Forward-pressure level calibration improves accuracy and reliability of pure-tone audiometry

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Audiogram reliability

- Pure-tone audiometry is less reliable above 4 [kHz] (Dobie, 1983)

- Headphone/earphone fittings, and individual-ear acoustics cause stimulus levels to vary from target

- Early noise-induced hearing loss occurs at high frequencies
  - Test-retest reliability limits the detection of a *significant threshold shift* (STS) (Lapsley Miller 2004, Dobie 2005)
  - Hearing conservation programs (HCPs) typically do not use 6-8 [kHz] due to reliability

Traditional stimulus calibration

- Pure-tone audiometry is conducted using headphones (e.g. TDH-39) or insert earphones (e.g. ER-2,3)

- Calibrated using an ear simulator "coupler" (average normal ear)
  - Individual-ear acoustics can vary considerably from average
  - Sound pressure level (SPL) depends on enclosed volume

- TDH-39 is widely used, despite high variability at 6 [kHz]

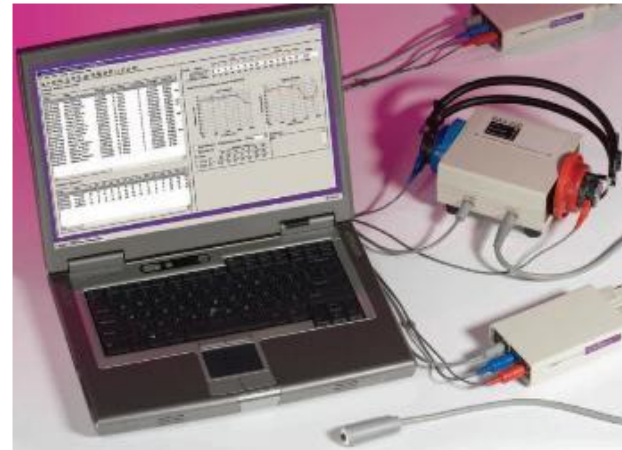
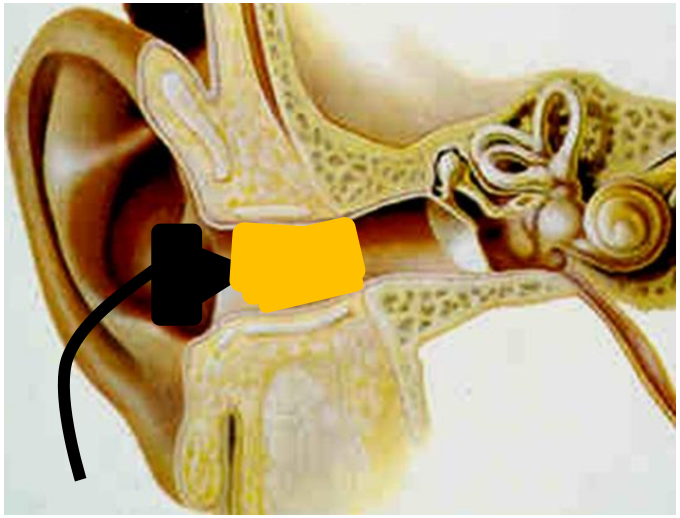


Image credit: Benson Medical Instruments, Etymotic Research

In-the-ear (ITE) calibration

Using probes (earphone + microphone) designed for otoacoustic emissions (OAE) testing, we can calibrate the probe *in situ*

- Evaluate the acoustics of an individual ear (e.g. "real-ear calibration")
- Set the stimulus level based on microphone measurements



However, acoustic standing waves (SWs) in the ear canal above 4 [kHz] cause large variations in the microphone pressure

