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

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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
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. Wideband Acoustic Immittance (WAI) of the ME (aka: Admittance/reflectance) is of special importance because it can more reliably provide key diagnostic information across a wider frequency range than tympanometry.

- WAI can accurately estimate tympanic membrane (TM) compliance. The ear canal compliance may be estimated based on the delay to the first significant (i.e., TM) reflection. We will explain why such an estimate is more reliable.
- WAI provides valuable ME diagnostic information for differential evaluation of TM perforations, otosclerosis, disarticulations, dehiscence, hypermobile TMs, ME reflex, and other TM and ME conditions through non-invasive and objective measurements.
- WAI allows for greatly improved real ear calibrations [forward pressure level (FPL) calibration], 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 it is not a viable clinical option.

Thus WAI has many advantages, strongly impacting on our ability to diagnose ME pathology and to obtain more accurate audiometric measurements, hence more accurate long-term monitoring of auditory status.
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?
Review of Reflectance/Admittance literature (2013)

- Wide-band power reflectance/admittance has been shown to be useful in diagnosing many sources of Conductive Hearing Loss (CHL):
  1. TM Perforation [Allen et al., 2005], [Feeney et al., 2003], [Voss et al., 2001]
  2. Ossicular disruption [Feeney et al., 2003, 2009]
  3. Analysis of Reflectance in clinical-CHL subjects [Rosowski et al., 2011]
  4. Semicircular canal dehiscence [Nakajima et al., 2012]
  5. CHL and DPOAE [Sanford et al., 2009]
  6. CHL in infants [Prieve et al., 2012]
  7. Cadaver studies of CHL [Voss et al., 2008, 2012]
  8. Otitis media [Beers et al., 2010]
  9. Otosclerosis [Shahnaz et al., 2009, Feeney et al., 2003]
  10. Biofilm (chronic condition) [Nguyen et al., 2013]
  12. ...
Conductive Hearing Loss in Children

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]
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![Graph showing absorbance vs frequency for different groups.](image)

- **Control Group**
- **CHL Groups**
- **ABG ≥ 25 dB**

2. The key frequency region is 1-5 [kHz].
Excellent discrimination between normal and CHL ears within 1-2 kHz.
DPOAE Infant Hearing Screening (ROC)

- ROC curves: Reflectance @ 2 [kHz] vs Tympanometry @ 1 [kHz]
- Reflectance discriminates better than Tymp

[ROC curves: Hunter et al., 2010, Fig. 5]
The basic assumption of Tympanometry

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

$$C_{probe} = C_{canal} + C_{tm} \rightarrow \hat{C}_{canal} \pm 200 \text{ daPa}$$
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- Subtracting \( \hat{C}_{canal} \) → TM compliance: \( C_{tm} = C_{probe} - \hat{C}_{canal} \)
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- Subtracting $\hat{C}_{\text{canal}} \rightarrow$ TM compliance: $C_{\text{tm}} = C_{\text{probe}} - \hat{C}_{\text{canal}}$

- The key objective is to measure SC: the volume of the TM
The basic assumption of Tympanometry

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\[ C_{\text{probe}} = C_{\text{canal}} + C_{tm} \rightarrow \hat{C}_{\text{canal}} \mid \pm 200 \text{ daPa} \]

- Subtracting $\hat{C}_{\text{canal}} \rightarrow$ TM compliance: $C_{tm} = C_{\text{probe}} - \hat{C}_{\text{canal}}$

- 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 $C_{probe}$:

$$C_{probe} = C_{canal} + C_{tm} \quad \text{where} \quad C_{canal} = \frac{Vol_{canal}}{1.4 \times P_{ambient}}$$
Objective of tympanometry

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Tympanometry at higher frequencies

How many people here use Tympanometry?
Tympanometry at higher frequencies

1. How many people here use Tympanometry?
2. How many people use Tympanometry above 600 Hz?

Tympanometry at higher frequencies

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2. How many people use Tympanometry above 600 Hz?
3. In what way does Tympanometry help you?
Tympanometry at higher frequencies (0.5-2 [kHz])

- Above 0.5 kHz the interpretation is more difficult since:

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2Details in presentation today by Robinson, Pod.III.A 2:45PM
[Robinson et al., 2014]
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- Possible Solution:

\[\text{\footnotesize \cite{Robinson et al., 2014}}\]
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- Possible Solution:
  1. Measure wide band Admittance/Reflectance between 0.2 – 6 [kHz] \(^2\)

\(^2\)Details in presentation today by Robinson, Pod.III.A 2:45PM
[Robinson et al., 2014]
Wideband admittance at higher frequencies: 0.2-6 kHz

- Wide-band admittance measured with a “Thevenin” calibrated probe
Wideband admittance at higher frequencies: 0.2-6 kHz

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1. Canal pressure measured by probe microphone
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![Diagram of ear canal and probe microphone]

2. Canal pressure measured by probe microphone

3. Pressure converted into the wideband probe admittance $Y_{probe}(f)$
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Pod.III.A, Today at 2:45 PM: Robinson & Allen
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5. resulting in quality estimates of the TM admittance $Y_{tm}$
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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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 $Y_{tm}(P_{induced}, @226$ Hz), i.e., admittance vs. induced pressure
2. Reflectance/Admittance $Y_{tm}(P_{induced}, f)$ 0.2 ≤ $f$ ≤ 6 [kHz];

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

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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
  2. **Ambient:** (NMEP $\approx 0$)
  3. Pressurized: $< -50 \text{ daPa of NMEP}$
  4. Conductance: $G_{tm}(f) = \Re Y_{tm}(f)$
  5. Susceptance: $B_{tm}(f) = \Im Y_{tm}(f)$
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Does everyone understand the experiment?

