Exploring the Interrelationship between Spontaneous and Low-Level Stimulus-Frequency Otoacoustic Emissions

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Motivation

- Some healthy cochleae produce spontaneous otoacoustic emissions (SOAEs); however their use in evaluating cochlear status is limited.
- Evoked emissions are more commonly measured and have significant clinical value; traditionally distortion product and transient-evoked OAEs (DPOAEs, TEOAEs) have been used, but their generation is complex.
- Stimulus-frequency otoacoustic emissions (SFOAEs), evoked using a single stimulus tone, may be simpler.
- However, controversy over interpretation of SFOAEs has limited their use.
- Previous research has suggested that SFOAEs (Talmadge et al, 2000) and SOAEs (Shera, 2003) arise from place-fixed reflection sources: cochlear perturbations or roughness.
- Linear coherent reflection model (Shera, 2003) further hypothesizes that SOAEs and low-level SFOAEs have a common origin.
- Model predictions suggest that this relationship is strongest at levels closest to threshold.
- However, previous studies considering SFOAE level have typically not used probe tones lower than 40 dB SPL.

Questions

- How do SFOAEs evoked with low-level probe tones (20 dB SPL) compare to the results of similar studies using higher levels?
- Do our data support predictions made by linear coherent reflection model?

Methods

- Subjects: 7 normal-hearing (thresholds ≤25 dB HL) females 20-39 years old, 11 ears; only included individuals with robust SOAE activity.
- Testing conducted in a sound-treated booth.
- ER-10A microphone used for all measurements; calibrated in situ at the beginning of each session.
- Frequency region investigated for presence of SOAEs: 200-6000Hz. SOAE presence confirmed with 40 dB SPL suppressor tone presented ≈100-200 Hz below each SOAE.
- SFOAEs measured with off-frequency suppression paradigm (suppressor 40Hz above probe); 20dB SPL probe tone, 35dB SPL suppressor.
- SFOAE amplitude and phase measured at ≈15Hz frequency resolution, excepting one ear that was tested at ≈33Hz resolution. Linear interpolation used to approximate phase values at specific frequencies.
- SFOAE measurements focused around frequency regions of known SOAE presence (beginning ≈200Hz below lowest-frequency SOAE and ending ≈200Hz above highest-frequency SOAE).

Results

Relating SFOAE Amplitude and Phase to SOAE Frequency

- A common trend across subjects is the correspondence of SOAE frequencies to peaks in SFOAE amplitude.
- There is variability in SFOAE amplitude and overall shape among different subjects. As illustrated below some subjects displayed relatively broad SFOAE responses (Subject 3), while other responses were more confined to areas around SOAEs (Subject 4).
- The phase for SFOAEs varies with respect to frequency, and the overall slope appears to be steeper at 20 dB SPL as compared to higher levels, 40-70dB SPL (Schairer et al, 2006).