Ear-canal standing waves

- *Standing waves* (SW) are due to eardrum-probe reflections
- The probe pressure is a sum of forward (+) and reverse (-) waves

$$P = P^+ + P^-$$

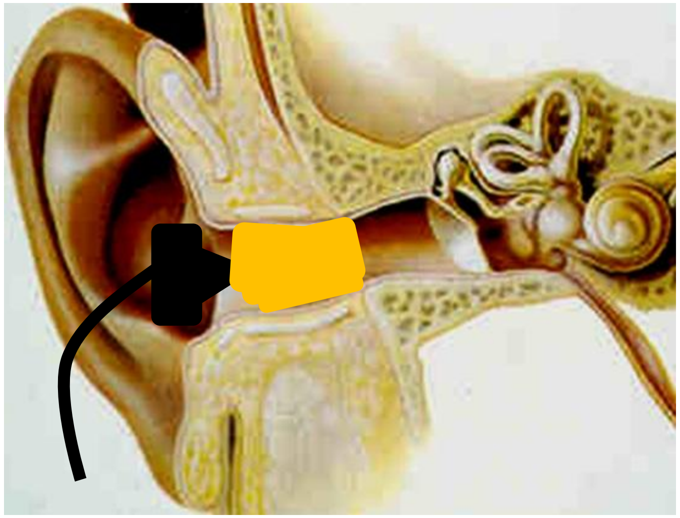
Depending on their relative phase, P^+ and P^- can largely cancel

- The SW frequency is related to a distance of $\lambda/4$ (4 [kHz] $\leftrightarrow$ 22 [mm])
  - SW frequency decreases as ear-canal length increases
  - Eardrum delay can also lower the SW frequency (Puria & Allen 1998)

In-the-ear (ITE) calibration

Using probes (earphone + microphone) designed for otoacoustic emissions (OAE) testing, we can calibrate the probe *in situ*

1. Measure the pressure level at the probe to a wideband stimulus
2. Characterize the acoustics of an individual ear (e.g. “real-ear calibration”)
3. Remove standing wave (SW) effects related to probe insertion



2 & 3 are accomplished using *wideband acoustic immittance* (WAI)

Two-step calibration: Thévenin + ITE

Forward vs. total pressure

- If the stimulus level is set based on the total microphone pressure ($P = P^+ + P^-$), it will be too high at the SW frequency

- The level should be set based on the forward pressure level (FPL) (Souza et al. 2014, Withnell et al. 2009, Scheperle et al. 2008)

$$R = P^- / P^+$$

The "reflectance"

$$P = P^+ + P^-$$
$$= P^+ + RP^+ = (1+R)P^+$$
$$P^+ = \frac{P}{1+R}$$

- The forward and total pressure can differ in level by 20 [dB]!!

Current study

- Compare reliability of 3 different calibration procedures (under typical testing conditions)
  1. Headphones calibrated in a coupler (standard audiometer, dB-HL)
  2. OAE probe calibrated using total microphone pressure “SPL” (dB-SPL)
  3. OAE probe calibrated using forward pressure “FPL” (dB-SPL)

- SPL audiograms are expected to have a notch (peak) at the SW frequency (Lewis et al. 2009, McCreery et al. 2009, Withnell et al. 2009)