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

- The canal admittance $Y_{canal}(f)$ significantly modifies $Y_{tm}(f)$
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- The canal admittance $Y_{canal}(f)$ significantly modifies $Y_{tm}(f)$
- Note large standing wave at 4 kHz @-probe (not present @-TM)

Solid: @-Probe, Dashed: @-TM;
Blue: Ambient; Red: Pressurized
N01, AMEP & NMEP
Effect of NMEP on Absorbance: Subj N01

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

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

![Graph of N01, AMEP](image-url)

\[
10\log_{10}(1 - |\Gamma|^2) \text{ [dB]}
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![Graph showing absorbance vs. frequency for N01, AMEP and N01, NMEP.](image)

- Note the separation in $Y_{tm}(f)$ for Ambient and Pressurized vs. $f$
Comparison across 2 subjects

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

![Graph showing comparisons of power absorbance between ambient and pressurized conditions for different subjects.](image-url)
Comparison across 2 subjects

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

Two different subjects N01 & N11
Absorbance separation (all ears): Ambient vs. NMEP

- **NYC/CUNY Mean** same as Boston/MEEI mean (black dashed)

![Absorbance Level graph](image)

10\log_{10}(1-|\Gamma|^2) [dB]

- Frequency [kHz]
- Absorbance Level
- Mean, AMEP
- Mean, NMEP
- Mean, Ros. 2012
- ± 1 SD, Ros. 2012
Absorbance separation (all ears): Ambient vs. NMEP

- NYC/CUNY Mean same as Boston/MEEI mean (black dashed)

The means below 500 Hz significantly overlap: ±σ (1-SD)
The two pressurized conditions separate ±σ over 1-oct (0.75-2.0 kHz)
For diagnostics, the most useful TM measures are between 0.5-6 [kHz]
Given the small separation in admittance @226 Hz, and the larger separation between 0.7-2 kHz,
\[ \Delta Y_{tm}(P_{induced}, f) \] 1-2 [kHz] wrt MEP @226 [Hz]

- Given the small separation in admittance @226 Hz, and the larger separation between 0.7-2 kHz, MEP @226 [Hz] & \( \Delta Y_{tm}(P_{induced}) \) seem uncorrelated.
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  - One must directly measure \( Y_{tm}(f) \) between 0.5-3 [kHz]
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$\Delta Y_{tm}(P_{\text{induced}}, f > 0.5 \ [kHz])$ is not predicted from MEP@226

- One must directly measure $Y_{tm}(f)$ between 0.5-3 [kHz]
- The reason(s) for this are not known (speculations are possible)
Can TM Reflectance/Admittance (WAI) supplement existing clinical methodology?

Back to our 4 questions:

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Jont B Allen, Sarah Robinson (UIUC) Sue T Real ear measurements: Diagnostics and cali
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- Is it practical? Yes: WAI is a working well defined technology.
- To what extent? WAI may be purchased: FDA status
- When can we have WAI? Now, from Mimosa Acoustics.
- For the details see: Hunter, Prieve, Beers, Rosowski, Nakajima, …
CONCLUSIONS:

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- These issues have been well documented Rabinowitz [1981]
- CUNY study clarifies many of these issues
  Robinson (Pod.IIIA, 2:45PM)
Wideband reflectance on the OtoStat (Handheld Version)
Wideband reflectance on HearID (USB-Desktop Version)
Practical considerations for WBI (Reflectance)

- 2 versions: HearID laptop & OtoStat handheld
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- $\Delta Y_{tm}(f)$ more meaningful than 226 [Hz] MEP
- MEP highly variable in the normal ME
Practical considerations for WBI (Reflectance)

- 2 versions: HearID laptop & OtoStat handheld
- Provides extensive CHL diagnostics (extensive literature)
- WAI is Wide-band: 0.2 - 6 [kHz]
- WAI can replace tympanometry (Tymp) (More research required)
- WAI faster than Tymp (i.e., no pressurization required)
- WAI more comfortable than Tymp (i.e., no pressurization required)
- Can use CPT codes
  - CPT 92567-M Tympanometry with a modifier
  - CPT 92700 Unlisted otorhinolaryngological
- OAE with the same probe insertion.
- $\Delta Y_{tm}(f)$ more meaningful than 226 [Hz] MEP
- MEP highly variable in the normal ME
  - $Y_{tm}(f)$ needs to be directly measure, NOT predicted from MEP


