Real ear measurements: Diagnostics and calibration via Wideband Acoustic Admittance
Comparisons of Tympanometry & Middle Ear Reflectance

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Abstract

The middle ear (ME) is the window into the cochlea. Middle-ear pathologies, especially with cochlear-impaired ears, are common, and objective diagnostic methods over relevant speech frequencies (0.3-7.3 kHz) are limited. For this reason, wide-band middle-ear acoustic power analysis (MEPA) of the middle ear is of special importance because it can provide diagnostic information across a wide frequency range.

- MEPA can accurately estimate the TM compliance (i.e., at low frequencies). The ear canal compliance may be estimated based on the delay to the first significant (i.e., TM) reflection. We will explain why we suspect such an estimate to be more reliable than the baseline obtained from pressuring the canal.

- MEPA provides valuable middle-ear diagnostic information for TM perforations, otosclerosis, disarticulations, dehiscents, hypermobile TMs, and ME reflex. These can be difficult differential diagnostics to make when using tympanometry and the air-bone gap.

- Reflectance allows for greatly improved middle-ear calibrations by removing the effect of ear-canal standing waves. These standing waves can range from 3-8 kHz, and cause errors up to 20 dB. Only a free-field calibration (FFC) can compete with FPL. But FFC is not a viable clinical option due to the requirement of a very high quality and large sound booth.

Thus acoustic reflectance has many advantages that can have a strong impact on our ability to diagnose middle-ear pathology.
Outcome results:

By the end of this presentation you should understand:

1. The operational principles of tympanometry
2. The impact of MEP on TM admittance
3. The operational principles of Middle ear impedance/reflectance
4. The operational principles of wide-band reflectance
5. The relative utility of Reflectance vs. Tympanometry
6. The importance of wide-band TM admittance to the clinical diagnostic utility of middle ear pathologies,
7. How to compensate for the residual ear-canal volume on the TM compliance/admittance estimate,
8. Practical differences between clinical Tympanometry and Reflectance
9. Key literature on middle ear diagnostics
Basic Definitions

1. Conductive Hearing Loss (CHL)
2. 3 sources of CHL variance [Voss et al., 2008]
   1. Residual canal length $L_c$
   2. Residual canal area $A_c$
   3. Tympanic cavity volume (i.e., Behind the TM)
3. The Residual ear canal compliance ($C_c$) is equivalent to ($\leftrightarrow$) the Residual ear canal volume $V_c = L_c \times A_c$
4. Measured admittance $Y_m(f)$ & impedance $Z_m(f)$:
   \[
   Z_m = 1/Y_m
   \]
5. Wideband Power Reflectance measure: $|R_m(f)|^2$
6. Wideband Absorbance measure: $A_m(f) = 1 - |R_m|^2$
7. Standing wave measure: $|1 + R_m(f)|/2$
Can TM Reflectance/Admittance supplement existing clinical methodology?

We will attempt to answer these questions.

1. What is the evidence?
2. Is it practical?
3. To what extent?
4. When can we have it?
Wide-band power reflectance/admittance has been shown to be useful in diagnosing many sources of Conductive Hearing Loss (CHL):

1. Unknown causes Prieve et al. [2012]
2. TM Perforation Allen et al. [2005], Feeney et al. [2003]
3. Ossicular disruption [Feeney et al., 2003, 2009]
4. Analysis of Reflectance in clinical-CHL subjects [Rosowski et al., 2011]
5. Semicircular canal dehiscence [Nakajima et al., 2012]
6. CHL and DPOAE [Sanford et al., 2009]
7. Cadaver studies of CHL [Voss et al., 2008, 2012]
8. Otitis media [Beers et al., 2010]
9. Perforations [Voss et al., 2001]
10. Otosclerosis [Shahnaz et al., 2009, Feeney et al., 2003]
11. Biofilm (chronic condition) [Nguyen et al., 2013]
12. Reduction of False Positives for OAE Infant Hearing Screening [Hunter, 2007, Hunter et al., 2010]
13. ...
Minimal overlap between 0.75-6 kHz for normal-hearing and CHL infants, diagnosed with an air bone gap (ABG) Keefe et al. [2012]
Conductive Hearing Loss in Children Keefe et al. [2012]