- FPL audiograms are expected to be less variable across probe insertions

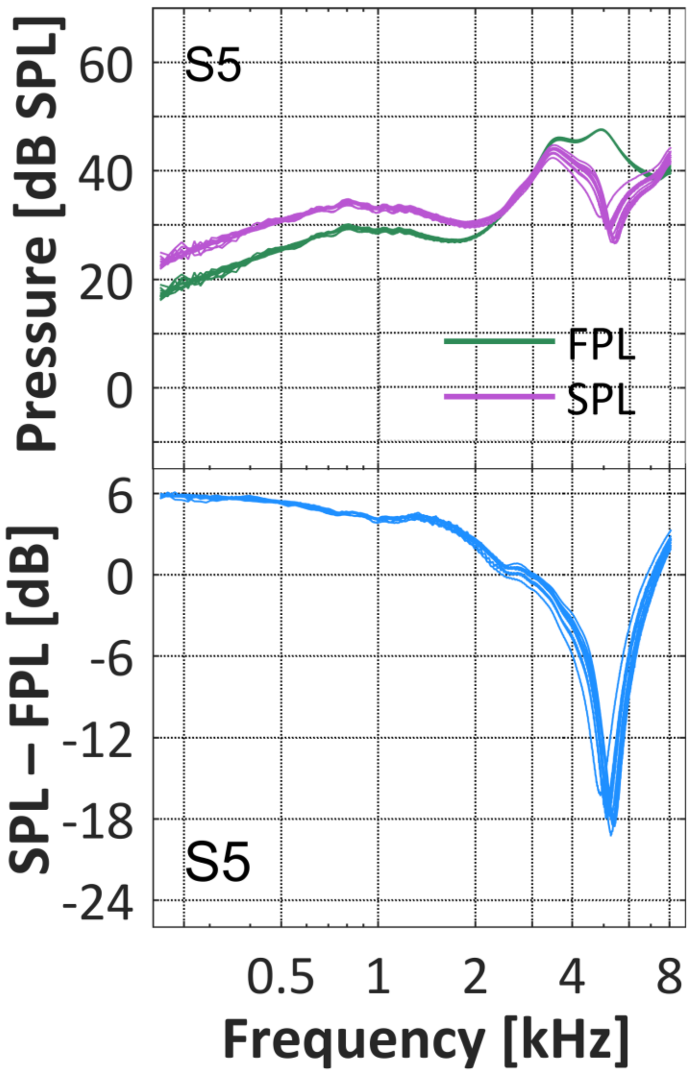
Experiment

- Fifteen subjects (10 women, 5 men; 18-30 yrs of age) with hearing levels up to 50 [dB-HL]

- Two audiometers were used for testing
  - Benson CCA-200mini with TDH-39P headphones
  - Mimosa Acoustics OtoStat prototype with an ER-10C probe

- 10 audiograms were collected for each subject on each audiometer (pure-tone thresholds @ 1, 2, 3, 4, 6, 8, 0.5 [kHz])
  - Each audiogram was taken with a <u>separate fitting</u> of the headphone or insert earphone
  - Audiograms were collected using an automated modified Hughson-Westlake method with pulsed tones

