1981) and Shanks and Lilly (1981).

Figure 11: Change in mean absorbance over the 0.8 to 1.8 [kHz] range as a function of mean magnitude tympanic peak pressure (TPP). Error bars show ±1 standard deviation for each quantity. While there is a significant correlation of these quantities ($r^2 = 0.74, p < 0.001$ using an unpaired $t$ test), there is a large variability across ears. Ambient middle ear pressure (AMEP) data are shown as open symbols, and negative middle ear pressure (NMEP) data are shown as filled symbols.
Tympanic Peak Pressures (TPPs)
Figure 2

Syringe Volume

$V_{\text{syringe}}$ [mL], Measured

$V_{\text{syringe}}$ [mL], Estimated from WAI

$y = 1.01x - 0.02$

$r^2 = 0.98$
Absorbance Level

Figure 4

1 - |Γ|^2 [dB]

| Frequency [kHz] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.5             | 1               | 1.5             | 2               | 2.5             | 3               |

- Rosowski et al., 2012
- Mean, NMEP
- Mean, AMEP
- ± 1 SD, NMEP
- ± 1 SD, AMEP

Note: The diagram shows the absorbance level as a function of frequency, with error bars representing ±1 SD for both NMEP and AMEP.
Figure 5

REC Group Delay

- **Probe shift**

- **Frequency [kHz]**

- **τ_{rec} [ms]**

- **S1** 
  -65 [daPa]

- **S2** 
  -107 [daPa]

- **S3** 
  -123 [daPa]

- **S4** 
  -129 [daPa]

- **S5** 
  -144 [daPa]

- **S6** 
  -156 [daPa]

- **S7** 
  -266 [daPa]

- **S8** 
  -349 [daPa]
Residual Ear Canal Volumes

\[ V_{\text{rec}} \, [\text{mL}], \text{Estimated from WAI} \]

TM Compliance Values

\[ C_{\text{tm}} \, [\text{mL}], \text{Estimated from WAI} \]
TM Admittance Magnitude at 226 [Hz]

\[ y = 0.66x + 0.41 \]

\[ r^2 = 0.67 \]
Figure 11

Absorbance Level vs. Magnitude TPP

\[ y = -0.01x - 2.7 \]

\[ r^2 = 0.74 \]
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