Effects of Stimulus Level and Hearing Status on OAE Latencies

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Outline

I. Traveling Wave Motion
II. Frequency Tuning
III. OAE Generation
IV. OAE Latency
   – Relation to Traveling Wave Delay
   – Relation to Generation Mechanisms
V. Experiment by Konrad-Martin & Keefe
VI. Future Directions
I. Traveling Wave Motion

- Each place is tuned (responds best) to a particular frequency
- Tuning actively sharpened at low stimulus levels by the cochlear amplifier (OHC motility?)
- Sharper tuning allows better frequency separation

Drawing found at http://www.bcm.edu/oto/research/cochlea/ by Stephen Neely, Communication Engineering Laboratory, Boys Town National Research Hospital
Traveling Wave Motion

- Stimulus frequencies are distributed according to BM place, with each characteristic frequency place determined by BM mass and stiffness
  - Stiff base (high frequencies vibrate best)
  - More compliant apex (low frequencies vibrate best)

- For each frequency, the BM responds with a traveling wave
  - Each bit of BM responds with a time delay
  - Short delay near base, delay increases at more apical positions

- For each traveling wave, the velocity decreases as the wave reaches its peak
1. **Traveling Wave Motion**

- Traveling wave slows down near the characteristic frequency place, with greater wave velocity decreases associated with sharper tuning of the resonant peak
  - At low levels (Zweig, 1991; Zweig & Shera, 1995)
  - For a BM modeled as a set of minimum phase filters (Zweig, 1976; de Boer, 1997)
II. Frequency Tuning

- Important for speech perception
- Established at basilar membrane
- Enhanced at low stimulus levels
- Diminished by hearing loss

High stimulus levels are required to elicit responses in impaired ears, amplified or not.

III. OAE Generation

Drawing adapted from S. Blatrix from “promenade around the cochlea” EDU website www.cochlea.org by Rémy Pujol et al., INSERM and University Montpellier
Evoked OAEs arise by a combination of coherent linear reflection & nonlinear distortion

- **Linear Reflection** – Due to coherent reflection of traveling wave from random impedance perturbations

- **Nonlinear Distortion** – Due to nonlinearities acting as sources of cochlear traveling waves
Basilar membrane function is nonlinear in normal ears, i.e., output is distorted version of input.

Nonlinear interaction between stimulus frequencies generates distortion at $2f_1-f_2$.

This “distortion emission” is emitted from the $f_2$ place.
Some DP energy will travel (apically) to the basilar membrane place tuned to the DP frequency ($2f_1-f_2$)

- Elicits a “reflection emission” from the $2f_1-f_2$ place
- DPOAE distortion & reflection sites about $\frac{1}{2}$ octave apart
Due to coherent linear reflection of forward-traveling basilar membrane response near TW peak
Reflection might be caused by slight anatomical abnormalities present in normal ears
I. OAE Generation (differences)

- **Stimulus frequencies** -
  - DPOAEs = two different frequencies
  - SFOAEs = one frequency (or two very similar frequencies)

- **Dominant generation mechanism (?)** -
  - DPOAEs = both mechanisms (at least at low levels)
  - SFOAEs = linear reflection (at least at low levels)

- **Space between sources** -
  - DPOAE = ½ octave apart
  - SFOAE = very close together
IV. OAE Latency

Time difference at peak SPL

Time difference at 6 dB down point

Stimulus

OAE

Tone-Pip-Evoked

Gated-Tone-Evoked
IV. OAE Latency

Relation to Traveling Wave Delay

- Theory indicates SFOAEs at low-mod levels arise near the peak of basilar membrane traveling wave

- Basilar membrane at low levels like a bank of overlapping minimum phase-shift filters
  - Bandwidths and delays inversely related

- Thus, SFOAE and basilar membrane latencies should be linked
IV. OAE Latency

Relation to Frequency Tuning

\[ Q_{\text{erb}} = kTf/2, \] in which \( k(f) \) varies with \( f \).

Fig. 4 from Shera, Guinan & Oxenham, 2002, PNAS 99, 3318-23.
IV. OAE Latency

Relation to Frequency Tuning

- SFOAE group delays (latencies) at 40 dB SPL predicted behavioral tuning curve data from 1-8 kHz in normal ears (Shera et al., 2002)

- Pip-evoked OAE latencies did not vary with SNHL (Priere et al., 1995)

- Distortion emissions predicted to have short group delays, which may not depend on cochlear tuning (Talmadge et al., 1999)
Research Questions

For SFOAE & DPOAE latencies, measured directly in the time domain

1) Do they vary with level and hearing status?

2) Do they allow separation of multiple components (e.g., reflection and distortion components, multiple internal reflections)?