OtoStat calibration: SPL vs. FPL

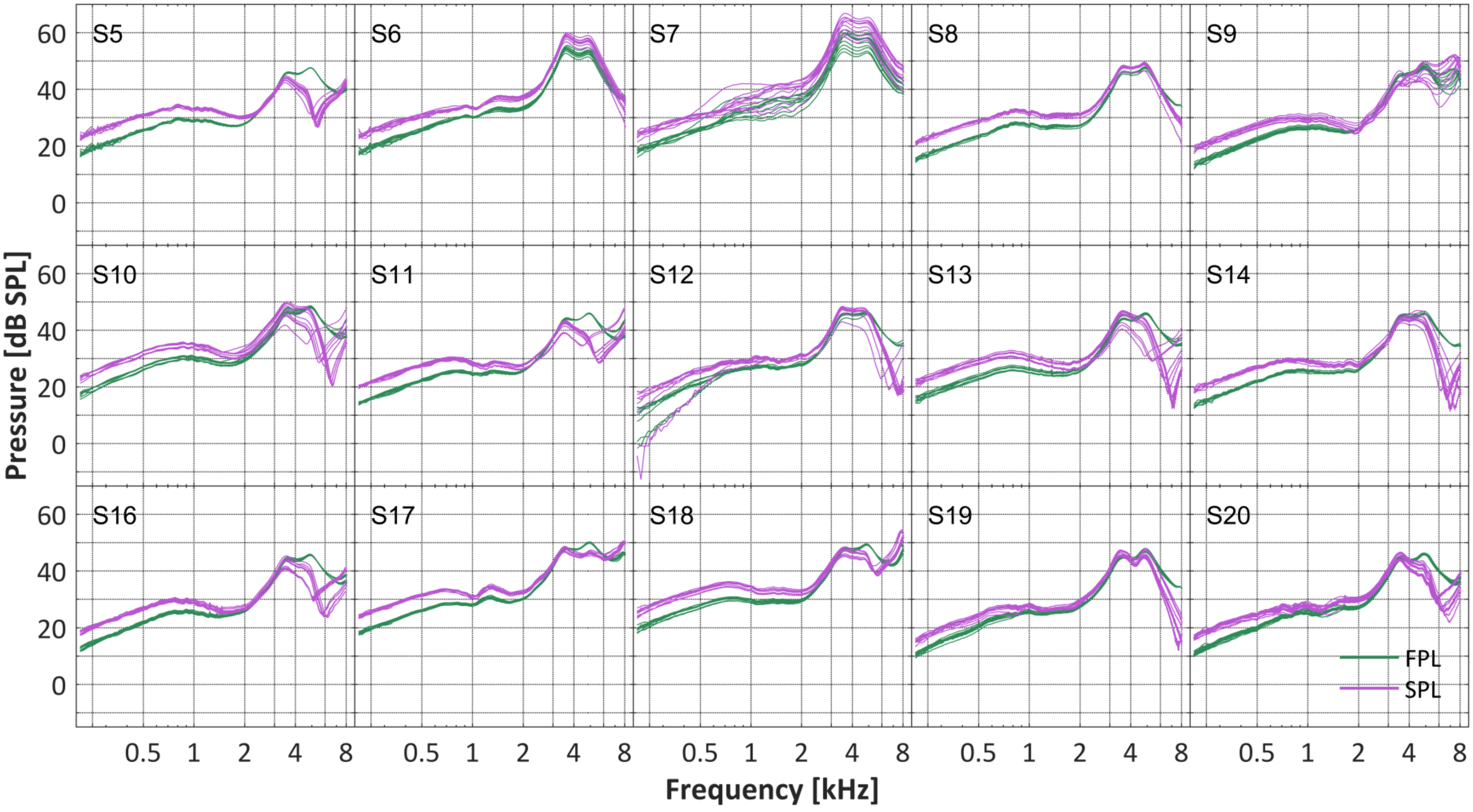


- A single ITE calibration yielded both SPL (P) and FPL (P^+) audiograms
- Stimulus level range set based on FPL
