Abstract

Tympanic membrane (TM) compliance/admittance is used to diagnose middle-ear (ME) pathologies. TM-compliance, as measured with tympanometry, is estimated by subtracting out the *residual ear-canal volume* (the space between probe-tip and TM). This is done by varying the static pressure, and subtracting the baseline from the peak compliance.

Above ≈0.5 kHz, sound is absorbed by the TM, thus the TM is no longer strictly a compliance (the TM admittance becomes frequency-dependent), limiting tympanometric clinical utility. Above 1.5 kHz the *residual ear-canal acoustical delay* results in *standing waves,* distorting the baseline estimate of the residual canal compliance. The frequency region between 0.8-2 kHz has been shown to have the most significant diagnostic utility. Thus a more general approach to estimating the TM admittance is required.

Reflectance is related to compliance/admittance via a transformation that decomposes the admittance into a ratio of forward and reflected pressure waves. Here the residual ear-canal acts as a round-trip delay, more easily estimated. Once removed, the desired TM reflectance/admittance may then accurately estimated. The single assumption required is that sound propagation is without loss in the residual ear-canal.

In summary: The desired TM compliance/admittance may be accurately estimated in the important frequency range of 0.2-6 kHz, from the frequency dependent reflectance measurements.

Outcome results:

By the end of this presentation you should understand:

1. The importance of wide-band TM admittance to the clinical diagnostic utility of middle ear pathologies,
2. The effect of the *residual ear-canal volume* on the TM compliance/admittance measurement,
3. The operational principles of tympanometry
4. The operational principles of wide-band reflectance
5. Differences between clincial Tympanometry and Reflectance
6. Key literature on middle ear diagnostics

The influence of the *residual ear-canal volume* on estimating the *tympanic membrane compliance*

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Basic Definitions

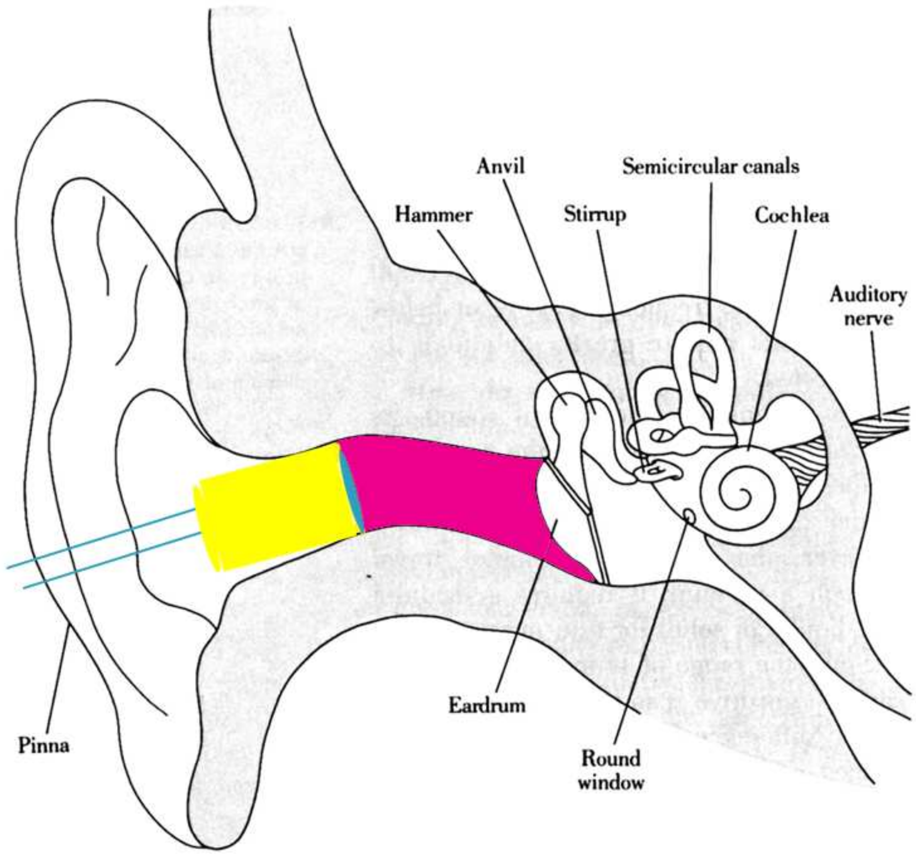
1. Conductive Hearing Loss (CHL)
2. 3 sources of CHL variance (Voss *et al.*, 2008)
   (a) Residual canal length L_c
   (b) Residual canal area A_c
   (c) Tympanic cavity volume (i.e., Behind the TM)
3. The *Residual ear canal compliance* (C_c) is equivalent to ($\leftrightarrow$) the *Residual ear canal 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:* $|1 + R_m(f)|/2$