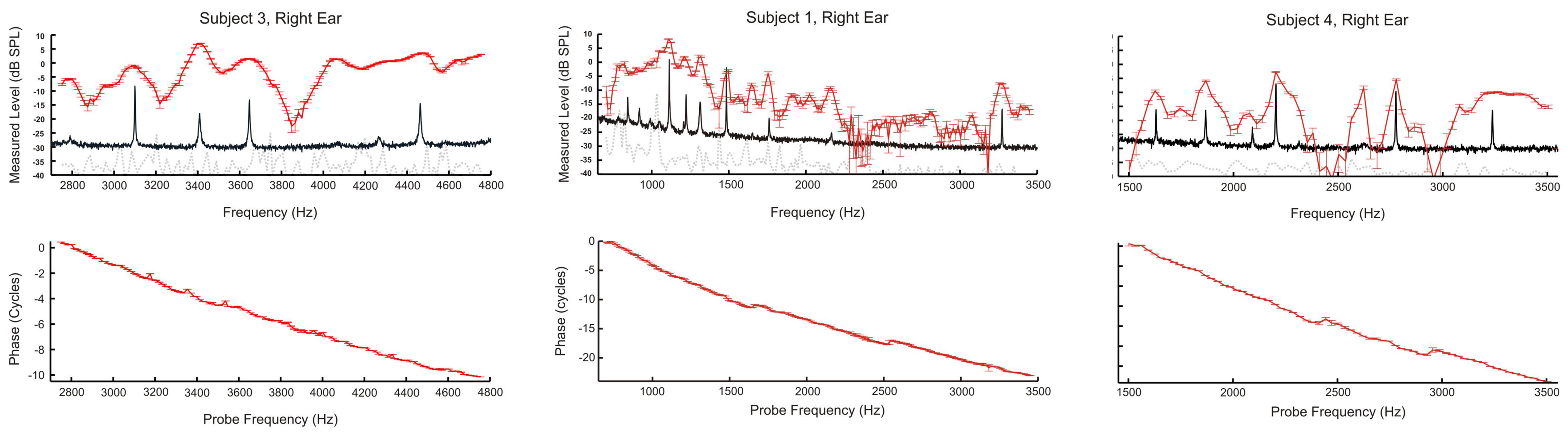
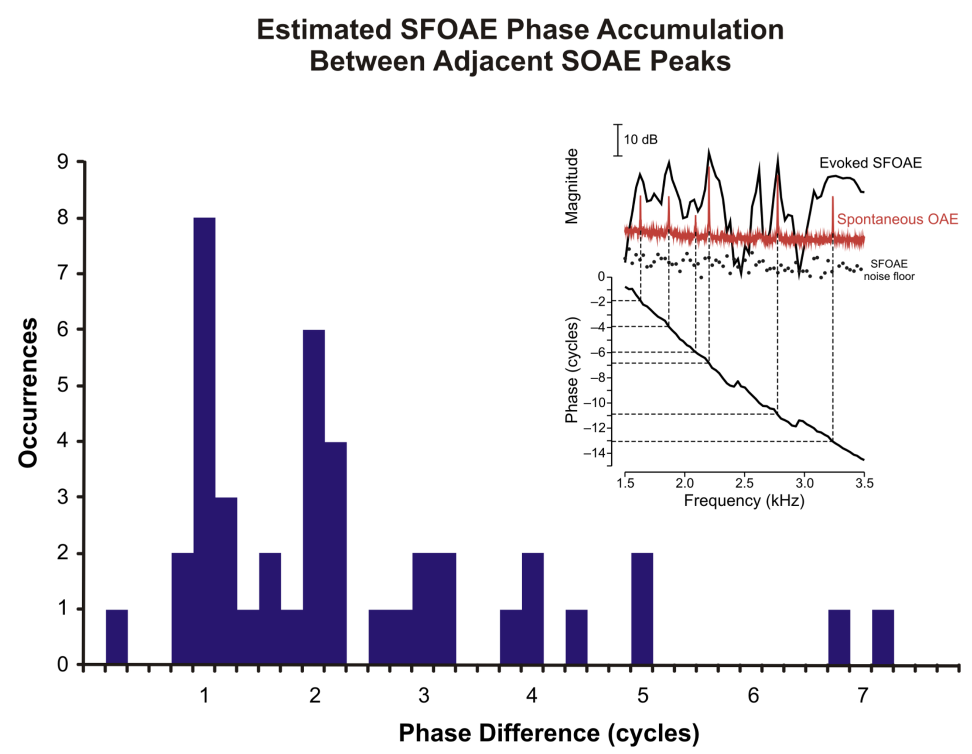


Figure 1: Relationship between SOAE and SFOAEs evoked at 20 dB SPL in three representative ears. Top plots show SFOAE amplitude evoked with 20 dB SPL probe level (red line) and SOAE amplitude (black line). SFOAE noise floor is represented by grey dotted line. Bottom plots show unwrapped SFOAE phase. Vertical bars in each plot represent standard error.

SFOAE Phase Accumulation between Adjacent SOAE Peaks



- Due to a common source, the differences in SFOAE phase between those frequencies of adjacent SOAE peaks are predicted to be integer numbers.
- Calculating these phase differences is another means to test our data with coherent reflection model which hypothesizes correlation between SOAE and SFOAE generation.
- Data tend to cluster around integer values, although several non-integer values are observed. This may be due to poor phase unwrapping or phase shifts that are indicative of mechanical perturbations.

Figure 2: Histogram displaying SFOAE phase accumulation between SOAE frequencies in 9 ears. Difference values greater than 8 (n=2) were excluded. Data points were sorted into 0.2-cycle bins.

Inset: illustration of the relationship between adjacent SOAE frequencies and cycles of phase difference in SFOAEs in Subject 4. Phase cycle differences approximate integer values. This method was used for all ears to extract information for histogram at left.

Level Dependence of SFOAE Phase-Gradient Delay (N_{SFOAE})

- Based on linear coherent reflection theory, SFOAE phase is expected to change with frequency.
- N values (Figure 3) represent the normalized rate of phase accumulation expressed in periods.
- The trend line for this data set, measured at 20 dB SPL, is greater than previous studies that have measured SFOAEs with higher stimulus levels (Shera, 2003; Schairer et al, 2006).
- Based upon data reported and observed, delays appear to increase with decreasing stimulus level (Schairer et al, 2006).

