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

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Negative middle ear pressure (NMEP)

- Static NMEP is very common
  - Typically due to Eustachian tube dysfunction
  - Often occurs concurrently with middle ear fluid or infection

- Middle ear (ME) pressure in normal ears varies
  - slightly negative during waking hours
  - a TPP smaller than -100 [daPa] is ‘normal’

- NMEP can affect other acoustic measurements such as otoacoustic emissions (OAEs)

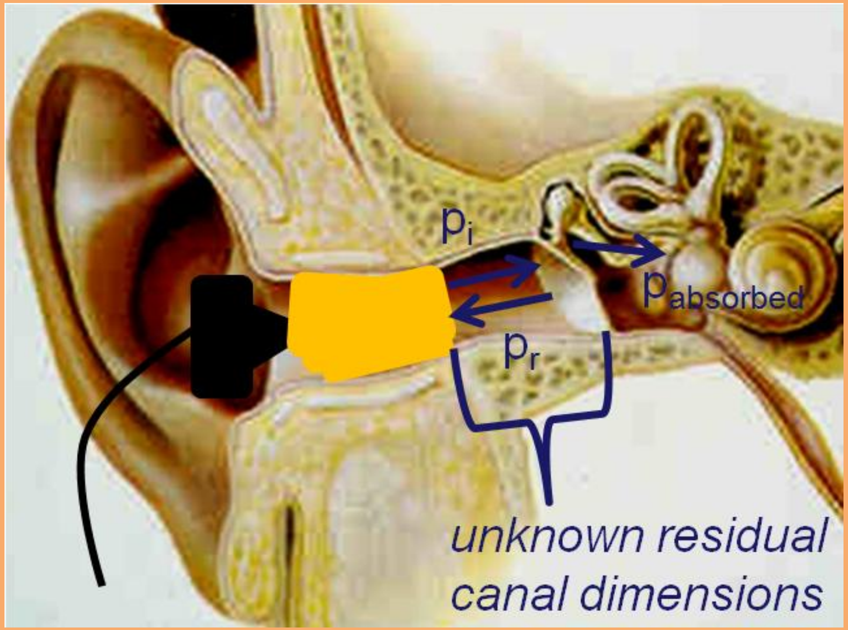
Wideband acoustic immittance (WAI)

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

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

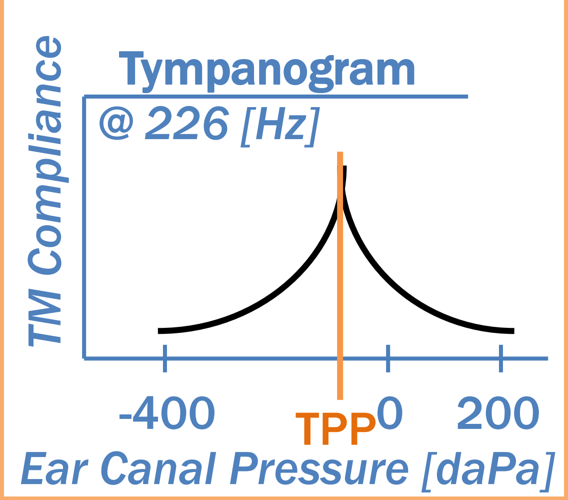
$$|\Gamma(f)|^2 \approx |\Gamma_{tm}(f)|^2$$

$$A(f) = 1 - |\Gamma(f)|^2$$



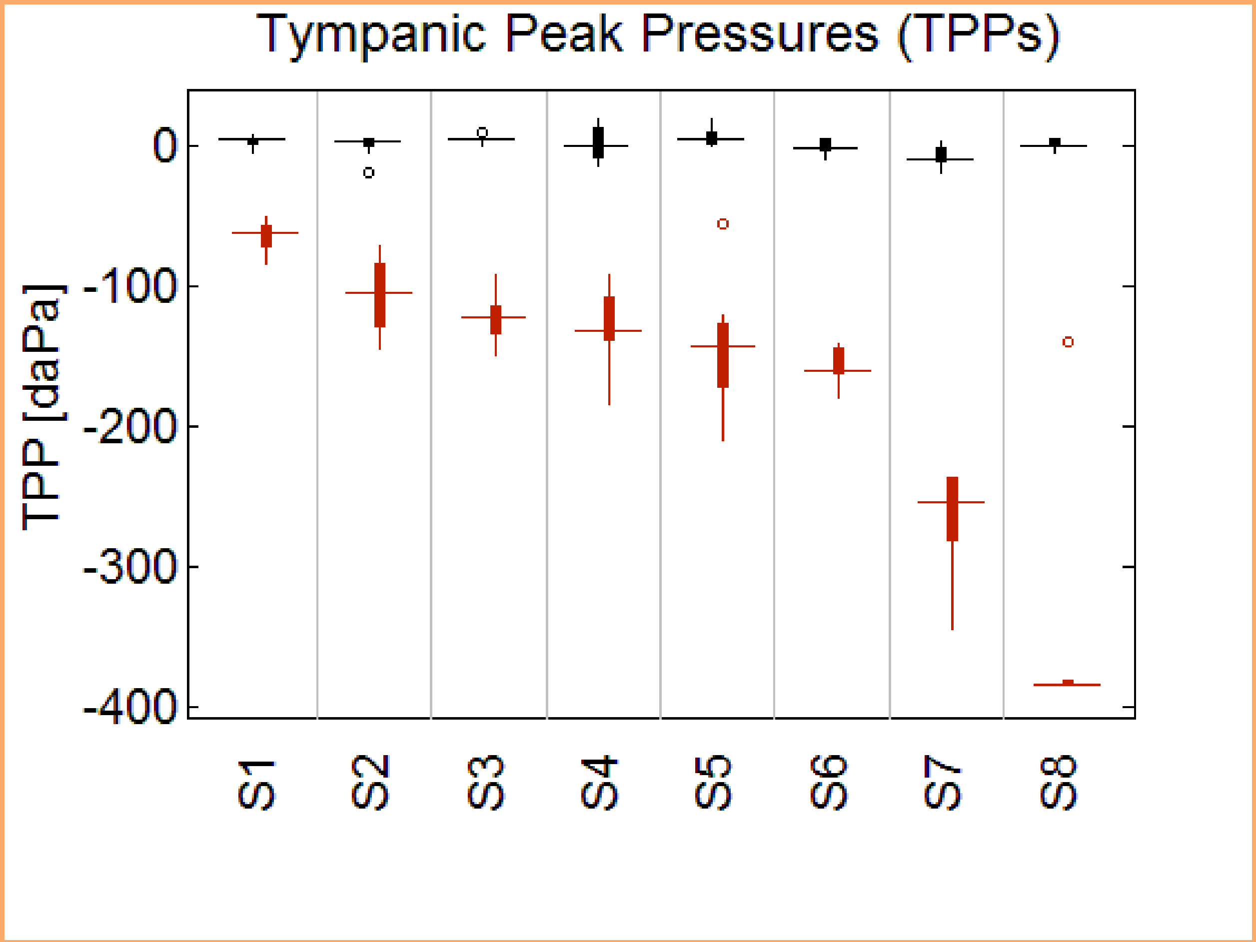
Experiment

- WAI was measured with ambient canal pressure
- Subjects with normal middle ears induced NMEP via the Toynbee maneuver (Sun & Shaver 2009, 2013)
- ME pressure was assessed separately via tympanometry
  - ME pressure = tympanic peak pressures (TPP)
  - 8 trials at ambient middle ear pressure (AMEP) were alternated with 8 trials at NMEP
  - Subjects were able to induce consistent NMEPs