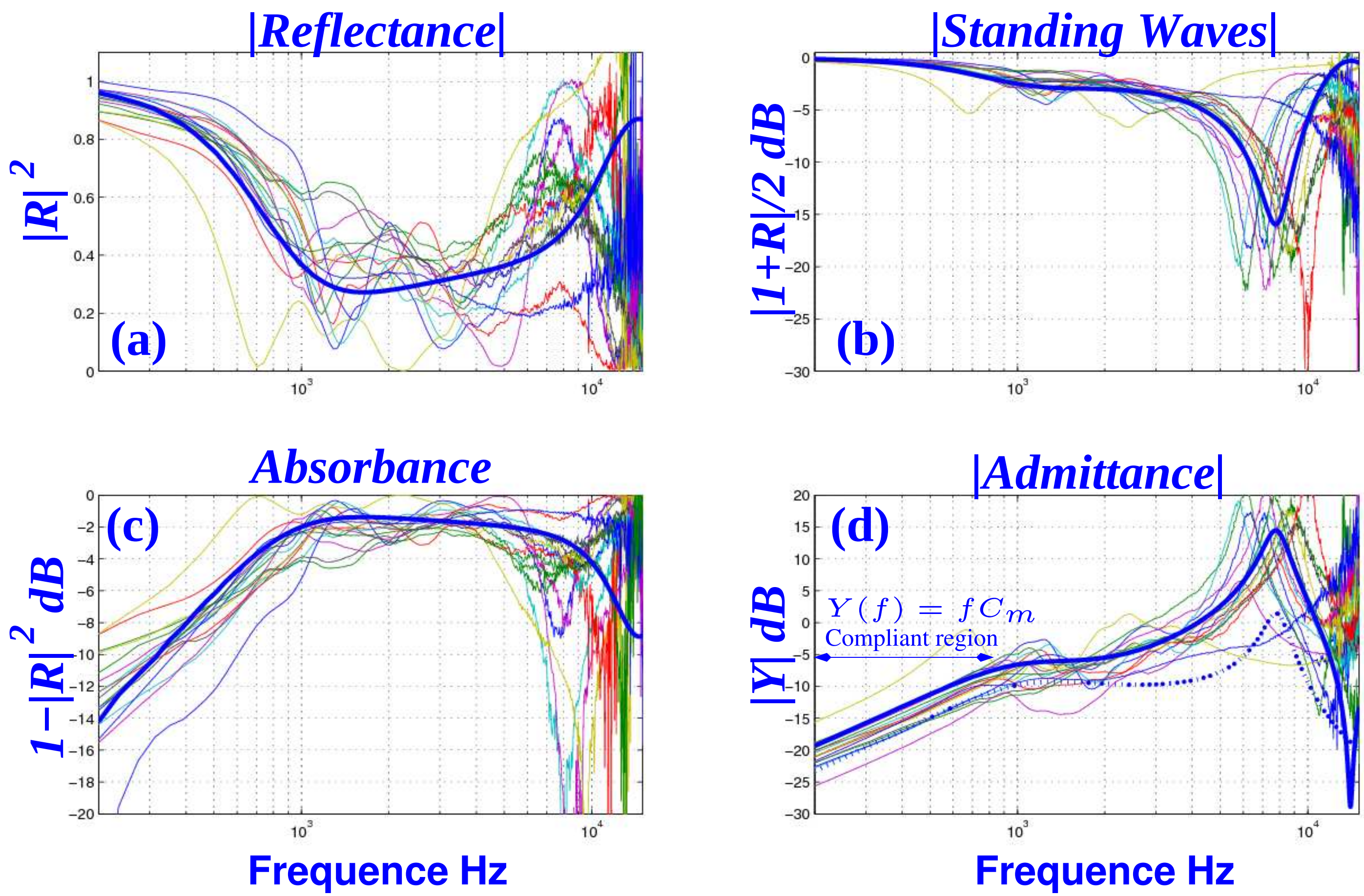
Residual ear-canal compliance

- The compliance of the ear canal C_c (the red region) ($V_c = C_c \times 1.4\,10^8$ mL) distorts the TM compliance (C_{tm}) estimate
- At higher frequencies, canal standing waves dramatically change the TM admittance (Y_{tm})



Canal Admittance and related measures

- Four ear canal *measures* (data of Voss & Allen (1996))



