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Characterizing the Eardrum Admittance: Comparisons of Tympanometry and Reflectance

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Abstract. The residual ear canal (REC) between the probe and tympanic membrane (TM) is a significant source of non-pathological variability for acoustic measurements made in the ear canal. Tympanometry and reflectance, which seek to characterize the middle ear based on the TM admittance, must account for unknown REC dimensions. In tympanometry, the REC volume and 226 Hz TM admittance are estimated by varying the canal static pressure. Using a reflectance parametrization developed by the authors, typical assumptions for removing the REC effect are extended, and methods to estimate the REC volume and TM admittance are presented and compared to tympanometry. Results of this method are shown for reflectance measurements of human ears with varying static middle ear pressures (MEPs). The data show that the 226 Hz TM compliance is non-zero at tympanometric pressure extremes, and that acoustic parameters of the middle ear have highly variable, nonlinear dependence on the MEP level.

INTRODUCTION

For assessment of the middle ear, tympanometry is the industry 'gold standard.' A tympanometer measures the ear canal admittance at single frequency, typically 226 Hz, using a probe that is hermetically sealed in the canal. To account for the REC, the static pressure in the ear canal is varied, with the assumption that the probe admittance may be modeled at 226 Hz as a network of two parallel compliances ($Y_{tm} \approx j2\pi f(C_{tm}+C_{rec})$) and that for extreme pressures the low frequency compliance of the eardrum (C_{tm}) approaches 0 [7]. Under this assumption, the high pressure tails of the tympanogram represent the REC compliance only. Thus, the REC volume compliance may be subtracted from the compliance at tympanic peak pressure (TPP). It has been shown that tympanometry typically overestimates the volume of the ear canal, underestimating the compliance of the eardrum [4, 7]. This compensation method is not valid at higher frequencies (e.g., above 500 or 600 Hz).

Wideband acoustic reflectance ($\Gamma(f)$), a separate and proven technology for middle ear assessment, is defined as the ratio of the reflected to incident pressure, as a function of frequency (e.g., from 0.2 to 6.0 kHz). It is related to the acoustic admittance ($Y(f)$) by

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

The quantity $r_0 = \rho_0 c / A_0$ is the surge resistance, where A_0 is the assumed area of the ear canal, ρ_0 is the density of air, and c is the speed of sound. Note that $\Gamma(f)$ and $Y(f)$ are both complex functions of frequency, meaning they have a magnitude and phase. For the purposes of this presentation, quantities without subscripts are those measured at the microphone location in the ear canal.

Assuming a lossless, uniform ear canal, the probe reflectance may be expressed as the product of the TM reflectance and a round-trip delay due to the REC,

$$\Gamma(f) = \Gamma_{tm}(f) e^{-j4\pi f L/c}, \tag{2}$$

where L is the length of the REC. For a non-uniform REC, the delay term will be a more complicated function of frequency. If the ear canal is assumed to be lossless, a reasonable assumption for adult ears [8, 9], then

$$|\Gamma(f)| = |\Gamma_{tm}(f)|, \tag{3}$$

which allows for comparison across different ears and probe insertions. Equation (3) is the standard assumption of most reflectance analyses, which typically consider the magnitude reflectance. The reflectance analysis presented here assumes the ear canal is lossless in order to compensate for the REC effect, but allows for TM admittance phase estimates as well, as required for proper modeling of the middle ear and its pathologies.

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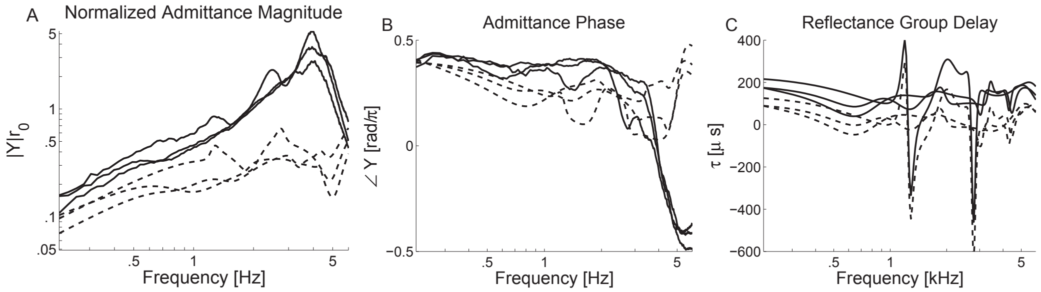

FIGURE 1. Measured quantities (solid lines), and TM quantities estimated via pole-zero factorization (dashed lines). (A) Admittance magnitude. (B) Admittance phase. (C) Reflectance group delay.