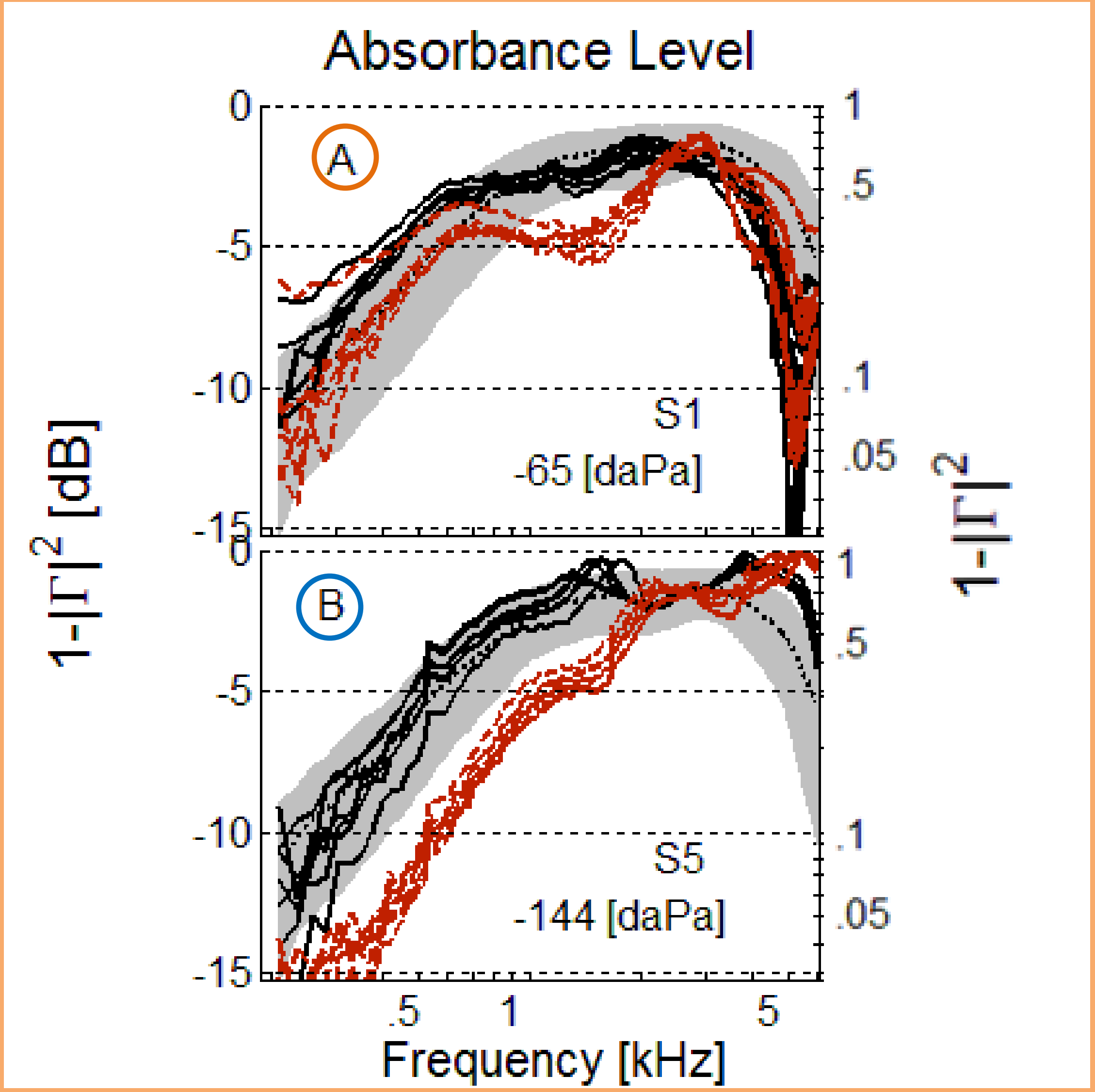


- Focus on individual ears (lots of retest data)

Experiment


Tympanic Peak Pressures (TPPs)
TPP [daPa]
0
-100
-200
-300
-400
S1
S2
S3
S4
S5
S6
S7
S8