  - (a) $|R|^2$, (b) $\frac{|1+R|}{2}$, (c) $1-|R|^2$, (d) $|Y(f)|$

- Note the large standing waves between 3-10 kHz due to the residual canal

Recent advances in ME diagnostics

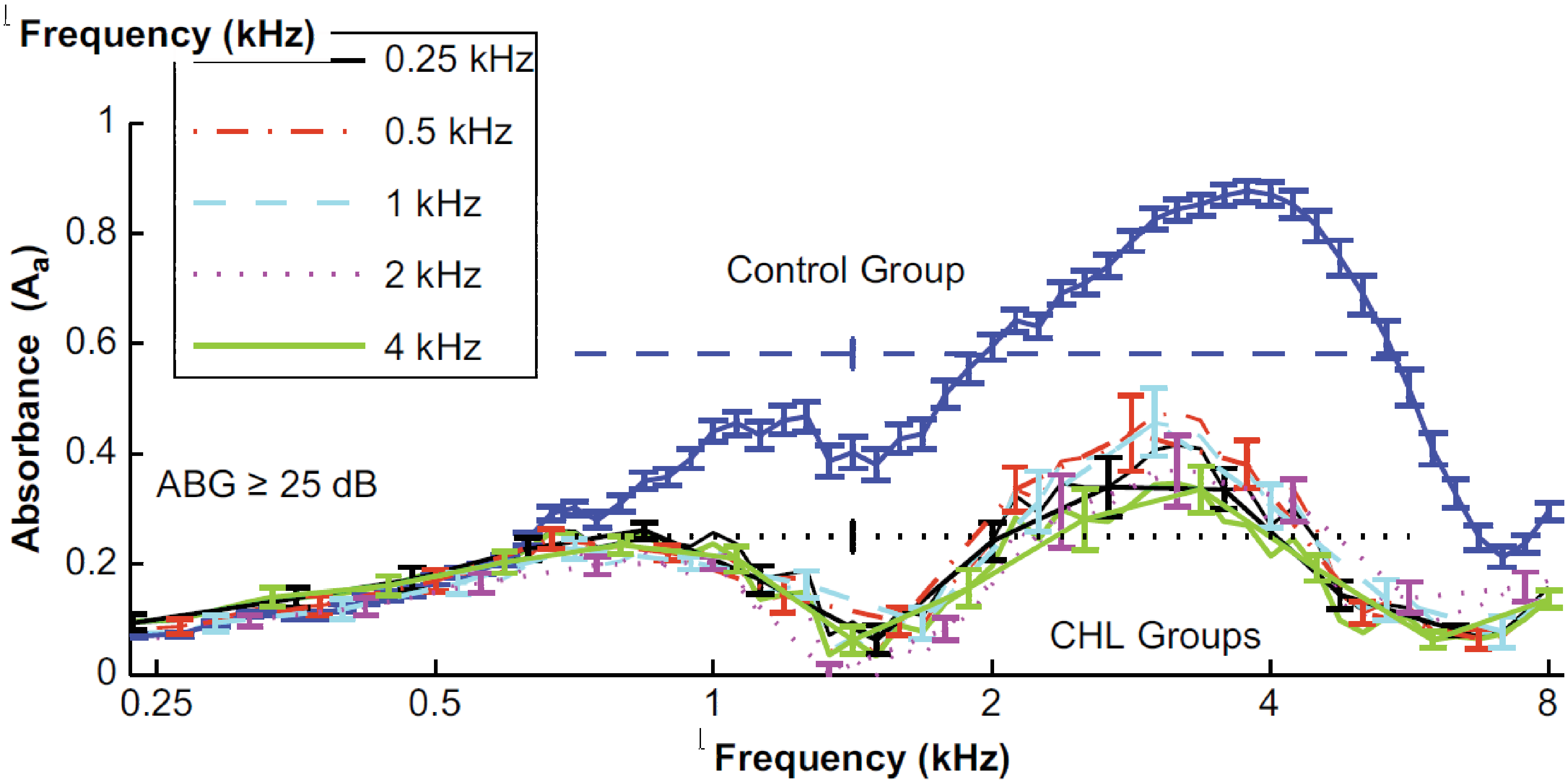
- Conductive Hearing Loss (CHL) detection in children has jumped from 76% to 96% accuracy
  Keefe et al., 2012
- CHL diagnosis in infants has systematically improved
  Prieve et al., 2012
- There is a new differential diagnosis of ossicular discontinuity and stapes fixation Nakajima et al., 2012
- More rigorous CHL norms in adults have been established Rosowski et al., 2012
- False-positives in infant hearing screening have been analyzed Sanford et al., 2009, Hunter et al., 2010

Keefe et al., 2012

- Goal: Differential diagnosis of CHL re normals
- CHL confirmed via air-bone gaps (ABG)
- Children's ages 3-8 years
- Results:
  - 226 Hz tympanometry: 76% accuracy
  - Wide-band reflectance: 96% accuracy
  - Ambient pressure is as good as peak-equalized

Keefe et al., 2012

- Minimal overlap between 1-6 kHz for normal-hearing and CHL children, diagnosed with an ABG