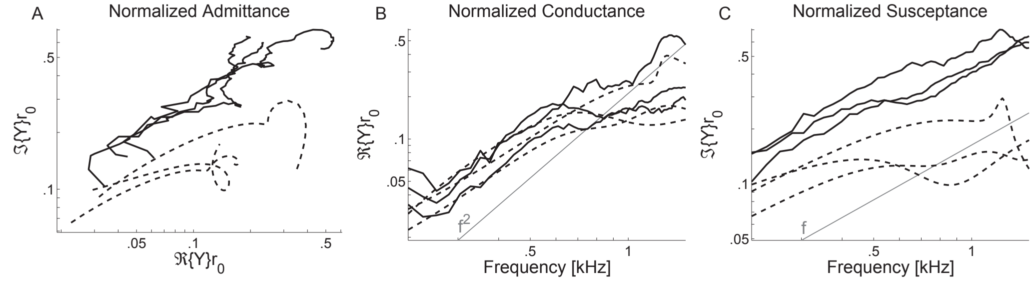

FIGURE 2. Complex measured (solid lines) and estimated TM (dashed lines) admittances below 1.5 kHz. (A) Complex admittance (real vs. imaginary parts). (B) Conductance ($\Re\{Y\}$) vs. frequency. (C) Susceptance ($\Im\{Y\}$) vs. frequency.

METHODS

Data in this study is drawn from the Ph.D. experiment of author S. Thompson. Eight subjects with normal middle ear function were trained to induce negative middle ear pressure (NMEP) using the Toynbee manuever. As a control, measurements were also made at ambient middle ear pressure (AMEP). For each subject, tympanometry was performed separately from reflectance measurement to assess the distribution of NMEPs each subject could induce. Once subjects had been trained to induce consistent NMEPs, 8 tympanograms each were taken for the AMEP and NMEP states. These trials were alternated, such that each NMEP was measured from a separate attempt of the Toynbee maneuver. Measuring the reflectance, 8 trials each of AMEP and NMEP conditions were similarly interleaved. During each trial, up to 8 test-retest measurements were made, for a total of approximately 64 measurements per condition (AMEP or NMEP) in each ear. Measurements presented here are chosen from sets of test-retest measurements to have the least measurement noise.

Pole-zero fitting of reflectance measurements is performed using an algorithm by Gustavsen and Semlyen [1] for rational approximation of a frequency domain response, as described in Robinson et al. [6]. The REC is accounted for by factoring the reflectance fit ($\hat{\Gamma}(s)$) into its minimum-phase and all-pass components, $\hat{\Gamma}(s) = \hat{\Gamma}_{mp}(s)\hat{\Gamma}_{ap}(s)$, which is a simple procedure using poles and zeros. The all-pass factor ($|\hat{\Gamma}_{ap}(s)|_{s=j2\pi f} = 1$) estimates the REC delay, assumed to be lossless, while the minimum-phase factor ($|\hat{\Gamma}_{mp}(s)|_{s=j2\pi f} = |\hat{\Gamma}(s)|_{s=j2\pi f}$) estimates the complex reflectance near the TM. Thus the TM admittance may be approximated by inverting Eq. (1). Since the resulting minimum-phase estimate of the TM reflectance is a quasistatic approximation, it may be modeled by lumped network elements.

Some examples of this factorization are given in Figs. 1 and 2 for three ears at AMEP. The measured quantities are shown as solid lines, and estimated TM quantities are shown as dashed lines. Panels A and B of Fig. 1 show a comparison of the measured and estimated TM admittance magnitude and phase; standing wave characteristics due to the REC are gone once the REC delay has been accounted for. The estimated TM admittance magnitude and phase are similar to the results of Rabinowitz [4]. Considering panel C, differences between the probe and TM group delay curves are consistent with removal of delay due to the REC [8].