- The SW causes a minimum in the probe microphone pressure near 5 [kHz]
- At low frequencies

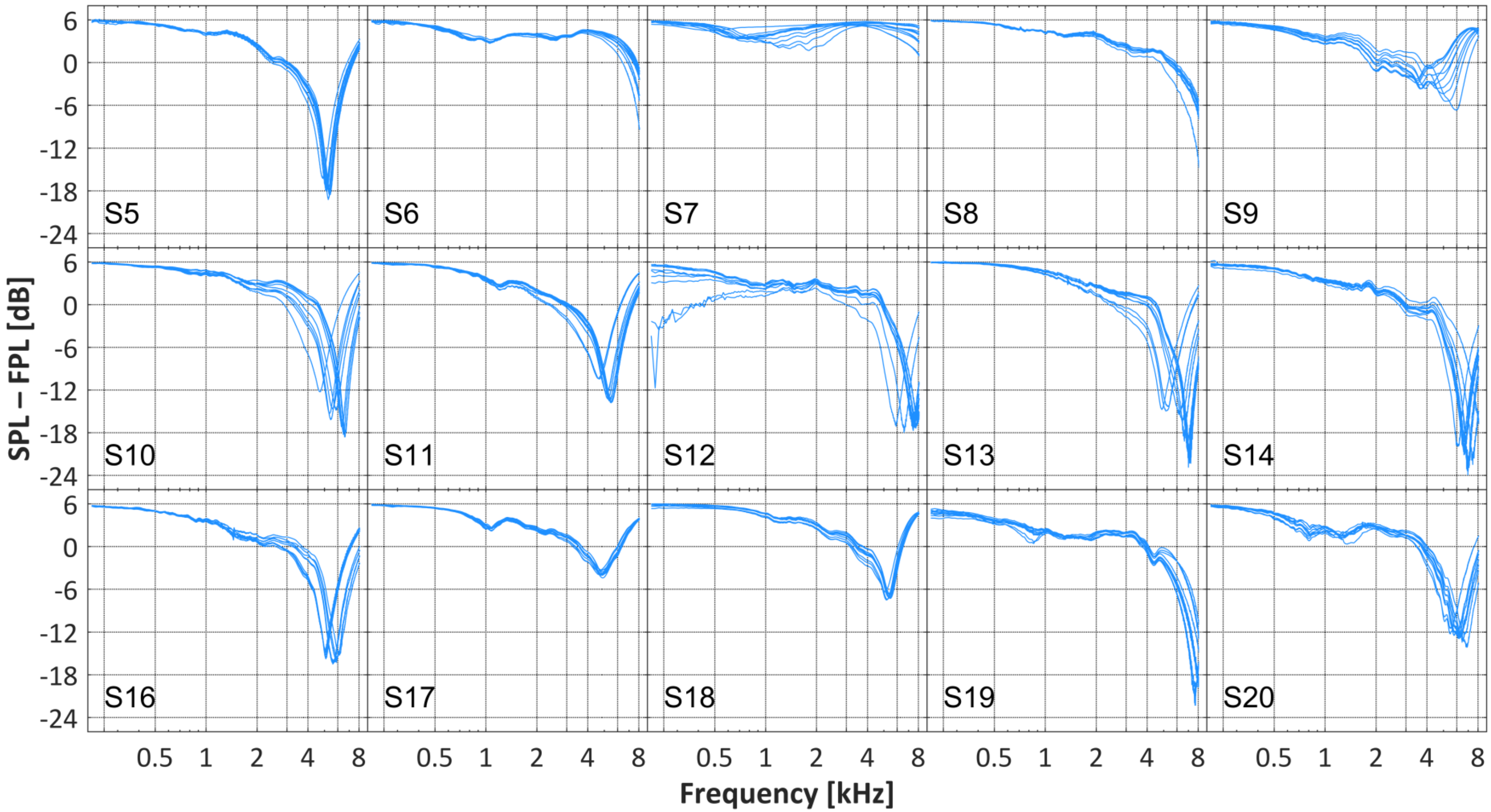
$$|P| = |P^+ + P^-| = |P^+(1+R)| \approx 2|P^+|$$