1. Minimal overlap between 0.75-6 kHz for normal-hearing and CHL infants, diagnosed with an *air bone gap* (ABG) Keefe et al. [2012]

2. The key frequency region is 1-5 [kHz].
Excellent discrimination between normal and CHL ears within 1-2 kHz.

Composite from Fig 3 Prieve et al. (2013)
ROC curves\(^1\): Reflectance @ 2 [kHz] vs Tympanometry @ 1 [kHz]

\[\text{Hit Rate vs False Alarm Rate}\]

\[^1\text{Hunter et al., 2010, Fig. 5}\]
The basic assumption of Tympanometry

- At 226 Hz, estimate the *residual canal compliance* \( \hat{C}_{\text{canal}} \)

\[
C_{\text{probe}} = C_{\text{canal}} + C_{\text{tm}} \rightarrow \hat{C}_{\text{canal}} \pm 200 \text{ dPa}
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- Subtracting $\hat{C}_{canal} \rightarrow$ TM compliance: $C_{tm} = C_{probe} - \hat{C}_{canal}$
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- The key objective is to measure SC: the volume of the TM
  - MEP is the second objective
Objective of tympanometry

- Estimate the TM compliance $C_{tm}$ from the canal compliance $C_{probe}$:
  
  $$C_{probe} = C_{canal} + C_{tm} \quad \text{where} \quad C_{canal} = \frac{\text{Vol}_{canal}}{1.4 \times P_{ambient}}$$
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Tympanometry at higher frequencies

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3. In what way does Tympanometry help you?
Above 0.5 kHz the interpretation is more difficult since:

\[^2\text{Details in presentation by Robinson \# this afternoon [Robinson et al., 2014]}\]
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  2. Which allows one to diagnose many more CHL pathologies, and
  3. Precisely deals with the residual ear canal problem\(^2\)

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Wideband admittance: 0.2-6 kHz

- Wide-band admittance measured with a “Thevenin” calibrated probe:
  - There is much more to a transducer calibration than [Pa/Volt]
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   [Robinson and Allen, 2013, Robinson et al., 2014]
5. resulting in quality estimates of the TM admittance $Y_{tm}$
What is the impact of the MEP on the TM admittance?

- Can we predict \( Y_{tm} \) given Tymp \( P_{max} \) @226 [Hz]?
  1. We will show that the tymp \( P_{max} \) is not correlate to \( Y_{tm}(f) \) for \( 0.5 \leq f \leq 2 [kHz] \)
  2. Thus: Tymp is not delivering what we wish to know
     This is not a surprise.

- Question to be addressed next:
  For normal middle ears: How does NMEP affect \( Y_{TM}(f, P_{MEP}) \)

- Next we look at the normal ME (i.e., non diseased) where NMEP is the main source of variability?

IS THE TRANSITION adequate?
Characterization of “normal” middle ear admittance

**Goal:** Characterize the effect of Negative middle ear pressure (NMEP) on the wide-band (0.2-6 kHz) Tympanic membrane (TM) admittance. 

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3 S. Thompson & PhD Advisor G. Long), CUNY, 2013
Characterization of “normal” middle ear admittance

**Goal:** Characterize the effect of Negative middle ear pressure (NMEP) on the wide-band (0.2-6 kHz) Tympanic membrane (TM) admittance.

**Task:** 8 subjects were trained to induce 2 ME pressure conditions: Ambient and NMEP, interleaved 8 times with 8 test-retests, resulting in 2*8*8 = 128 measurements/ear:

1. Tympanometry $Y_{tm}(P_{induced}, @226 \text{ Hz})$, i.e., admittance vs. induced pressure
2. Reflectance/Admittance $Y_{tm}(P_{induced}, f)$ $0.2 \leq f \leq 6 \text{ [kHz]}$;

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2. Reflectance/Admittance \( Y_{tm}(P_{induced}, f) \) \( 0.2 \leq f \leq 6 [\text{kHz}] \);