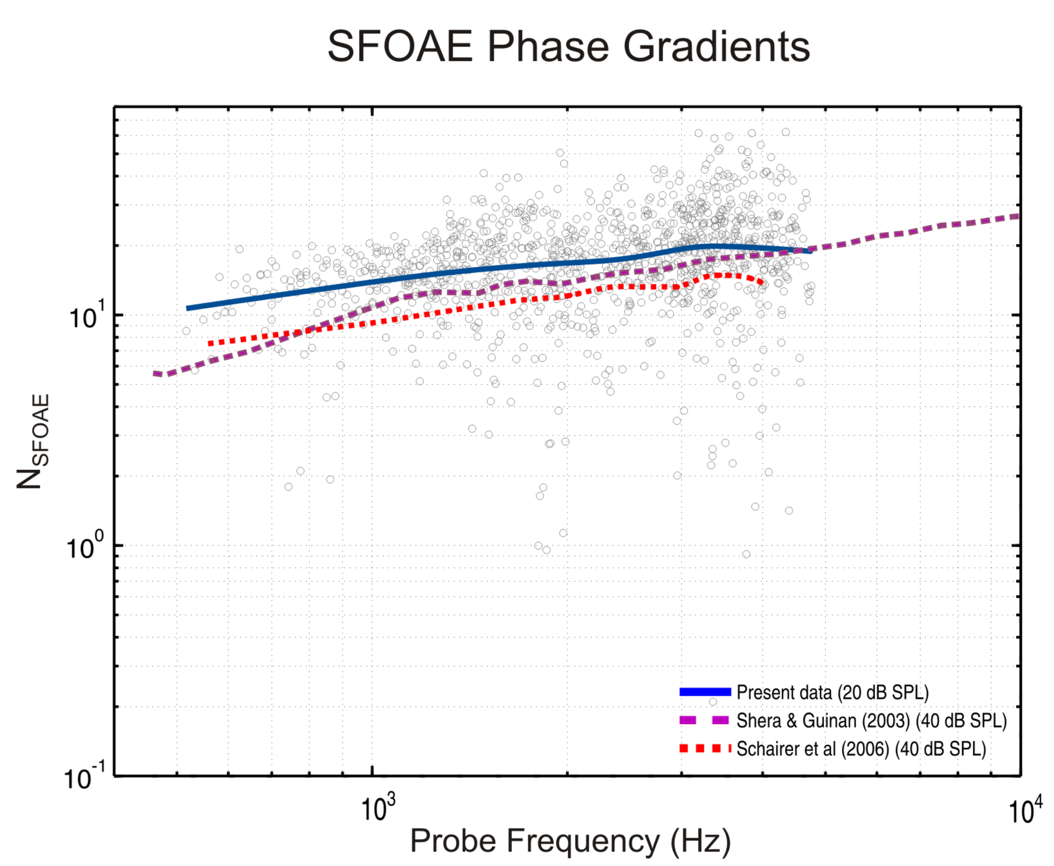


Figure 3: SFOAE phase gradient delay for 9 ears at 20 dB SPL probe level. Excludes points that are less than 10 dB SNR. Three loess fit lines are shown; present data at 20 dB SPL (blue), Shera (2003) at 40 dB SPL (purple dashed), and Schairer et al (2006) at 40 dB SPL (red dotted).

Middle Ear Effects?

- 39-year-old female.
- History of chronic otitis media with effusion; multiple tympanic membrane ruptures in childhood.
- Hypermobile tympanic membranes (Figure 5).
- Behavioral thresholds within normal limits (Figure 6).
- Subject displayed robust SOAEs bilaterally.
- SFOAEs were generally low amplitude with high error.
- SFOAE responses were most reliable at frequencies of SOAE presence.

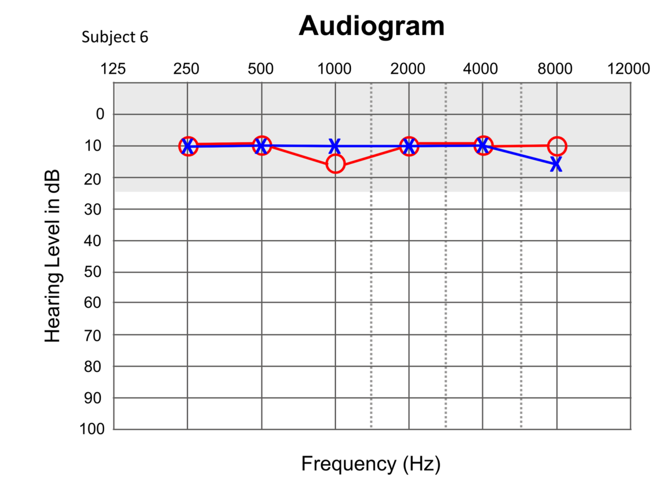


Figure 5: Behavioral thresholds were obtained using standard audiometric techniques (insert phones, good reliability). Results reveal hearing sensitivity within normal limits (≤25 dB HL, indicated with grey shading) from 250 to 8000 Hz bilaterally.