corresponds to a difference of 6 [dB]

Microphone pressure: SPL vs. FPL

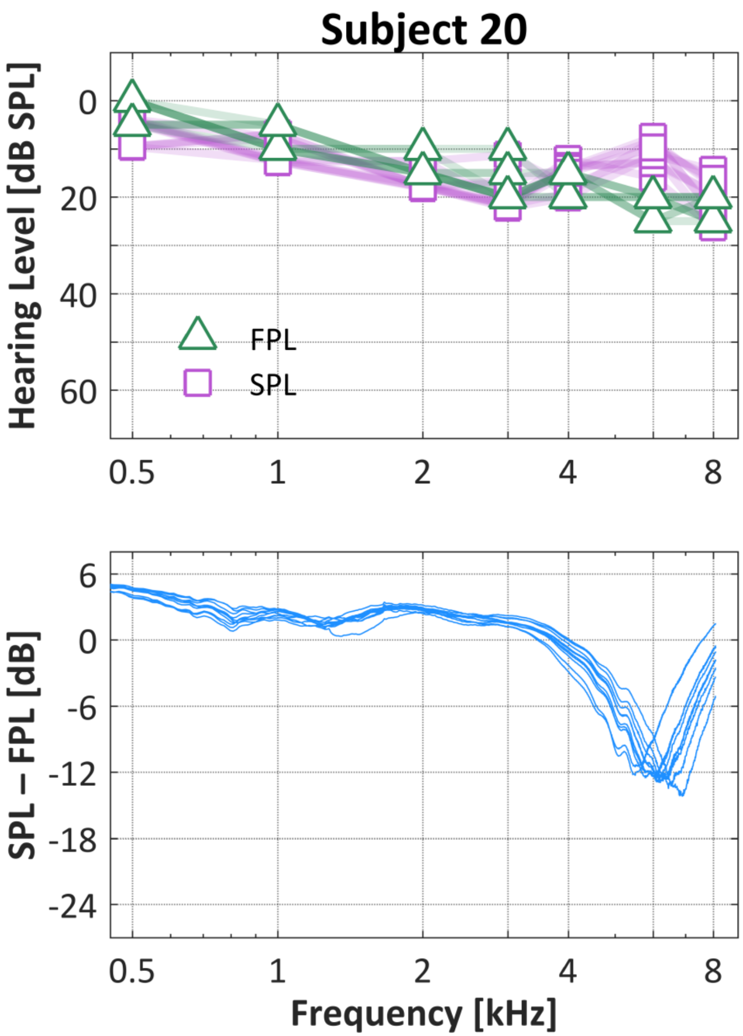


Stimulus difference: SPL-FPL



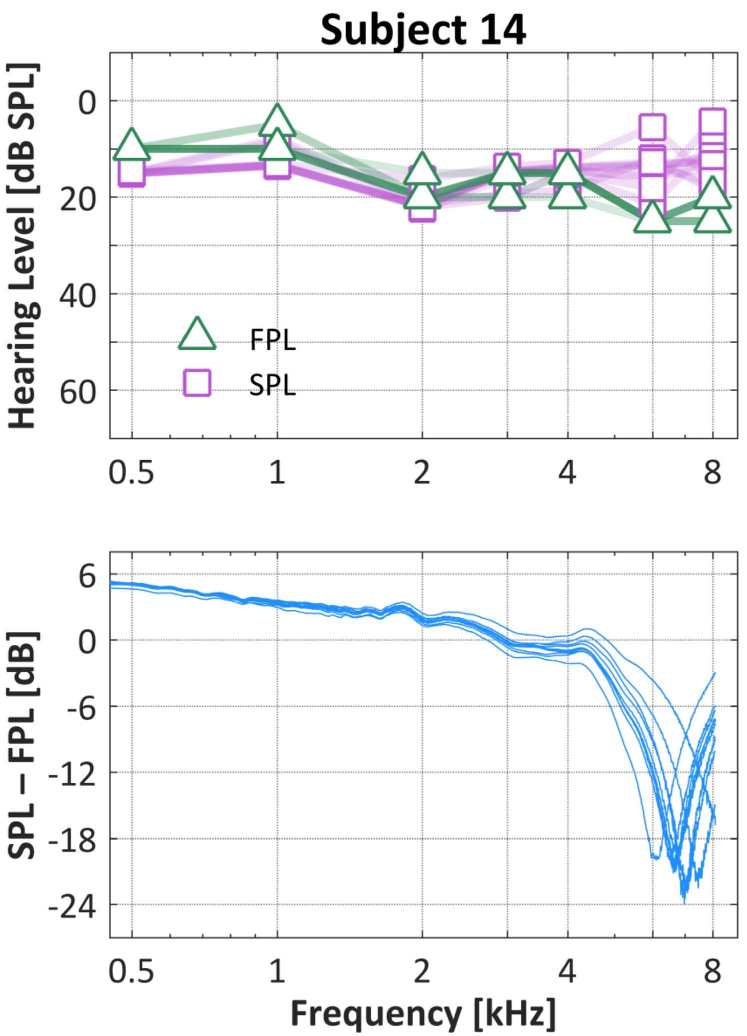
Audiogram accuracy

- SPL calibration estimates a lower signal level, thus a better hearing level at the SW frequency
- FPL is expected to better represent the effective stimulus level (compared to SPL)
- SPL calibration could lead to false negatives at the SW frequency when detecting hearing loss