**Methods:** Compare TM admittance \( Y_{tm}(f) \), from \( 0.2 < f < 6 [\text{kHz}] \):

1. Clinically–Normal middle ears (use Suzanne’s terms)
2. Ambient: (NMEP \( \approx 0 \))
3. Pressurized: < –50 daPa of NMEP
4. Conductance: \( G(f) = \Re Y_{tm}(f) \)
5. Susceptance: \( S(f) = \Im Y_{tm}(f) \)

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Effect of the Residual Ear Canal on $Y_{tm}(f)$

- The canal admittance $Y_{canal}(f)$ significantly modifies $Y_{tm}(f)$
- Note large standing wave at 4 kHz Voss and Allen [1994]

Blue: Ambient; Red: Pressurized

N01, AMEP & NMEP

![Graph showing the effect of the residual ear canal on admittance](image-url)
Effect on NMEP on Absorbance

- Ambient AMEP and Presurized NMEP Absorbance [dB] (N01)

**NOTE:** Absorbance = 1 - Power Reflectance = Transmittance in dB units

![Graph showing N01, AMEP absorbance vs frequency in dB units](image)
Effect on NMEP on Absorbance

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Effect on NMEP on Absorbance

- Ambient AMEP and Presurized NMEP Absorbance [dB] (N01)

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- Note the separation of Ambient and Pressurized vs. frequency
Comparison across 2 subjects

- Examples of *Power Absorbance*: Ambient vs. Pressurized (NMEP)
Comparison across 2 subjects

- **Examples of Power Absorbance**: Ambient vs. Pressurized (NMEP)

![Graphs showing power absorbance for Ambient vs. Pressurized (NMEP) for two subjects, N01 and N11.](image)
Absorbance separation (all ears): Ambient vs. NMEP

- The means below 500 Hz are nearly identical $\pm \sigma$ (1-SD)
- The two pressurized conditions separate $\pm \sigma$ over 1-oct (0.75-1.5 kHz)
Change in $Y_{tm}(P_{\text{induced}}, f)$ wrt MEP @226 [Hz]

- MEP @226 [Hz] fails to predict $\Delta Y_{tm}(P_{\text{induced}}, f > 0.5 \text{ kHz})$
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- MEP @226 [Hz] fails to predict $\Delta Y_{tm}(P_{induced}, f > 0.5 \text{ kHz})$
  - The most useful TM measures are between 0.5-6 [kHz]
Change in $Y_{tm}(P_{induced}, f)$ wrt MEP @226 [Hz]

- MEP @226 [Hz] fails to predict $\Delta Y_{tm}(P_{induced}, f > 0.5$ kHz)
  1. The most useful TM measures are between 0.5-6 [kHz]
  2. One must measure $Y_{tm}(f)$ between 0.5-3 [kHz]
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  1. The most useful TM measures are between 0.5-6 [kHz]
  2. One must measure $Y_{tm}(f)$ between 0.5-3 [kHz]
  3. $\Delta Y_{tm}(P_{induced}, f > 0.5$ kHz) is not accurately predicted from MEP@226
Change in $Y_{tm}(P_{induced}, f)$ wrt MEP @226 [Hz]

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  5. Relationship is either negligible, nonlinear, or random
  6. The reason(s) for this are not known (speculations may be possible)

Slide NEEDS WORK: Too dense –JLM
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We will attempt answer these questions.

- Is there a case for Reflectance over Tymp:
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4. When can we have it? Now, from Mimosa acoustics.

**NEED CONCLUSIONS SLIDE**

Need to say more clearly why these NMEP results are clinically interesting. I’m not sure that as presented it passes the ”So what?” test. Need some sort of segue to get back from NMEP to more general issues. –JLM

Add that OtoStat provides extended diagnostic info based on Hunter, Prieve, Beers, and Nakajima research - ie it provides the numbers needed to use their results.
Wideband reflectance on the OtoStat
Wideband reflectance on the OtoStat
Practical considerations

1. Reflectance is as fast as tympanometry
2. Works from 0.2 - 6 [kHz]
3. Can use CPT codes
   1. CPT 92567-M Tympanometry with a modifier
   2. CPT 92700 Unlisted otorhinolaryngological
4. Make OAE measurements at the same time with the same equipment and probe fit.
5. No pressurization required
6. Fully-featured HearID laptop system or convenient OtoStat handheld device