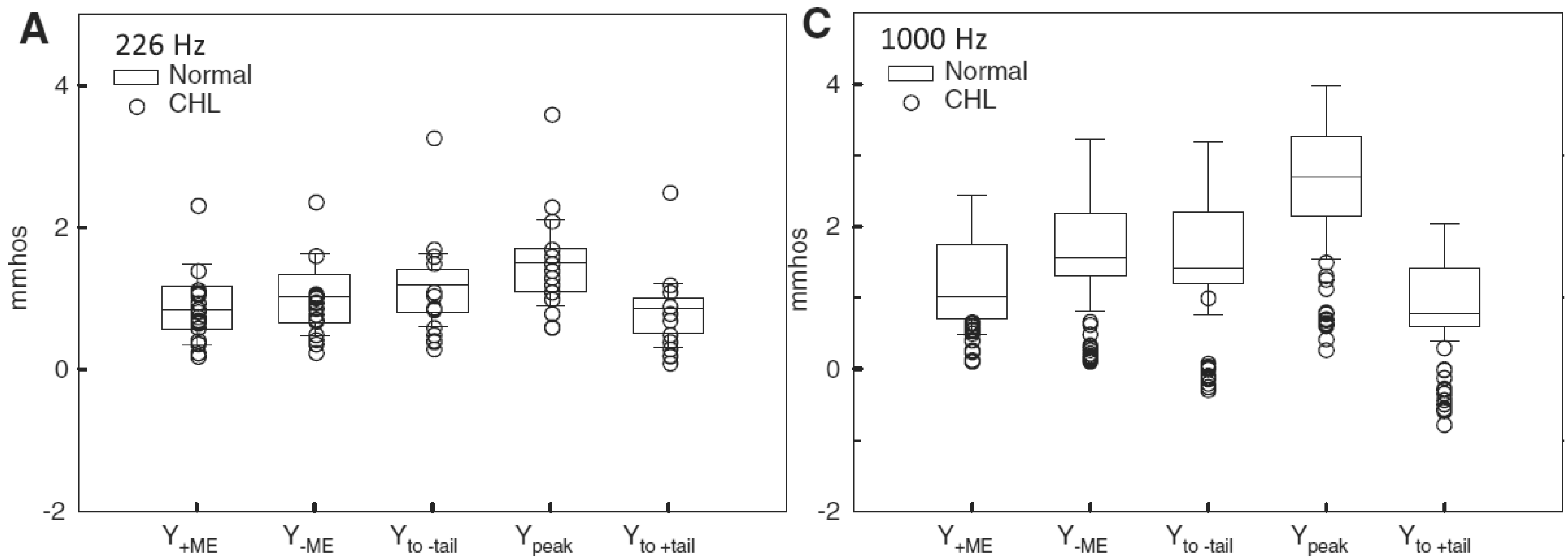
From Fig 1 Keefe et al.. (2012); absorbance is 1-reflectance

Prieve et al., 2012

- Diagnosing infant ears with CHL
- Hearing status determined from ABR & OAE
- Infants aged 3 to 36 weeks
- Results:
  - 226 Hz tymp: did not discriminate normal & CHL ears
  - 678 and 1000 Hz tymp and wide-band reflectance: excellent discrimination
  - Normalization for the residual canal volume is still uncertain: 5 normalization methods were studied: $Y_{\text{peak}}, Y_{\text{+ME}}, Y_{\text{-ME}}, Y_{\text{to -tail}}, Y_{\text{to +tail}}$