WAI Results: Power Absorbance



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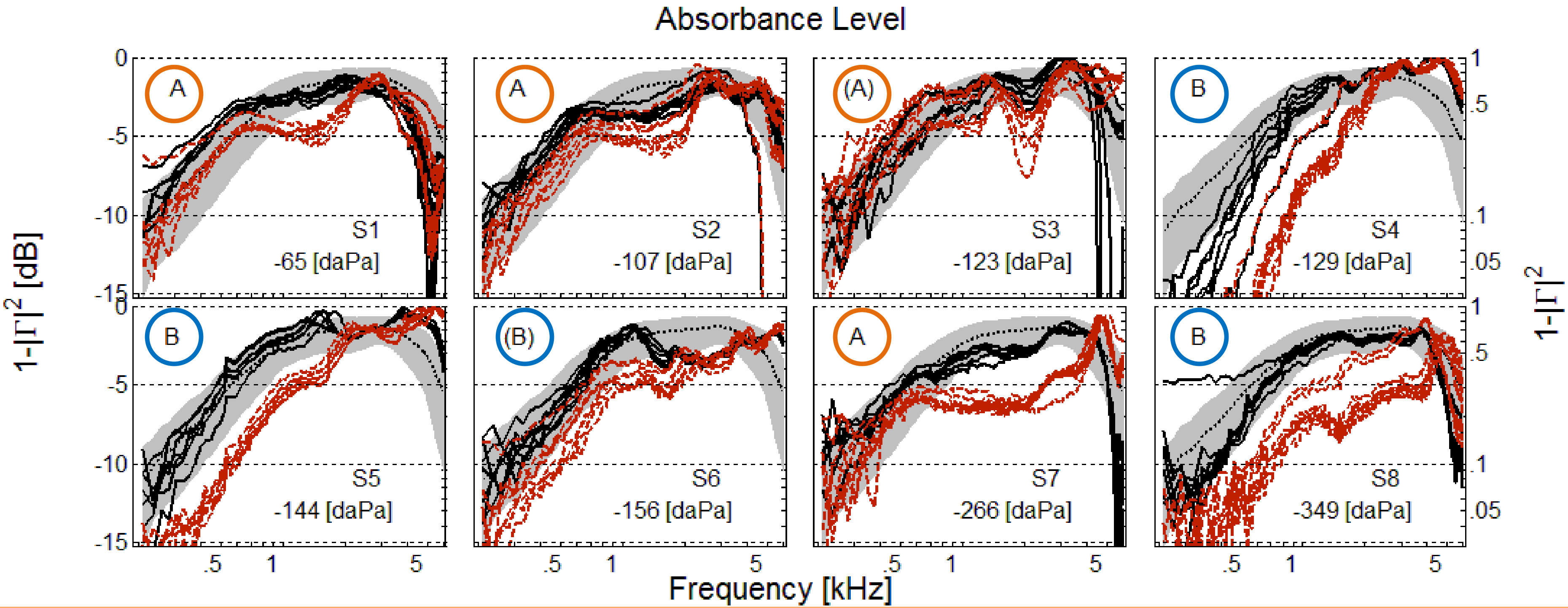
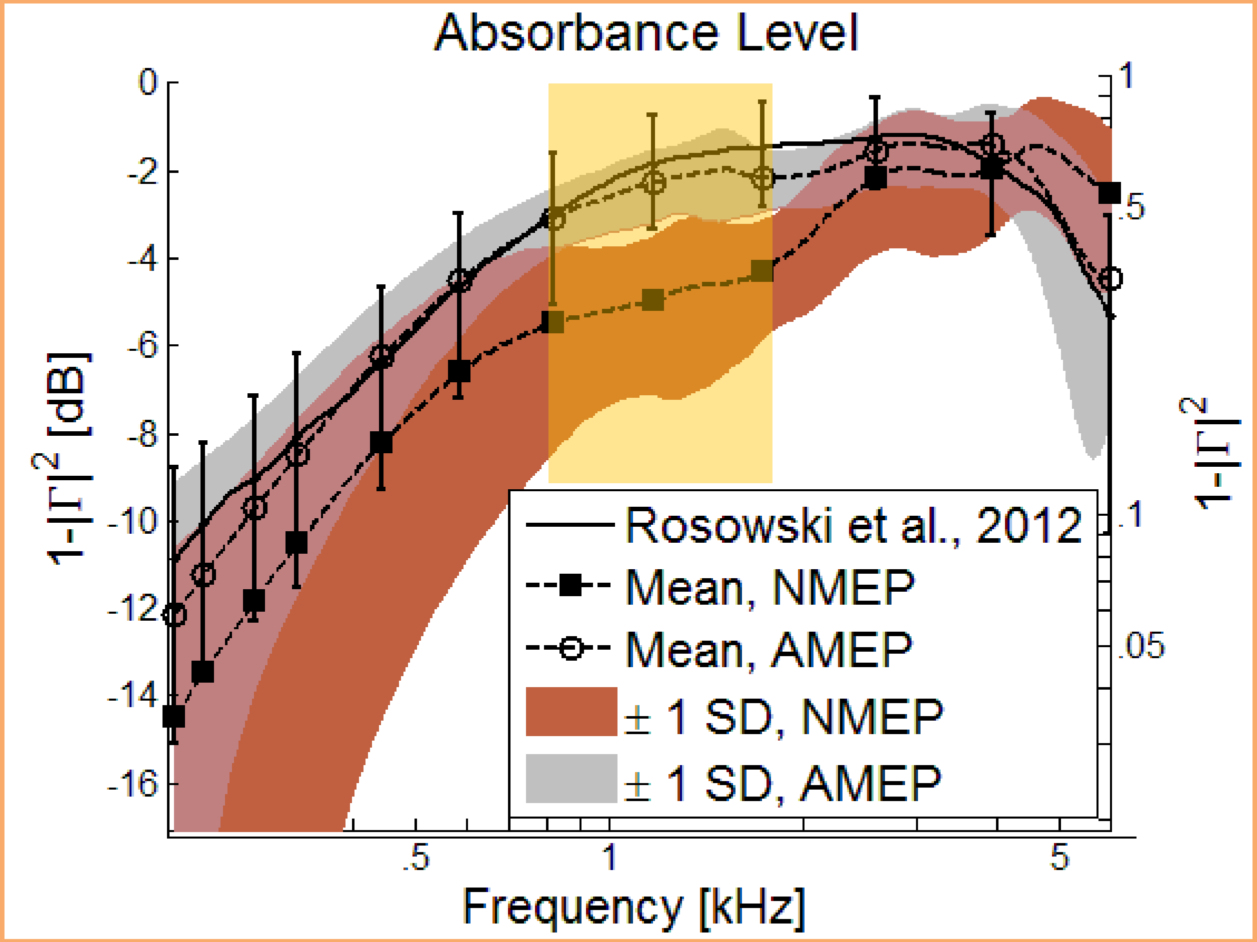


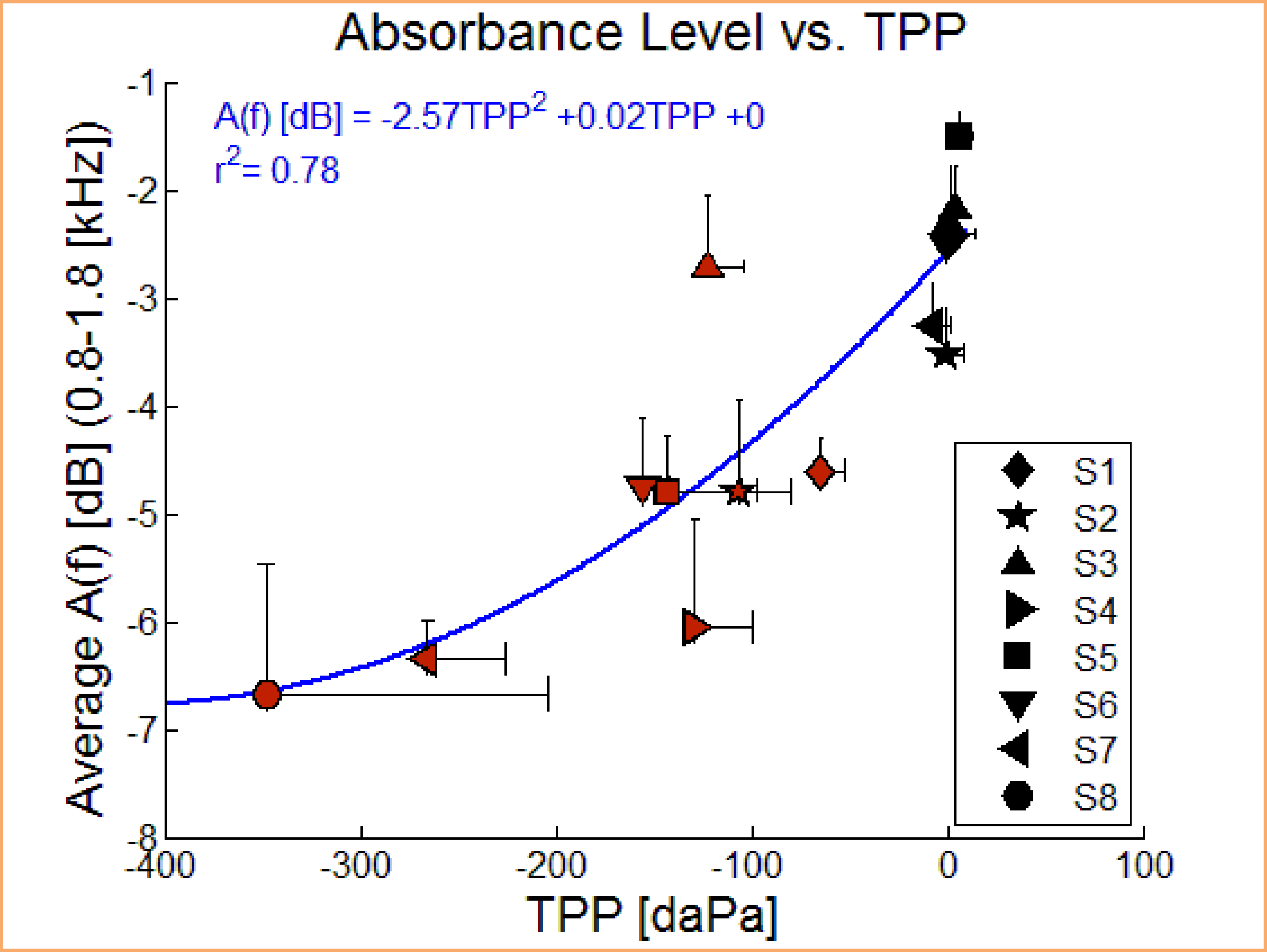
Wideband changes in power absorbance due to NMEP…