Figure 2 shows the complex measured admittances (solid lines) and estimated TM admittances (dashed lines) from 0.2-1.5 kHz; note that all three plots are on log-log scales. Panel A shows these measurements in the complex plane, while panels B and C give the conductance (the real part, $\Re\{Y\}$) and susceptance (the imaginary part, $\Im\{Y\}$) as functions of frequency. It is clear that the TM admittance is not purely imaginary at low frequencies, and thus cannot

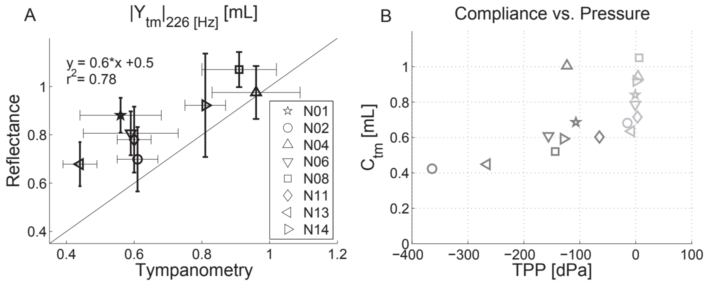

FIGURE 3. (A) Comparison of mean 226 Hz $|Y_{tm}|$ values measured by tympanometry to those estimated using the pole-zero analysis of the reflectance. Errorbars show ±1 standard deviation. (B) Mean estimated C_{tm} values at AMEP (light gray) and NMEP (dark gray) as a function of mean TPP.

be simply modeled as a parallel combination of compliances [7]. Thus a resistor r must be added in series with the TM compliance (C_{tm}), accounting for energy passed to the cochlea. With this simple network model, in the low frequency limit

$$\Re\{Yr_0\} \approx 4\pi^2 f^2 C_{tm}^2 r \longrightarrow \Re\{Y_{tm}r_0\} \approx 4\pi^2 f^2 C_{tm}^2 r \tag{4}$$

$$\Im\{Yr_0\} \approx 2\pi f(C_{tm}+C_{rec}) \longrightarrow \Im\{Y_{tm}r_0\} \approx 2\pi f C_{tm}. \tag{5}$$

From Fig. 2B-C, this model works well below 500 Hz. In panel B, the data and factored fit lines are in close agreement, as predicted by Eq. (4), and have an f^2 dependence (because the curves run parallel to the f^2 line on this log-log plot). In panel C, the estimated TM susceptances fall below well the probe data and have an f dependence, as predicted by Eq. (5). The 226 Hz probe compliance $C = C_{tm} + C_{rec}$ and TM compliance C_{tm} may be accurately estimated from the normalized low frequency data (Yr_0) and factored pole-zero fit ($\hat{Y}_{tm}r_0$) over the regions where $\Im\{Yr_0\}$ and $\Im\{Y_{tm}r_0\}$ are approximately linear. Errors in this method occur if the data have low frequency noise due to leaks, for example. The REC volume may be determined from the normalized compliance estimates as $V_{rec} = C_{rec}A_0c = (C - C_{tm})A_0c$.

RESULTS

Measurements were made over a volume range of 0.2 to 1.7 mL in a syringe, corresponding to a length range of roughly 3 to 25 mm. The syringe had a diameter of approximately 8 mm. For each of two calibrated probe tips, 32 measurements were made, for a total of 64 measurements. The syringe volume was estimated as described in the previous section. The syringe had a slightly peaked rubber stopper (analogous to the TM), which should have a small non-zero compliance and a slight influence on the cavity volume.

Estimates of $V_{syringe}$ were well correlated with the the measured values ($r^2 = 0.98$). To give a slope of 1, it was necessary to correct for the syringe area, which was slightly different from that used for calibration, as

$$V_{syringe,true} = CA_{syringe}c = \left(\frac{A_{true}}{A_0}\right)V_{syringe,measured} \tag{6}$$

with $A_{true}/A_0 = 1.1$ (the diameter of the syringe was slightly larger than the diameter assumed by the calibration). Estimates of REC volume for 62 measurements of 8 subjects at AMEP ranged from 0.18 to 1.11 mL (mean 0.62 mL, standard deviation 0.22 mL), a reasonable range for human, adult ears.

Figure 3 shows a comparison of 226 Hz $|Y_{tm}|$ values estimated by pole-zero analysis of the complex reflectance to those estimated by tympanometry. $|Y_{tm,226Hz}|$ was calculated from the low frequency model described previously for comparison with peak magnitude admittance tympanograms [7]. Plotted points show mean values, and errorbars show ±1 standard deviation for both the reflectance and tympanometry estimates. Uncertainty of these estimates is comparable for both methods of middle ear assessment. Estimates of $|Y_{tm,226Hz}|$ are consistently higher using the reflectance pole-zero method, as predicted by Shanks et al. [7] and Rabinowitz [4]. Panel B shows mean estimated C_{tm} values at AMEP (light gray) and NMEP (dark gray) as a function of median TPP. An induced NMEP generally causes a decrease in the 226 Hz TM compliance. As might be expected, a roughly tympanogram-shaped distribution is seen.