Tymp results Prieve et al., 2013

- CHL ears overlap with normal ears for 226 Hz tymp, but not for 1000 Hz tymp

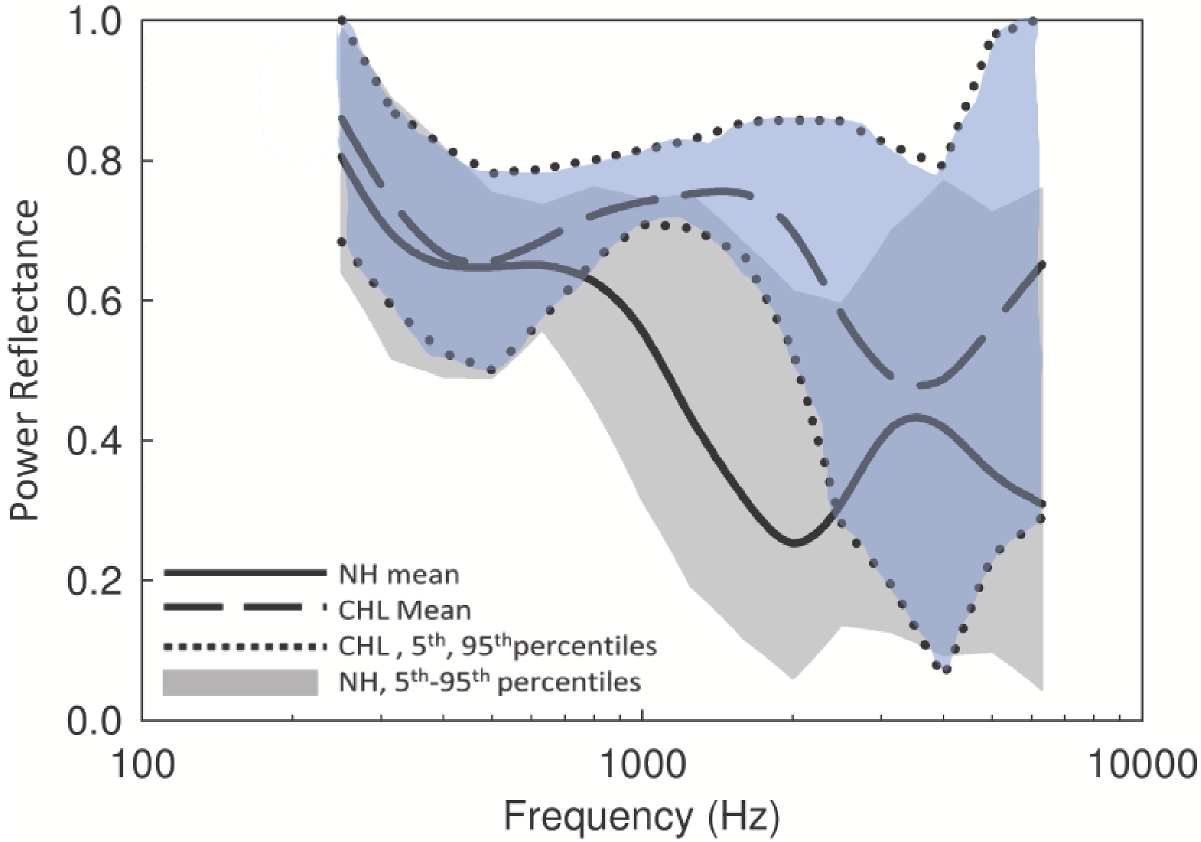


Composite from Fig 2 Prieve et al. (2013)

- Unclear which of the five normalization methods, to remove the residual ear canal volume, is best
  - Does the normalization method depend on CHL?

Reflectance results Prieve et al., 2013

- Excellent discrimination between normal and CHL ears within 1-2 kHz.
- Poor discrimination at other frequencies



Composite from Fig 3 Prieve et al. (2013)

Nakajima & Rosowski et al., 2012

- Differential diagnosis of ossicular discontinuity and stapes fixation
- Healthy TM and aerated ME
- Adult ears (N=58)
- Rigorous norms on normal population
- Standard clinical tests: poor discrimination
- Air-bone gap (ABG) and umbo-velocity: excellent discrimination
- ABG and wide-band reflectance: excellent discrimination

Nakajima et al., (2012)

- Plotting ABG and wideband reflectance reveals three distinct groups with little overlap.

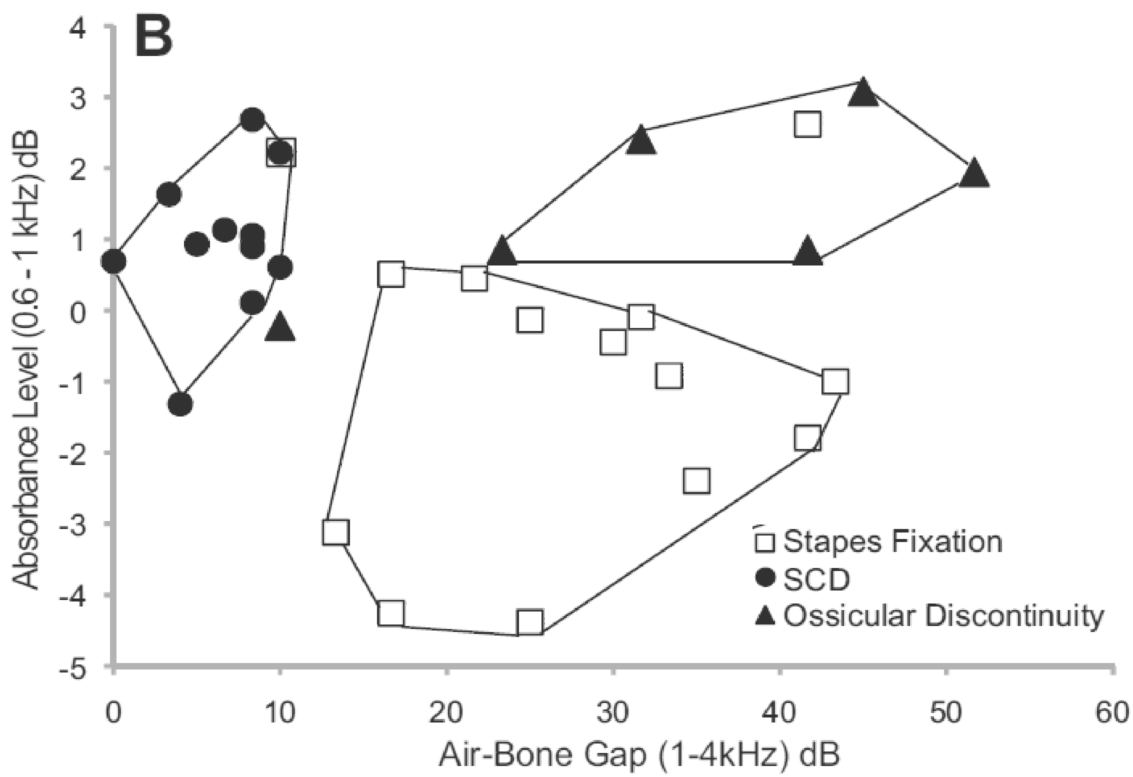


Fig 6b from Nakajima et al., (2012), absorbance (1-power-reflectance) [dB]

Sanford et al. 2009, Hunter et al. 2010

- Newborn hearing screening
- Determine if DPOAE refers were due to ME to reduce false-positive referrals
- Reflectance at 2 kHz predicted DPOAE pass/refer status better than 1 kHz tympanometry

Hunter et al. (2010)

- Ability to discriminate between DPOAE refer and DPOAE pass ears best for 2 kHz reflectance compared to 1 kHz tympanometry.

