Effects of static negative middle-ear pressure on wideband acoustic immittance

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Positive middle ear pressure (NMEP)

- NMEP can affect other acoustic measurements of hearing (e.g. otoacoustic emissions)
- Static NMEP is very common
  - It is typically due to Eustachian tube dysfunction
  - It often occurs concurrently with middle ear fluid or infection
- Middle ear pressure in normal ears varies often
  - It is slightly negative during waking hours
  - A NMEP smaller than -100 [daPa] is considered ‘normal’
Wideband acoustic immittance (WAI)

- WAI refers to a set of quantities, including the admittance, impedance, reflectance, absorbance, etc.
- Many applications consider the power reflectance and absorbance ($\approx$ independent of ear canal length)

\[ |\Gamma(f)|^2 = \left| \frac{p_{\text{reflected}}(f)}{p_{\text{incident}}(f)} \right|^2 \]

\[ |\Gamma(f)|^2 \approx |\Gamma_{tm}(f)|^2 \]

\[ A(f) = 1 - |\Gamma(f)|^2 \]
Methods

• WAI was measured with ambient ear canal pressure

• Subjects with normal middle ears induced negative middle ear pressure (NMEP) via the Toynbee maneuver

• Middle ear pressure was assessed separately via tympanometry
  – Middle ear pressure = tympanic peak pressure (TPP)

  – 8 trials at ambient middle ear pressure (AMEP) were alternated with 8 trials at NMEP

  – Subjects were able to induce consistent NMEPs

• We focus on individual ears (lots of retest data)
Methods

Tympanic Peak Pressures (TPPs)

TPP [daPa]

S1  S2  S3  S4  S5  S6  S7  S8

AMEP
NMEP
WAI Results: Power Absorbance

Absorbance Level

$1 - |\Gamma|^2 [\text{dB}]$

$S1$

$-65 [\text{daPa}]$

$S5$

$-144 [\text{daPa}]$

Frequency [kHz]

$1 - |\Gamma|^2$

AMEP

NMEP
WAI Results: Power Absorbance
Wideband changes in power absorbance due to NMEP...

- vary in both magnitude and frequency range
- do not appear to have a simple dependence on pressure
WAI Results: Power Absorbance

![Graph showing absorbance level versus frequency with error bars and different mean values for AMEP and NMEP, along with shaded areas indicating standard deviation.](image)
WAI Results: Power Absorbance

Absorbance Level

Frequency [kHz]

1 - |Γ|^2 [dB]

1 - |Γ|^2

Rosowski et al., 2012
Mean, NMEP
Mean, AMEP
± 1 SD, NMEP
± 1 SD, AMEP
Dependence on static ME pressure

Absorbance Level vs. Tympanic Peak Pressure (TPP)

\[ A(f) [\text{dB}] = -2.54TPP^2 + 0.02TPP + 0 \]
\[ r^2 = 0.81 \]

Average \( A(f) [\text{dB}] \) (0.8-1.9 [kHz])

TPP [daPa]

AMIPE

NMEP
WAI at the tympanic membrane (TM-WAI)

- The unknown residual ear canal (REC) delay may be removed from the reflectance phase (Robinson et al., 2013)
- Using our methods, $\Gamma_{rec}(f)$ may account for a lossless REC of varying area

\[
\Gamma(f) = \Gamma_{rec}(f) \times \Gamma_{tm}(f)
\]

\[
|\Gamma(f)| = 1 \times |\Gamma_{tm}(f)|
\]
WAI at the tympanic membrane (TM-WAI)

- At low frequencies, the REC volume is approximated by a compliance.
- A resistor is necessary to match the transmission lines of the middle ear and cochlea (Zwislocki 1962, Lynch 1982)

\[ \Gamma(f) = \Gamma_{\text{rec}}(f) \times \Gamma_{\text{tm}}(f) \]

\[ |\Gamma(f)| = 1 \times |\Gamma_{\text{tm}}(f)| \]

Low frequency approximation
TM-WAI: Impedance

TM Impedance Magnitude

$\frac{|Z_{tm}(f)|}{r_0}$

Frequency [kHz]

S6
-156 [daPa]
TM-WAI: Impedance

The diagram illustrates the TM impedance magnitude and the real and imaginary parts of the impedance over frequency. The graphs show how the impedance changes with frequency, with specific labels indicating the real and imaginary components.

The circuit diagram on the left includes components labeled $C_{tm}$ and $r_c$, indicating the elements involved in the impedance measurement. The labels $S6 \ -156$ [daPa] are referenced in the graphs, possibly indicating specific data points or conditions.

The graphs are labeled with $|Z_{tm}(f)/r_0|$ for the magnitude and $r_c$ for the real part, with corresponding frequency ranges from 0.5 to 5 kHz.

The diagram provides a visual representation of how the impedance behaves under different frequencies, which is crucial for understanding the acoustic properties in the context of TM-WAI.
TM-WAI: Impedance

\[ Z_{tm}(f) = r_c \left( -\frac{1}{2\pi f C_{tm}} \right) \]

**TM Impedance Magnitude**

**TM Impedance: Real & Imaginary**

\[ r_c \]

\[ -1/2\pi f C_{tm} \]
TM-WAI: Impedance

TM Impedance Magnitude

NMEP = -156 [daPa]

Real & Imaginary parts of $Z_{tm}(f)/r_0$

- Real
- Imaginary

NMEP = -156 [daPa]
Residual ear canal (REC) volume

- The REC volume does not depend on NMEP

![Diagram of ear canal model with parameters Crec, Ctm, and rc.](image)

![Bar graph showing residual ear canal volumes for AMEP and NMEP.](image)
TM Compliance

- The REC volume **does not** depend on NMEP
- The TM compliance **does** depend on NMEP
Mechanisms for NMEP-dependent change

- NMEP decreases the compliance $C_{tm}$ at the tympanic membrane (TM)

- The TM is retracted (Shaver & Sun 2013, Voss et al. 2012)
  - Often assumed to be the main source of compliance change
  - The TM acts as a delay line in normal ears (Puria & Allen 1998)

- Nonlinear compliance is likely related to middle ear ligaments
  - WAI changes due to NMEP resemble stiffened annular ligament (AL) changes (e.g. acoustic stapedius reflex, Feeney & Keefe 1999)
  - The tensor tympani (TT) may cause similar WAI changes to the AL (Møller 1983, Bance et al. 2013, Aron et al. 2015), but little data exists to quantify this in human ears
Conclusions

• We can directly estimate the complex WAI at the TM
  – The residual ear canal delay (independent of NMEP) is removed

• WAI changes due to NMEP vary in magnitude and frequency range
  – The most significant decrease in power absorbance level occurs from 0.8-1.9 [kHz]
  – TPP is a significant but imperfect predictor of WAI change

• The aggregate middle ear compliance $C_{tm}$ decreases due to NMEP
  – WAI change is well described by a simple model
  – This does not require selective averaging of frequency bands
Clinical Implications

• WAI is not a strong predictor of NMEP level (typically measured by TPP)
  – However, we can evaluate Eustachian tube function using WAI

• WAI provides frequency-specific information about middle ear transmission that tympanometry does not

• Changes in WAI due to NMEP are generally too small to impact hearing thresholds, however...
  – Can affect measurement of otoacoustic emissions (OAEs), due to forward and reverse transmission through the middle ear
  – We predict that frequency-specific changes in DPOAEs/TEOAEs are related to changes in WAI
Thanks for listening!

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