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 $\approx 0.5$ 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 clinical 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) ($V_c = C_c \times 1.4 \times 10^8$ 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
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.
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: \( Y_{\text{peak}}, Y_{+\text{ME}}, Y_{-\text{ME}}, Y_{\text{to} \,-\text{tail}}, Y_{\text{to} \,+\text{tail}} \)
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 $C_{tm}$:

$$C_m = C_c + C_{tm} \rightarrow \hat{C}_c \mid \pm 200 \text{ dPa}$$

where $\hat{C}_c$ is the baseline estimate.

- At $\pm 200$ dPa, $C_{tm} \rightarrow 0$, thus $\hat{C}_c \rightarrow C_m \mid \pm 200 \text{ dPa}$

- Subtracting the baseline gives $C_{tm} = C_m - \hat{C}_c$
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, cancellation unresolved? *(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
- $|\text{Reflectance}|$ 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