After removing the effect of the REC, Fig. 4B-F shows distributions of the estimated TM quantities for the AMEP (light gray) and NMEP (dark gray) states. The absorbance $1 - |\Gamma|^2$ is shown, along with the real and imaginary parts of both the admittance and impedance ($Z = 1/Y$). For reference, panel A shows the distribution of NMEPs induced by subjects, compared with the AMEP state. Considering the separation of AMEP and NMEP distributions, there is

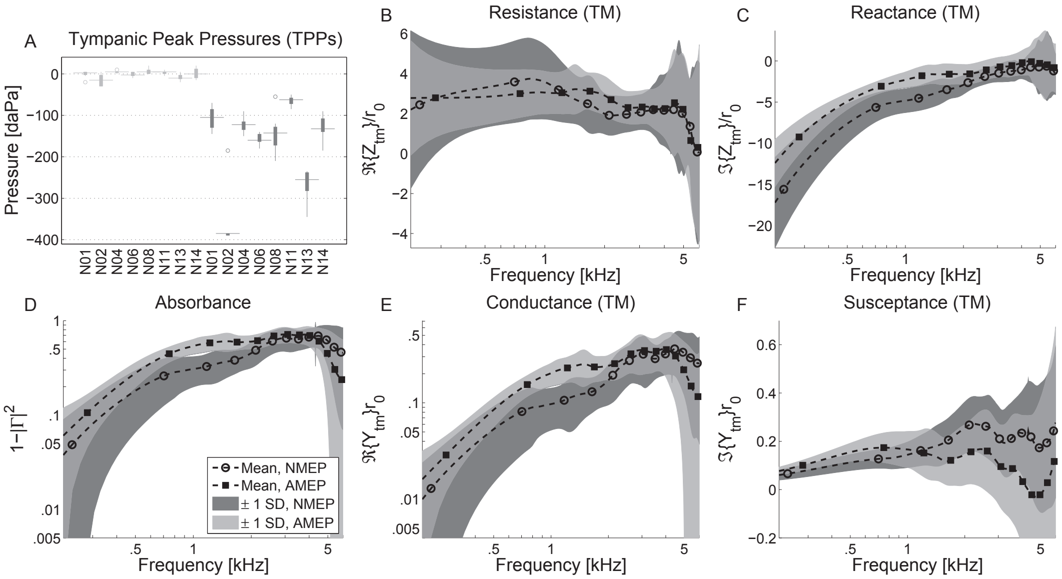

FIGURE 4. (A) Boxplots of measured TPPs in the AMEP (light gray) and NMEP (dark gray) states. The TPP value is assumed to be equivalent to the middle ear pressure level. TPPs have lower variability for the AMEP state, but subjects were able to induce fairly consistent NMEPs using the Toynbee maneuver. B-F Distributions of estimated TM quantities for the AMEP (light gray) and NMEP (dark gray) states. The absorbance $1-|\Gamma|^2$ is shown in D, along with the real and imaginary parts of both the admittance (E,F) and impedance (B,C).

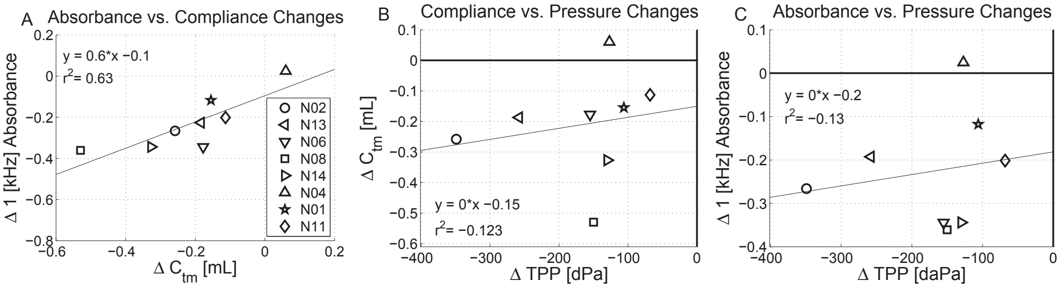

FIGURE 5. (A) Change in 1 kHz absorbance vs. mean change in the 226 Hz TM compliance C_{tm} between the AMEP and NMEP states. (B) Mean change in the 226 Hz TM compliance vs. change in mean MEP. (C) Change in 1 kHz absorbance vs. change in mean MEP. Changes in the 1kHz absorbance and 226 Hz compliance are poorly correlated with MEP.