- **vary in both magnitude and frequency range**
- **do not appear to have a simple dependence on TPP**

WAI Results: Power Absorbance

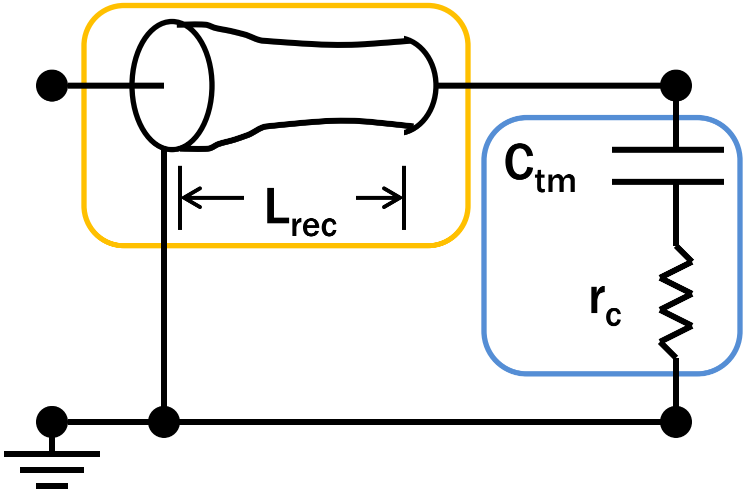


Dependence on static ME pressure



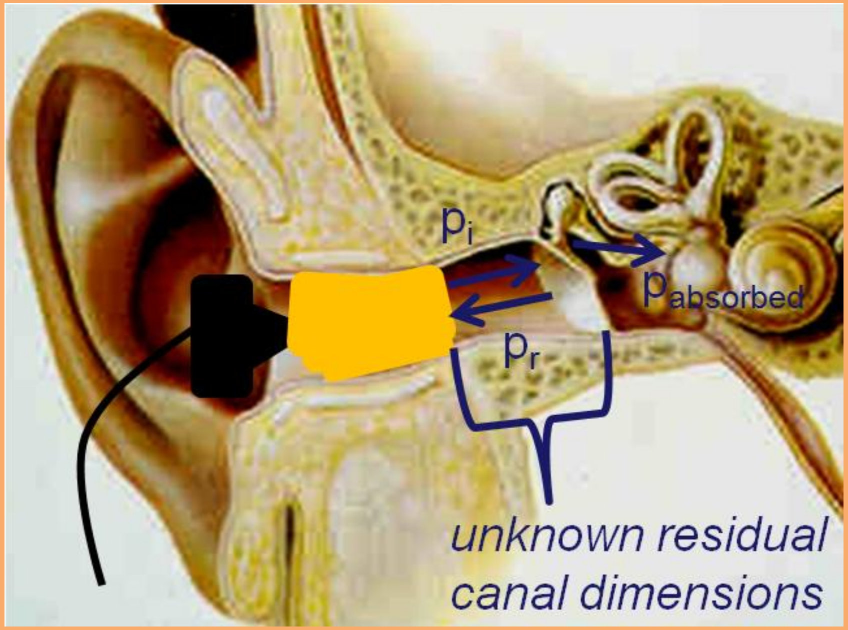
WAI at the tympanic membrane (TM-WAI)

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



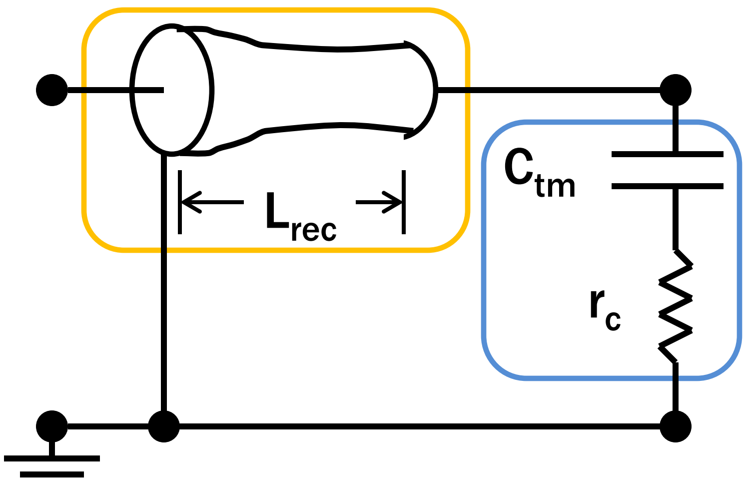
$$\Gamma(f) = \Gamma_{rec}(f) \times \Gamma_{tm}(f)$$

$$|\Gamma(f)| = 1 \times |\Gamma_{tm}(f)|$$



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)