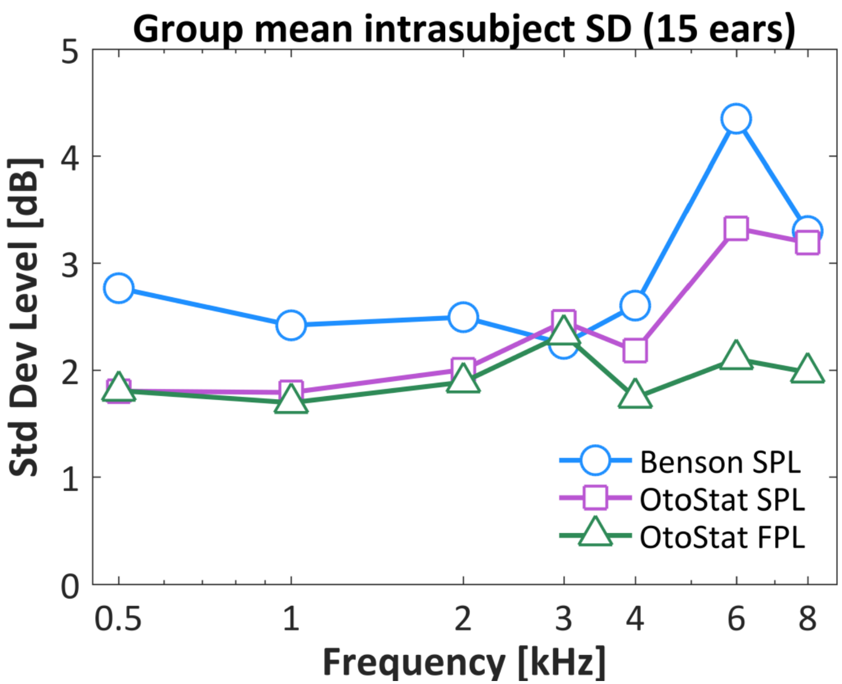


Audiogram accuracy & reliability

- SW effects occur between 6 and 8 [kHz] (probe depth changes across measurements)
- Effects of the SW depend on frequency, depth, and width of the SPL-FPL minimum
- The FPL audiogram is reliable, while the SPL audiogram is highly variable (could lead to false negatives)