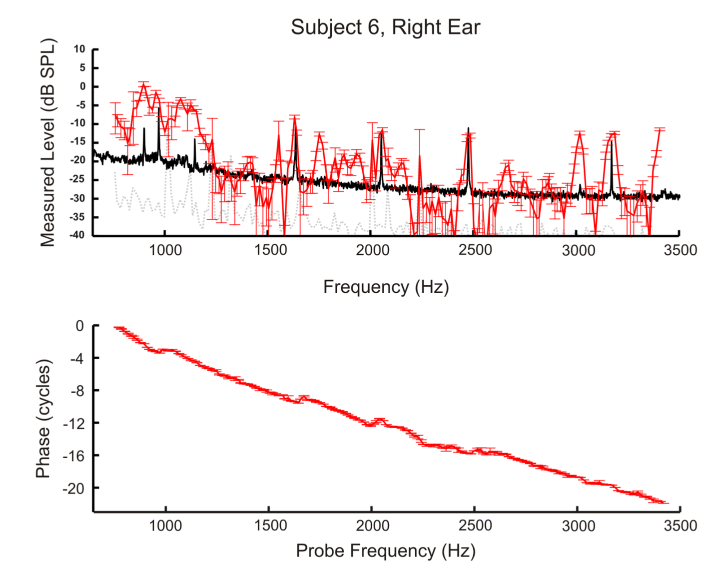


Figure 4: Relationship between SOAE and SFOAEs evoked at 20 dB in the right ear. Top figure displays SOAE and SFOAE magnitude, measured from the right ear, as a function of frequency. Bottom figure is the unwrapped SFOAE phase. Similar results were observed in the left ear.

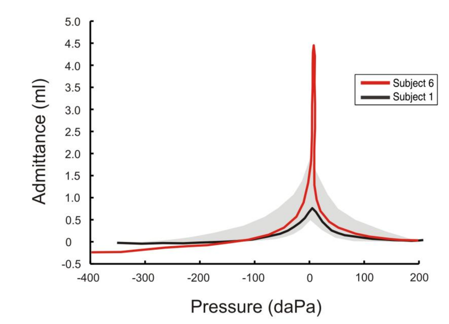


Figure 6: Tympanometry measured in the right ear with a 226 Hz probe tone. Ear canal volume 1.3 ml, peak pressure 10 daPa, acoustic admittance 4.4 ml (red curve). Acoustic admittance is beyond normal limits for adults (0.3-1.40ml, indicated with grey shading). Similar results were seen in left ear. Normal tympanogram from Subject 1 (admittance 0.8ml) is included for comparison (black curve).

Discussion

- Regardless of the validity of the linear coherent reflection model, our results indicate a clear inter-relationship between SOAEs and SFOAEs observed both in magnitude and phase characteristics.
- The relationship between SOAEs and SFOAEs is readily apparent when stimulation is at low levels.
- Presumably, because generation of SOAEs and low stimulus level SFOAEs is confined to a more focused region of the basilar membrane, this limits the interference from other sources, such as nonlinear distortion.
- The present data are broadly consistent with linear coherent reflection model, both with increased SFOAE amplitudes about SOAE frequencies, and SFOAE phase behavior demonstrating a degree of correlation regarding SOAE peak spacing.
- At low levels, responses may be more affected by individual threshold differences. Could stimulating at sensation level provide less variable results across subjects?
- One normal-hearing subject with middle-ear pathology suggests different effects of middle ear on SOAEs and SFOAEs. It may be that SOAEs are "one-way," while SFOAEs are a "two-way" process. Can a simple middle ear model account for such differences?

Acknowledgements

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References

Schairer, K., Ellison, J.C., Fitzpatrick, D., & Keefe, D. (2006). Use of stimulus-frequency otoacoustic emission latency and level to investigate cochlear mechanics in human ears. *Journal of the Acoustical Society of America, 120*, 901-914.

Shera, C. (2003). Mammalian spontaneous otoacoustic emissions are amplitude-stabilized cochlear standing waves. *Journal of the Acoustical Society of America, 114*, 244-262.

Shera, C.A., & Guinan, J.J. (1999). Evoked otoacoustic emissions arise by two fundamentally different mechanisms: A taxonomy for mammalian OAEs. *Journal of the Acoustical Society of America, 105 (2)*, 782-798.

Shera, C.A., & Guinan, J.J. (2003). Stimulus-frequency-emission group delay: A test of coherent reflection filtering and a window on cochlear tuning. *Journal of the Acoustical Society of America, 113*, 2762-3883.

Talmadge, C.L., Tubis, A., Long, G.R., Tong, C. (2000). Modeling the combined effects of basilar membrane nonlinearity and roughness on stimulus frequency otoacoustic emission fine structure. *Journal of the Acoustical Society of America, 108 (6)*, 2911-2932.