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

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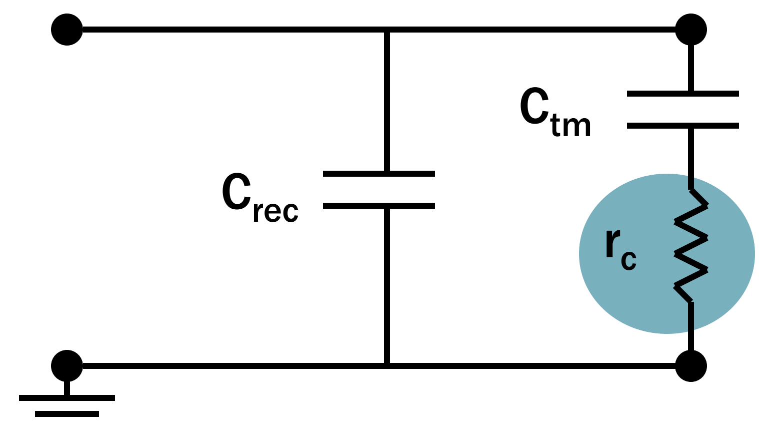
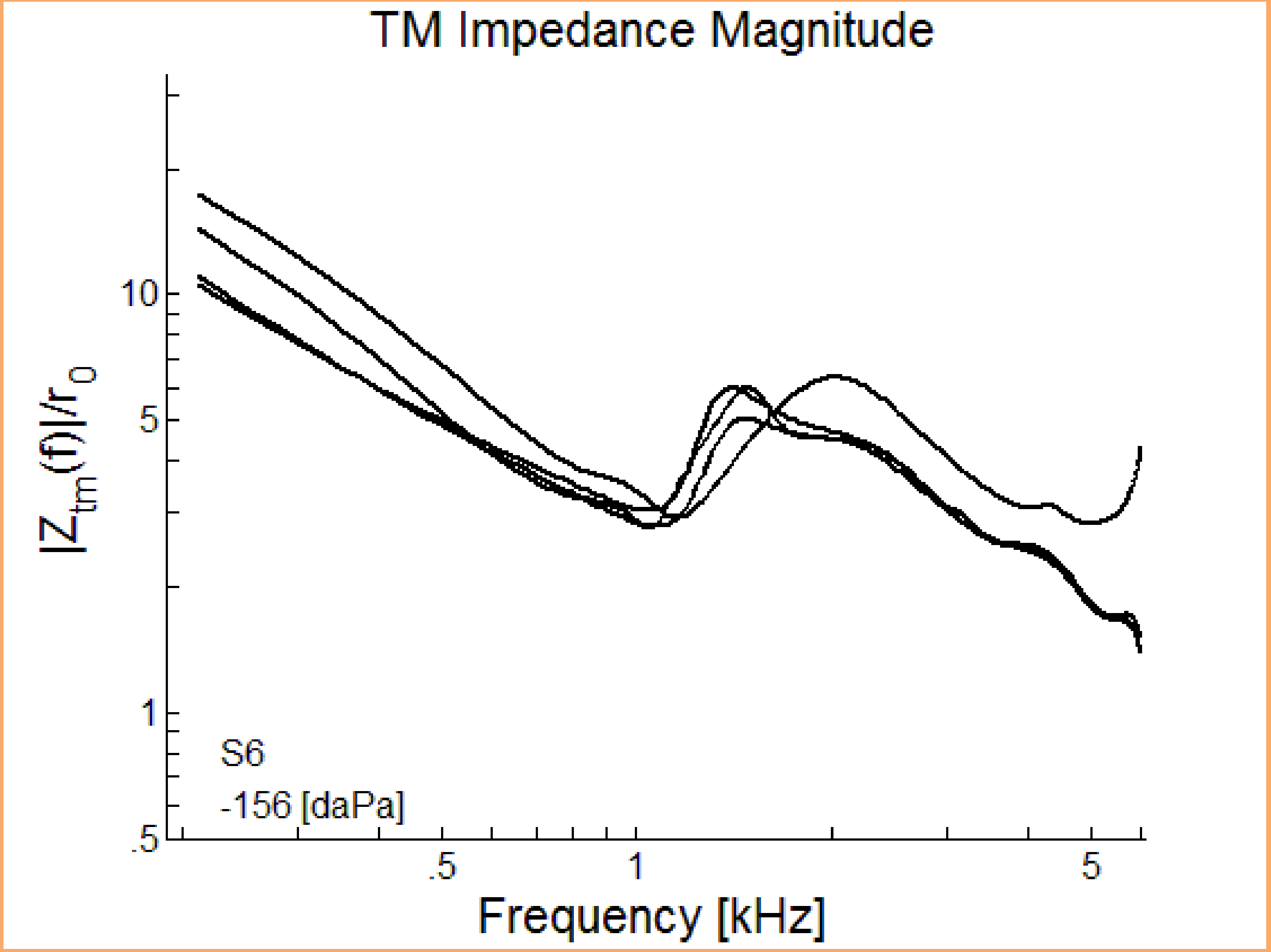
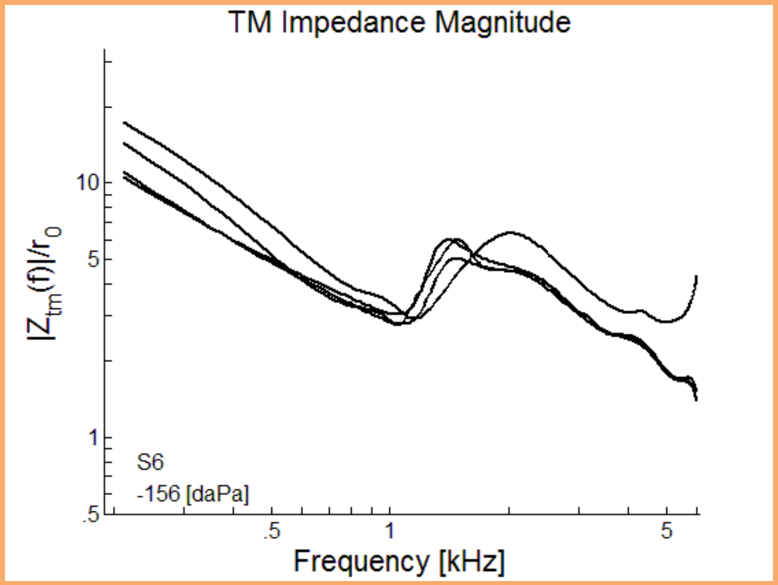