a close resemblance between the absorbance ($1-|\Gamma|^2$) in panel D and the TM conductance ($\Re\{Y_{tm}\}r_0$) in panel E. Specifically, both quantities show the largest separation between the two distributions from about 0.7-2 kHz, and the regions have a similar pattern of overlap across frequencies. The susceptance ($\Im\{Y_{tm}\}r_0$) regions in panel F are best separated at low frequencies below about 500 Hz, though it is hard to see on a linear scale. This separation is due to a decrease in the low frequency (e.g., 226 Hz) compliance with MEP. It is interesting to note that the best separation at both low and mid frequencies occurs in the TM reactance ($\Im\{Z_{tm}\}/r_0$), shown in panel C.

Figure 5A shows the relationship between the changes in 1 kHz absorbance and low frequency compliance (C_{tm}) that occur between the mean AMEP and NMEP states. There is a correlation between these two quantities ($r^2 = 0.63$), indicating that there is a systematic change in the ear due to the induced NMEP. Figures 5B and C show the dependence of these changes on the value of the induced NMEP change. Panel B shows the mean change in TM compliance C_{tm} due to a change in mean middle ear pressure, and panel C shows the change in the absorbance at 1 kHz due to a change in mean middle ear pressure. Considering both plots, a NMEP almost exclusively causes a decrease in these quantities. However, changes in the response of the middle ear are poorly correlated to the MEP. This indicates that the effects of a given NMEP may be highly variable across ears. For instance, N04 has mean NMEP of -123 [daPa], and the response of the middle ear does not change appreciably. Ears N01 and N14 have similar mean TPP values of

-107 and -129 [daPa], respectively, and show very different changes from N04, and from each other.

DISCUSSION

All reflectance quantities may be affected by discrepancies between the true and assumed surge resistance r_0, for instance, the use of an incorrect area value A_0 [2, 5]. The estimate of $\hat{\Gamma}_{tm}$ will also be impacted by an incorrect r_0 value, and further, may have a different r_0 value than the reflectance calculation at the probe, due to changes in the area function along the length of the ear canal. However, it has been argued that small variations in the ear canal area relative to the calibration cavity area, within 20%, cause a negligible change in the magnitude reflectance [2, 8].

In theory, pole-zero fitting may be used to estimate the actual surge resistance r_0 [6]. The inverse Laplace transform of the reflectance fit $\hat{\Gamma}(s)$ is

$$\hat{\gamma}(t) = d\delta(t) + \sum_{i=1}^{N_p} r_i e^{p_i t} u(t) \longleftrightarrow \hat{\Gamma}(s) = \sum_{i=1}^{N} \frac{r_i}{s - p_i} + d. \tag{7}$$

As discussed in Robinson et al. [6] and Rasetshwane and Neely [5], $d = 0$ for a reflectance function. However, the δ-function may arise if an incorrect value of r_0 is used. If $\bar{r}_0$ is taken to be the true surge resistance, then

$$d = \frac{\bar{r}_0 - r_0}{\bar{r}_0 + r_0}. \tag{8}$$

In practice, the bandwidth of the data is too limited to achieve accurate estimates of d. This is consistent with the observed low sensitivity to variations in r_0 (or equivalently, A_0).

Our factorization reasonably accounts for the REC, and shows that the 226 Hz TM compliance is non-zero at tympanometric pressure extremes. While induced negative MEPs cause a decrease in the 226 Hz TM compliance, separation of the data is largest between 0.7 and 2.0 kHz. This important mid-frequency effect appears to be nonlinearly related to the negative MEP measured via tympanometry, and is highly variable across ears. Tympanometry is able to accurately measure MEP, but because the middle ear transfer function does not have a simple dependence on MEP, reflectance rather than tympanometry is better suited to quantify variable MEP effects. MEP is known to have implications for distortion product otoacoustic emissions (DPOAE) measurements, which are affected by MEPs within a 'normal' range, for normal middle ears [3].

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COMMENTS AND DISCUSSION

Lynne Marshall: Does a non-zero TM compliance at tympanometric pressure extremes produce errors that are clinically significant? - Lynne & Judi [Lapsley Miller]

Sarah Robinson [reply to Lynne Marshall]: Hi Lynne and Judi, I'm not sure, it is not something we have yet considered. I would say that it is highly likely, given that we find eardrum compliance volumes around 0.4 mL (instead of 0, Fig. 3B) at extreme static pressure, while the peak compliance values measured via tympanometry fall in the range 0.4-1.0 mL (Fig. 3A). Thanks for your comment! - Sarah