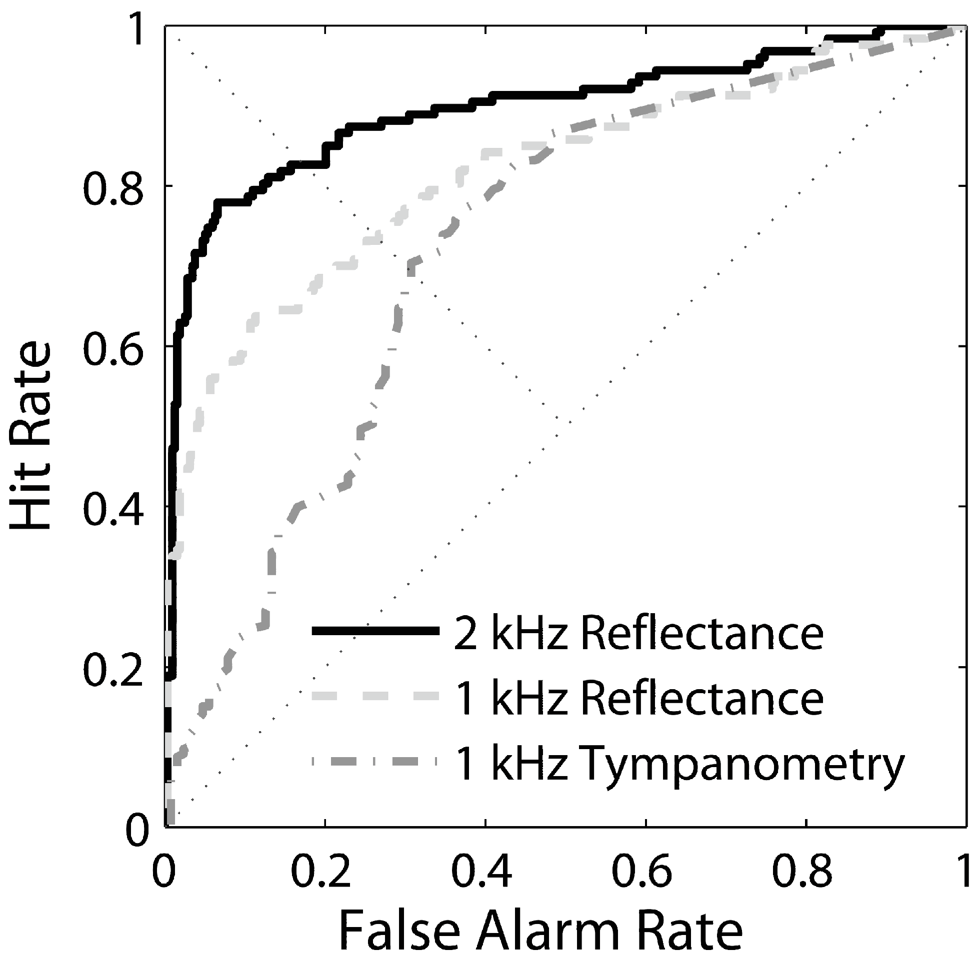


Fig 5 from Hunter et al. (2010)

Objective of tympanometry

- Estimate the TM compliance C_{tm} re normal
- Compliance is the inverse to stiffness:
  - Compliance - how easy to push
  - Stiffness - how hard to push
- Below 1 kHz, the TM and residual ear-canal volume are compliances, which add

$$C_{measured} = C_{canal} + C_{tm}$$

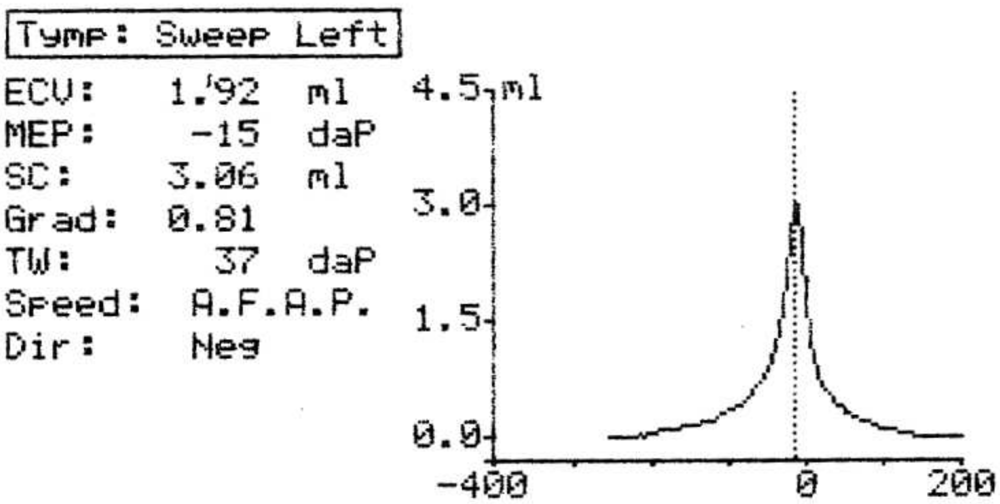
How does tympanometry work?