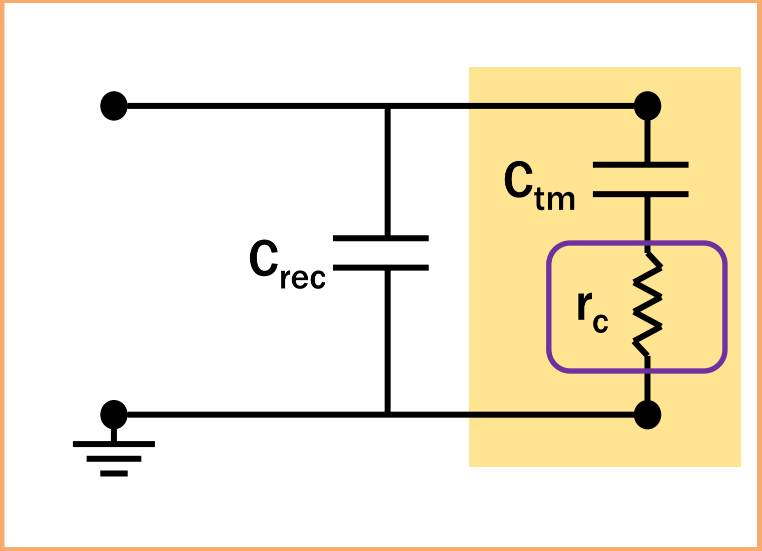
Low frequency approximation

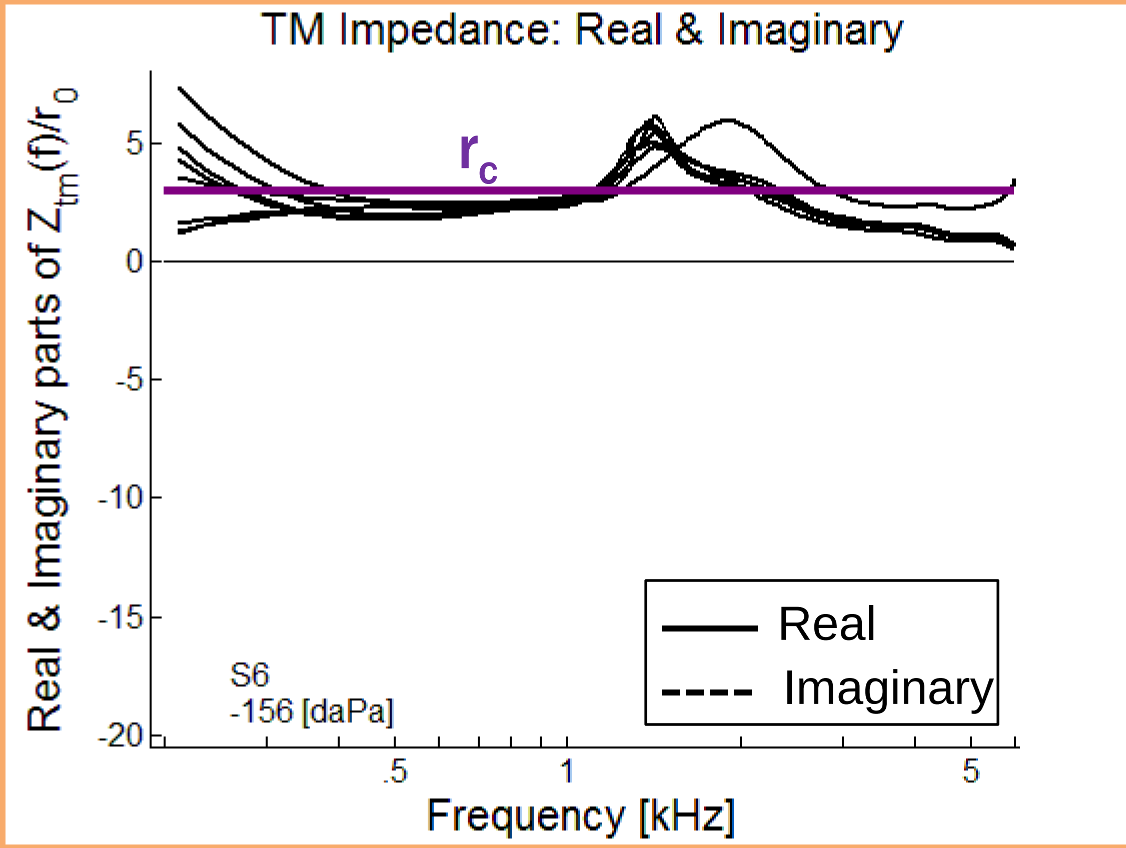
TM-WAI: Impedance



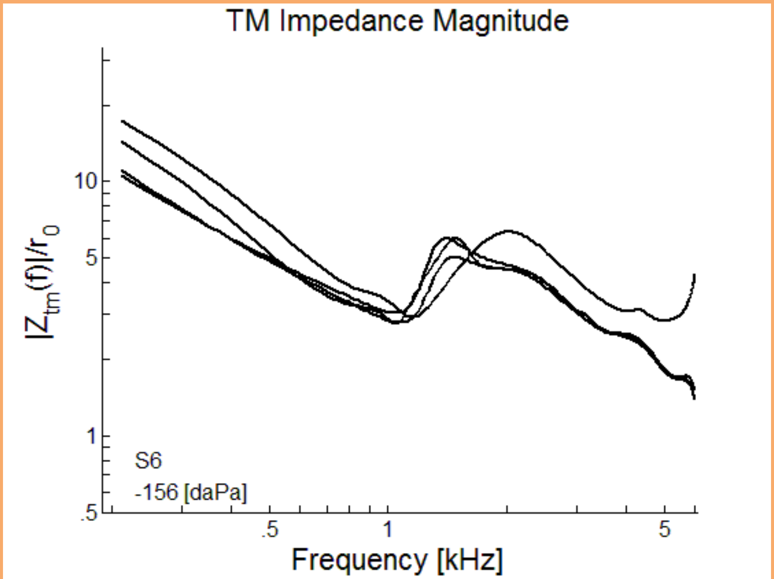
TM-WAI: Impedance

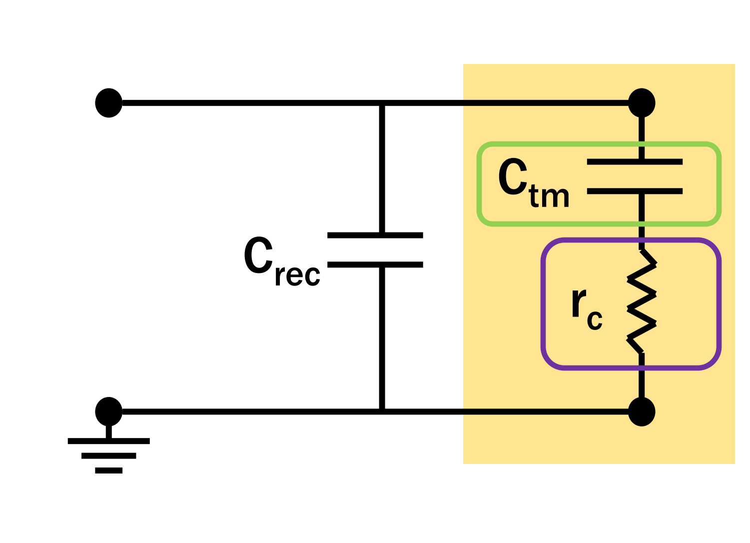


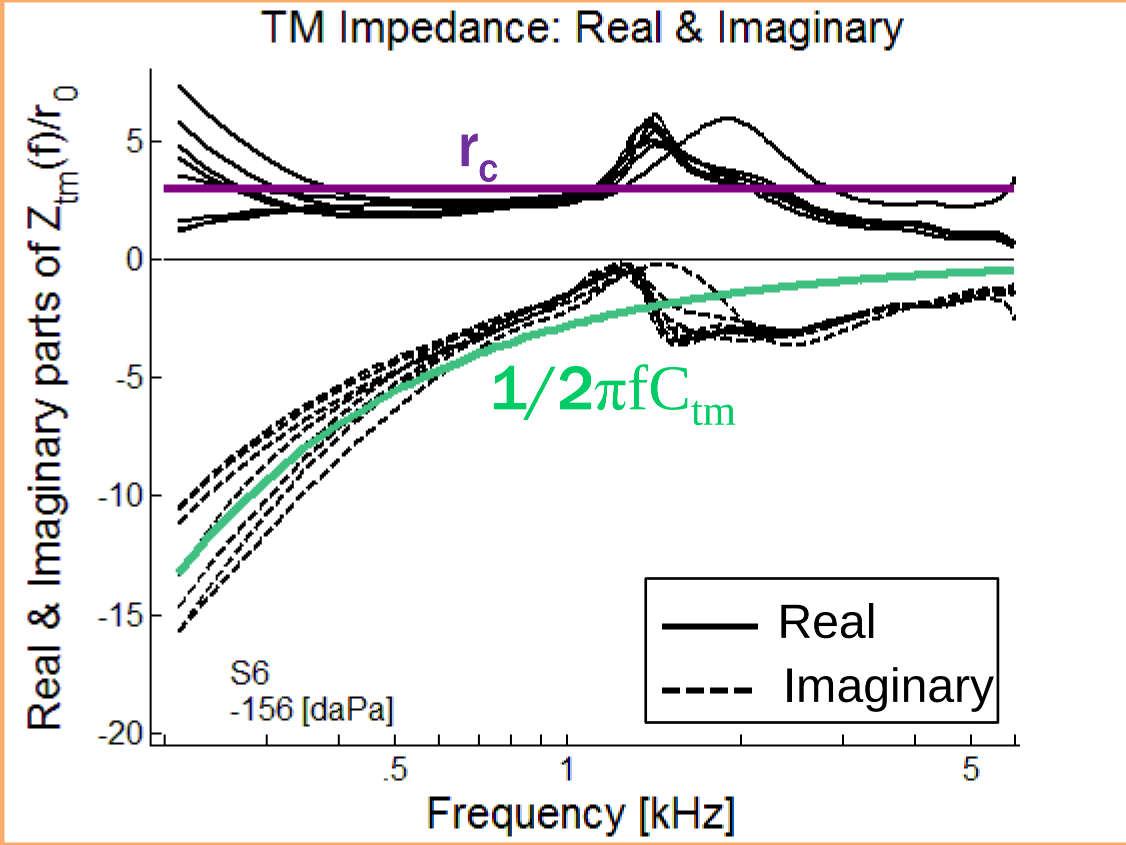




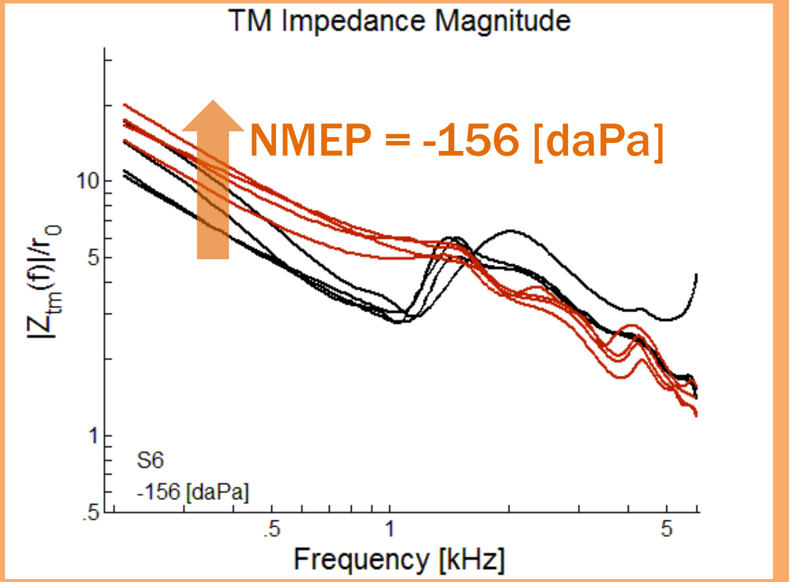
TM-WAI: Impedance

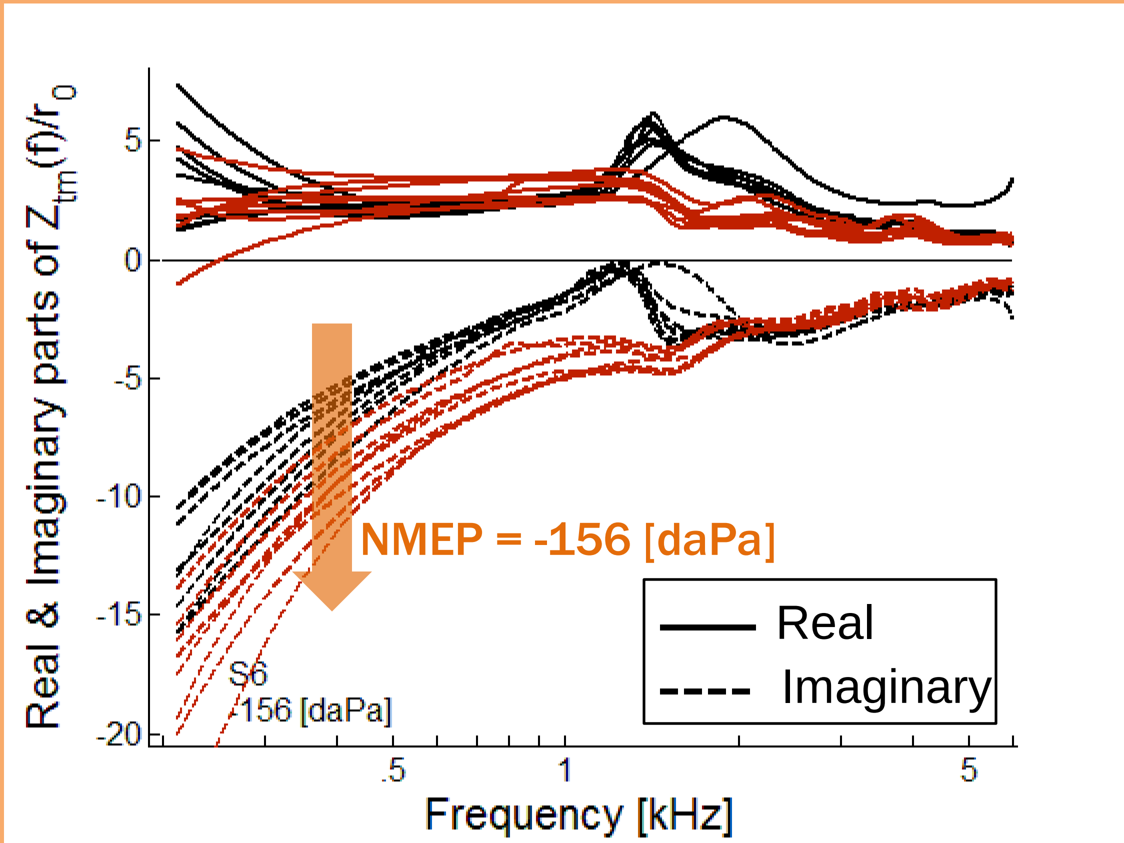




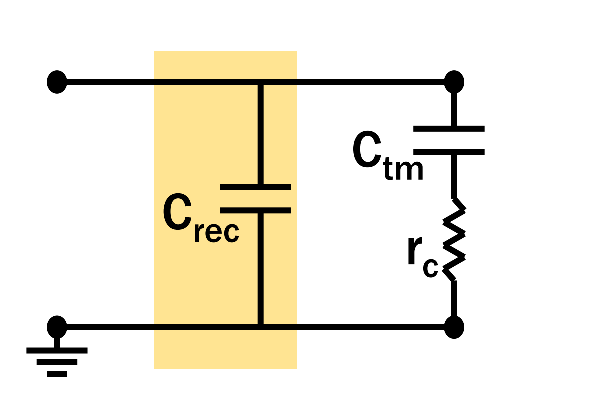


TM-WAI: Impedance

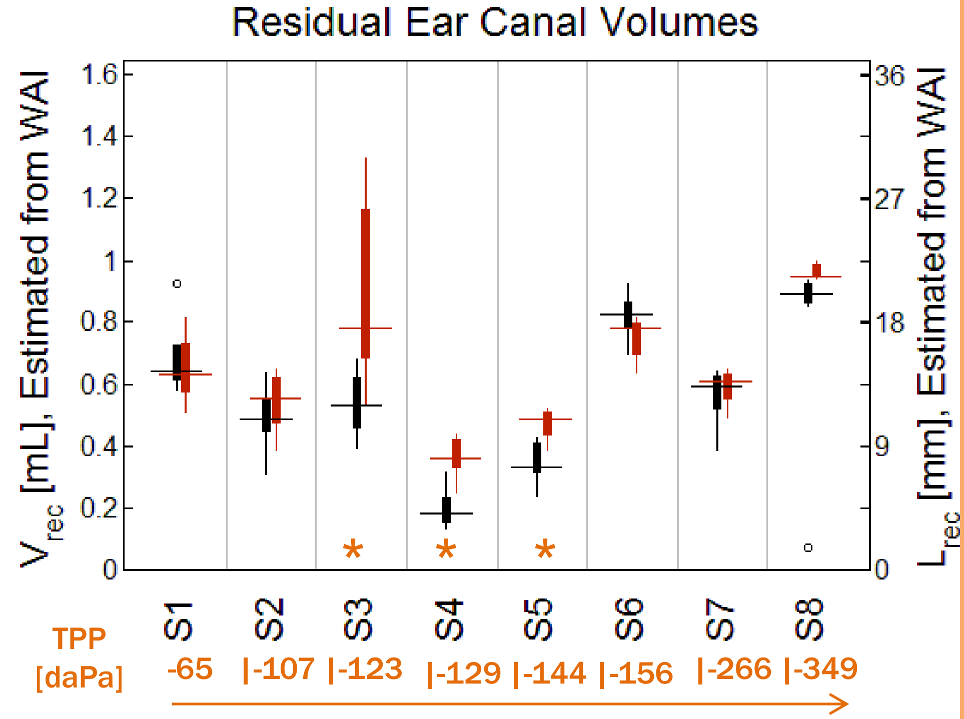




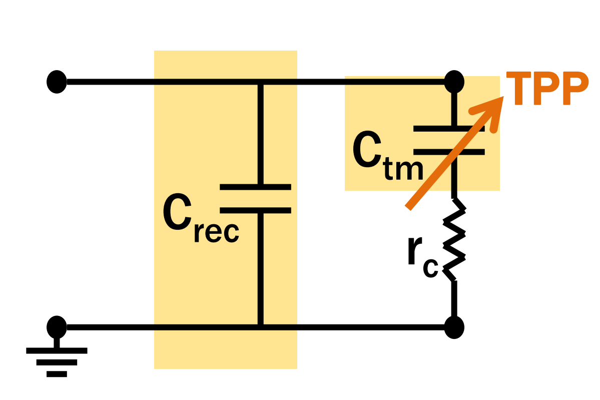
Residual ear canal (REC) volume



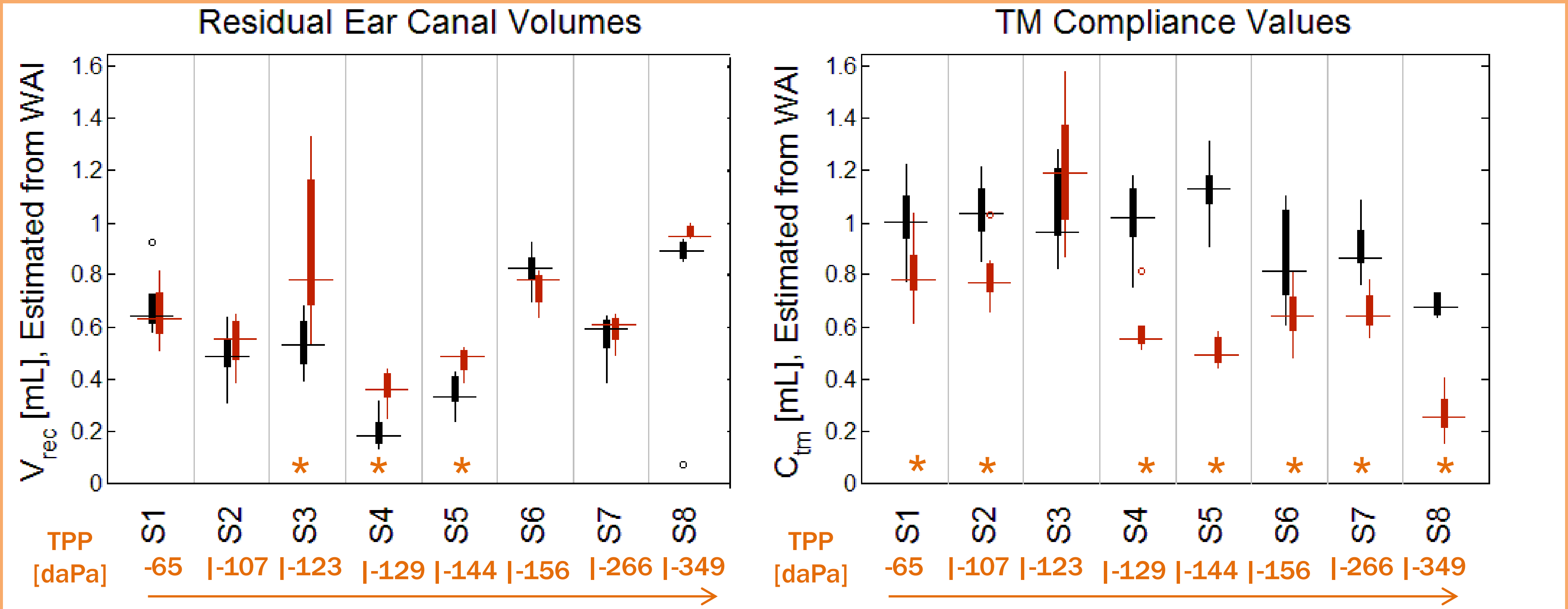
- The REC volume does not depend on NMEP



TM Compliance



- The REC volume does not depend on NMEP
- The TM compliance does depend on NMEP



Mechanisms for NMEP-dependent change

- Decreased compliance (increased stiffness) at the TM could be due to multiple ME structures
- WAI changes resemble data with a stiffened annular ligament (AL) (e.g. acoustic reflex)
- NMEP causes a retraction of the TM (Shaver & Sun 2013, Voss et al. 2012)
  - The TM itself functions primarily as a delay line in normal ears (*Puria & Allen 1998*)
  - Nonlinear changes most likely associated with ligaments (*reference?*)