3) Are they consistent with model results?
Methods
Subjects

- 17 normal-hearing subjects
  - pure-tone thresholds 15 dB HL or better at half-octave frequencies from 0.25 to 8.0 kHz

- 10 subjects with impaired hearing
  - 10 had thresholds > 20 dB HL at 4 kHz
  - 9 had thresholds > 20 dB HL at 3 kHz

- All subjects had normal 226-Hz tympanometry at time of testing
Stimuli: Types of Transients

- **Tone pip pairs (pp)**, band-limited impulses
- **Gated tone pairs (gg)**, well-defined onset, steady state and decay
- **Continuous plus gated tones (cg)**, (DPOAE only)
DPOAE Stimuli

- $f_1 < f_2$, with $f_2 / f_1 = 1.2$
- $f_2 = 4000$ Hz
- $L_1 = L_2$ for ppDPOAE
- $L_1 = L_2 + 10$ dB for ggDPOAE, cgDPOAE
  - Not optimal based on Kummer et al., 1998, in which $L_1 = 0.4L_2 + 39$ dB for $L_2 < 65$ dB SPL
- $L_2$ varied from about 35 to 70 dB SPL, depending on transient type
SFOAE Stimuli

- $f_1 = f_2$ (Equal-frequency)
- $f_2 = 2.7$ kHz and 4.0 kHz
- $L_1 = L_2$ (Equal-level)
- $L_2$ varied from about 30 to 75 dB SPL in 5-dB steps
SFOAE and DPOAE responses recorded in the time domain
  - Narrow-band filtered (Kaiser) at SF or DP frequency,
  - and envelopes extracted (Hilbert transform)

For SFOAE, equivalent auditory filter bandwidth calculated \( (\varepsilon Q_{\text{ERB}}) \)
  - \( \varepsilon Q_{\text{ERB}} = kTf/2 \)
  - \( k \) values were 2.15 for 2.7 and 2.09 for 4.0 kHz

Synchronous SOAEs measured to assess their contribution to SFOAE and DPOAE
Results
- Valid responses (shown) had a 6 dB SNR
- Excluded latencies shorter than $T_{\text{min}}$, since they could possibly be related to artifact
Effect of Stimulus Level

A

Latency (ms)

ppDPOAE
O maximum SPL

L₁ Level (dB SPL)

B

ppDPOAE
● peak 1
★ peak 2

WKB reflection

WKB distortion
Results

Envelopes of ppDPOAE provide evidence for two $2f_1 - f_2$ DPOAE sources.

Latency variations explained in part by variations in the dominant generator source.

Latencies of transient DPOAE were consistent with model predictions.
Effect of Hearing Status on SFOAE Latencies
Proportion of subjects with valid tone pip (pp) and gated tone (gg) SFOAEs.

<table>
<thead>
<tr>
<th></th>
<th>ppSFOAE</th>
<th>ggSFOAE</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>2.7 kHz</td>
<td>4.0 kHz</td>
</tr>
<tr>
<td>normal hearing</td>
<td>16/17</td>
<td>16/17</td>
</tr>
<tr>
<td>impaired hearing</td>
<td>5/9</td>
<td>4/10</td>
</tr>
</tbody>
</table>
Results

Responses with 6 dB signal to noise ratio (SNR) obtained for a wide range of audiometric threshold levels.

However, valid latencies ($> T_{\text{min}}$) were obtained only in subjects with pure-tone thresholds below about 45 dB HL.

Impaired ears were more likely to have SFOAEs present than DPOAEs present.
Effect of Stimulus Level on SFOAE Latencies
Results

Increasing the stimulus level decreases ggSFOAE & ppSFOAE latencies.

Valid impaired-ear latencies were similar or shorter compared to normal-ear latencies at equal SPL.

Low-level SFOAE latencies consistent with model predictions for reflection mechanism; high-level latencies consistent with distortion mechanism.
Comparing Temporal Details of DPOAE Waveforms: Narrow-band filtering vs. time-frequency response (TFR) technique
DPOAE

A

Total Response
SPLs of P1 and P2 (dB)

B

2EOAE Spectra
OAE SPL (dB)

C

Total Response
P1 and P2 Pressures (mPa)

D

2EOAE Waveforms
Pressure (mPa)

E

734876R; Max TFR -3.2 dB; L1=54.9, L2=55.0 dB

F

Level vs. Time at OAE f = 2.672 kHz
Results

Good correspondence between temporal envelopes using narrow-band filtering and TFR analysis
Conclusions
Conclusions

SFOAE latency variation with level and hearing status are consistent with expected changes in BM traveling wave under the same conditions. Thus, transient-evoked SFOAE may provide a rapid, non-invasive measure of cochlear tuning.

Transient-evoked DPOAE may provide a means for separately evaluating distortion and reflection components.

TFR technique valid for exploring OAE elicited by complex stimuli.
Future Directions

Determine the extent to which temporal (time) and spectral (frequency) analysis are abnormal in the auditory periphery of older adults

Isolate cochlea and auditory nerve using OAE and CAP measurements

Determine the functional (behavioral) consequences of abnormal temporal and frequency analysis for processing of speech

(1) temporal speech cues (VOT)
(2) isolated (time-gated) words