- At 226 Hz the measured compliance C_m is the sum of the compliance of the canal C_c and TM C_{tm}:

$$C_m = C_c + C_{tm} \rightarrow \widehat{C}_c \Big|_{\pm 200 \text{ dPa}}$$

where $\widehat{C}_c$ is the baseline estimate

- At $\pm$ 200 dPa, $C_{tm} \rightarrow 0$, thus $\widehat{C}_c \rightarrow C_m|_{\pm 200 \text{ dPa}}$
- Subtracting the baseline gives $C_{tm} = C_m - \widehat{C}_c$

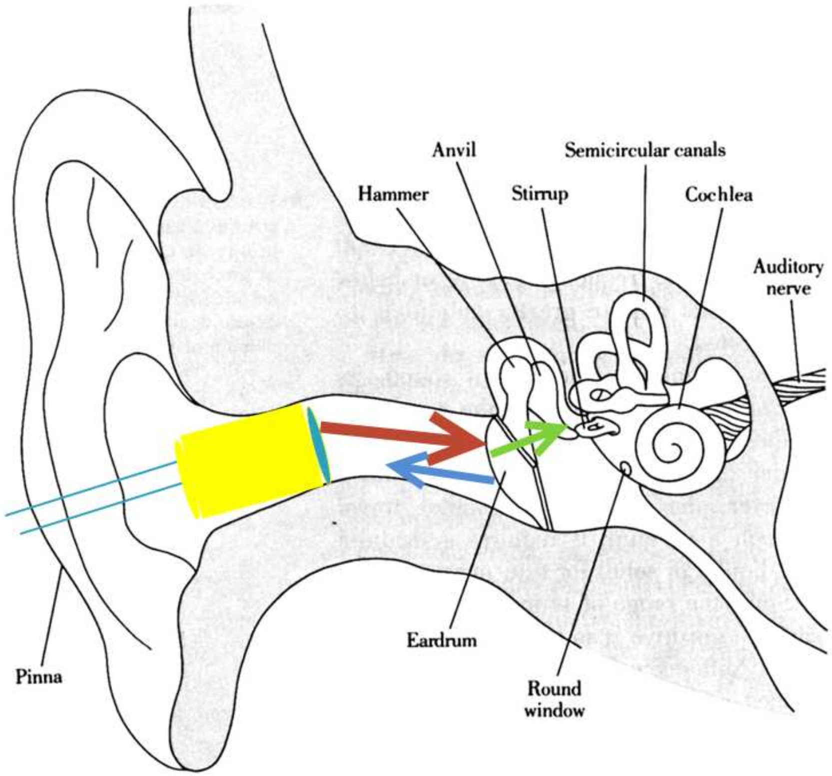


Tympanometry at higher frequencies

- Below 1 kHz, TM compliance C_{tm} characterizes the normal eardrum
- Critical diagnostic data is between 0.7-6 kHz (Refs).
- How about tympanometry at higher frequencies?
- One *can* do tympanometry at and below 1 kHz
- Above 1 kHz the interpretation is limited since
  - The TM not a compliance
  - The measured admittance $Y_m(f)$ is dominated by *standing waves*, again *due to the residual canal*
- The residual canal significantly distorts $Y_m(f)$
  - Thus no conclusions about TM admittance $Y_{tm}(f)$