  - Tensor tympani effects expected to be similar to AL effects, but little data exists to quantify this in humans *(Møller 1983)*

Conclusions

- NMEP causes the largest change in the power absorbance $(1-|\Gamma|^2)$ from 0.8-1.8 [kHz]
- TPP is a significant, but imperfect predictor of WAI change
  - The relationship between Absorbance and TPP is nonlinear
- WAI changes due to NMEP…
  - Vary in magnitude and frequency range
  - Are consistent with an increased stiffness in the ME, potentially related to the annular ligament and TM-malleus coupling
- The WAI magnitude & phase at the TM are estimated
  - REC volume is effectively removed
  - TM-WAI simply modeled by a compliance and a resistance
  - The TM compliance is highly dependent on NMEP, as expected (but not well predicted by TPP)

Clinical implications

- Severity of WAI changes due to NMEP is highly individual
- WAI changes indicate ears where other measures (e.g. DPOAEs) could be compromised, in a frequency-specific manner
- We can remove the ear canal volume and estimate TM compliance C_{tm} analogous to tympanometry

Thanks for listening!

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References

1. Lynch III, T. J., Nedzelnitsky, V., Peake, W. T. (1982). Input impedance of the cochlea in cat. *J Acoust Soc Am*, *72(1),* 108–130.