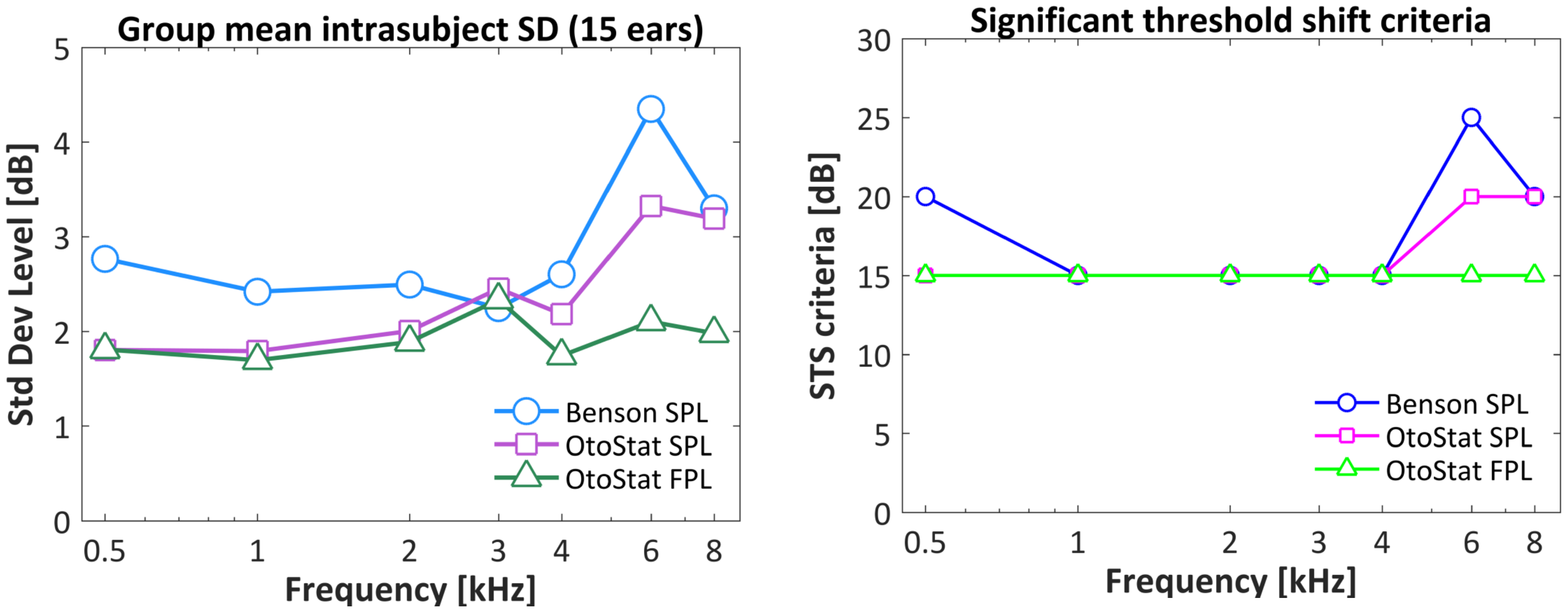


Audiogram reliability



- Benson vs. OtoStat: variability in [dB] may be compared
- FPL-calibrated audiograms are the most reliable

Audiogram reliability



FPL improves significant threshold shift (STS) criteria (Lapsley Miller 2004) by 10 [dB] at 6 [kHz] and 5 [dB] at 8 [kHz]

Conclusions

- FPL calibration improves audiogram accuracy
  - Standing wave effects may seem small on average, but can have 20 [dB] effects in individual ears
- FPL calibration improves audiogram reliability
  - FPL accounts for variability due to SWs across probe insertions
  - ITE + FPL audiograms are much less variable than the industry standard Benson audiograms
- Implications for hearing conservation programs (HCPs)
  - Smaller significant threshold shift (STS) criteria at 6 and 8 [kHz]
    → Earlier detection of hearing loss
    → Improved monitoring for ototoxicity
- Normative studies are needed to convert FPL results to dB-HL

Thank you!

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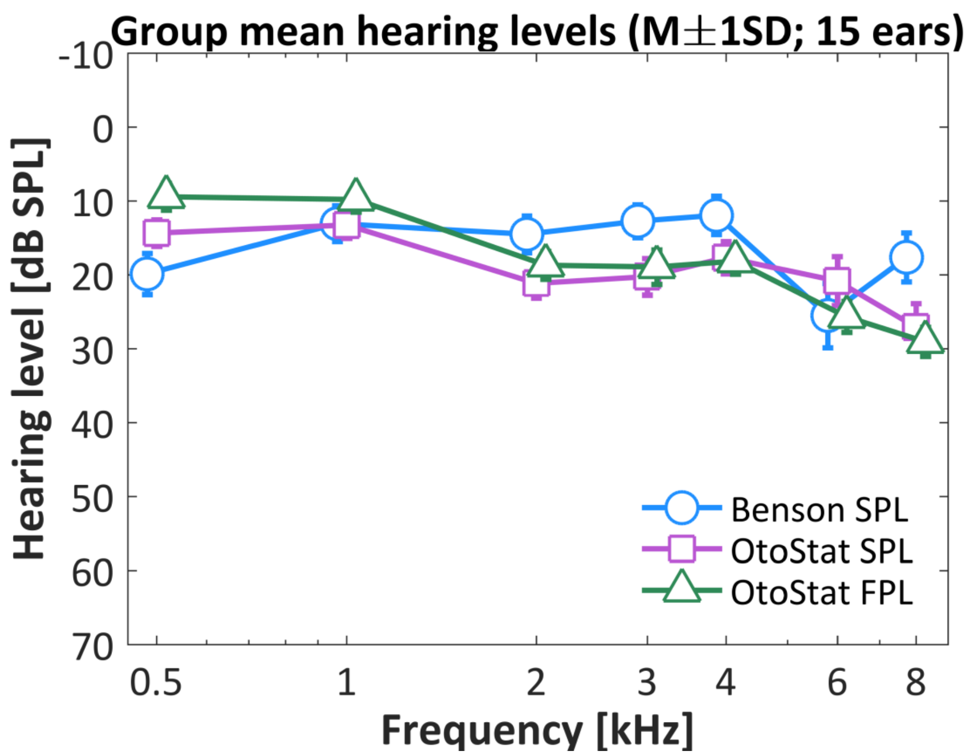
Audiogram results



For comparison with the OtoStat prototype audiometer, the dB-HL results were converted back to dB-SPL by removing the THD-39 headphone adjustment (ANSI, 2004b)