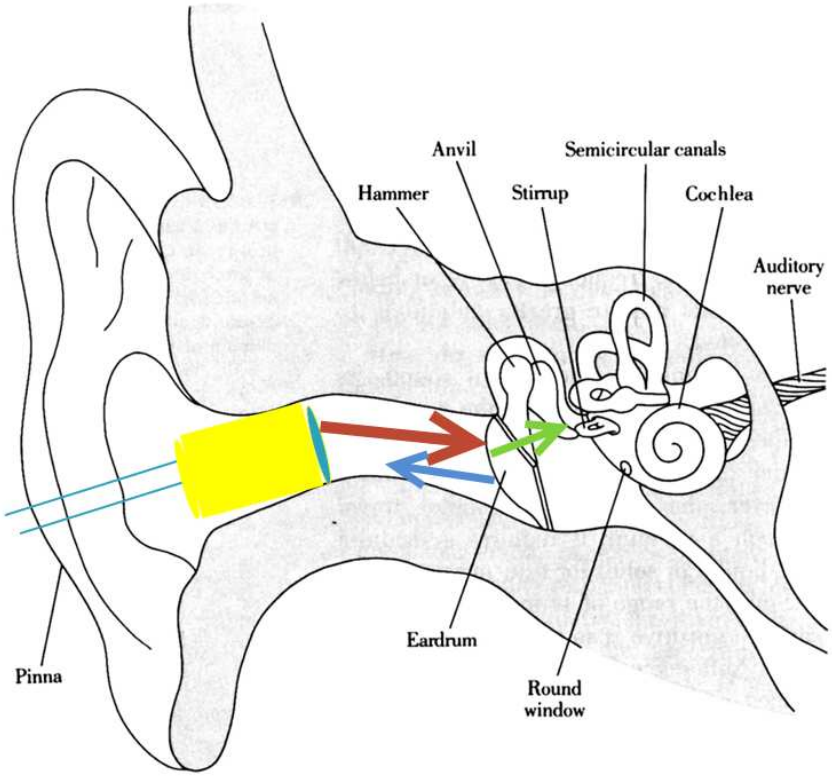
Wideband admittance: 0.2-6 kHz

- Measure wide-band admittance using a specially calibrated probe (pressurization not required)
  - Wideband chirp played in ear canal
  - Waves reflected from TM (i.e., standing waves!)
- Like tymp, admittance is strongly influenced by the residual ear canal volume, due to standing waves



Wideband reflectance: 0.2-6 kHz

- Reflectance is ratio of reflected to incident pressure
  - Reflectance has magnitude and phase (delay)
  - Phase is the due to the residual ear canal delay
- The *magnitude reflectance* is insensitive to the probe insertion depth (Voss *et al.*, 2008)



Removing the residual canal effect

Now have *two ways* to remove residual volume:

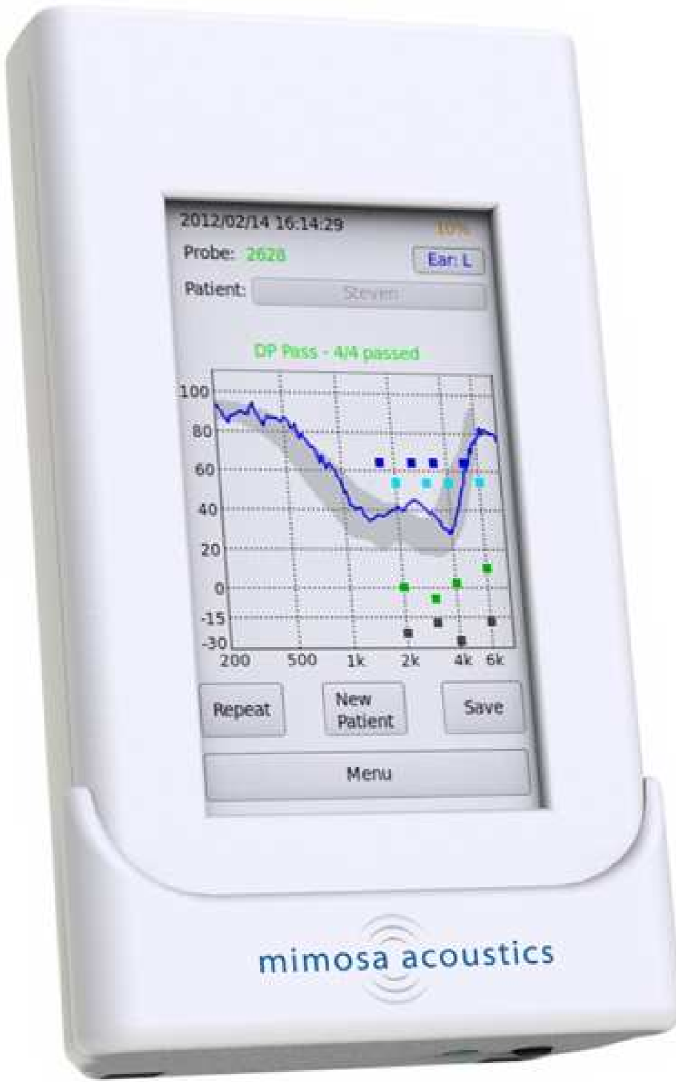
1. For tympanometry: subtract out baseline residual canal compliance
   - This only applies below 0.5 kHz (hence 226 Hz)
   - Between 0.5-1 kHz, calcellation unresolve? (Prieve *et al.*, 2012)
2. Take reflectance magnitude, which removes the round-trip residual ear canal delay (Voss *et al.*, 2008)
   - Phase removal applies at all frequencies

Wideband reflectance magnitude

Summary:

- Reflectance can be measured from 0.2 to 6 kHz
- |Reflectance| independent of probe depth
  (i.e., residual canal volume) (Voss *et al.*, 2008)
- Basic Assumption: the residual ear canal is lossless
- Removing the canal delay (i.e., phase) removes the residual ear canal effect, at all frequencies
- Grand Summary:
  This allows for new diagnostic opportunities
  (as demonstrated in the Refs)

Wideband reflectance on the OtoStat



Practical considerations

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

References

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