2. Møller, A. R. (1983). *Auditory Physiology*. Academic Press, Inc., New York, New York.
3. Puria, S. & Allen, J. B. (1998). Measurements and model of the cat middle ear: evidence of tympanic membrane acoustic delay. *J Acoust Soc Am, 104,* 3463–3481.
4. Robinson, S. R., Nguyen, C. T., Allen, J. B. (2013). Characterizing the ear canal acoustic impedance and reflectance by pole-zero fitting. *Hear Res*, 301, 168–182.
5. Rosowski, J. J., Nakajima, H. H., Hamade, M. A., et al. (2012). Ear-canal reflectance, umbo velocity, and tympanometry in normal- hearing adults. *Ear Hear*, *33(1),* 19–34.
6. Shaver, M. D. & Sun, X. M. (2013). Wideband energy reflectance measurements: effects of negative middle ear pressure and application of a pressure compensation procedure. *J Acoust Soc Am*, *134(1),* 332–341.
7. Sun, X. M. & Shaver, M. D. (2009). Effects of negative middle ear pressure on distortion product otoacoustic emissions and application of a compensation procedure in humans. *Ear Hear*, *30(2),* 191–202.
8. Voss, S. E. , Merchant, G. R., Horton, N. J. (2012). Effects of middle-ear disorders on power reflectance measured in cadaveric ear canals. *Ear Hear, 33(2),* 195–208.
9. Zwislocki, J. (1962). Analysis of the middle-ear function. Part I: Input impedance. *J Acoust Soc Am*, *34*, 1514–1523.