Otoacoustic Emissions Textbook

- Overview of otoacoustic emissions
- Anatomy and physiology
- Classification of OAEs
- Instrumentation and calibration
- Clinical measurement of OAEs: procedures
- OAE analysis
- OAE applications in children
- OAE applications in adults
- Efferent auditory system and OAEs
- New directions in research and clinical application

OAEs in AUDIOLOGY TODAY: Main Points

- OAEs are important in the diagnostic audiological assessment of children and adults.
- OAE findings and the audiogram do not always agree ... that's good ... OAEs provide unique information on auditory status.
- Abnormal OAEs can be recorded with a normal audiogram ... and can detect cochlear dysfunction.
- OAEs should be a part of the basic audiological test battery.

Giuseppe Tartini (April 8, 1692 - February 26, 1770)

OAE: Classic Quote from Yesteryear by Thomas Gold

"I had discussed at length in 1948 with von Bekesy at Harvard that the observations he made on the dead cochlea were unrepresentative. But he wouldn't have that!"

"It is shown that the assumption of a 'passive' cochlea, where the elements are brought into mechanical oscillation solely by means of the incident sound, is not tenable."

"... the nerve ending abstracts much energy from a mechanical resonator."

William Rhode demonstrates cochlear nonlinearity in the squirrel monkey in 1971.

Discovery of OAEs by David Kemp

(Kemp DT. Stimulated acoustic emissions from within the human auditory system. JASA 64: 1978.)

"A new auditory phenomenon has been identified in the acoustic impulse of the human ear...
This component of the response appears to have its origin in some nonlinear mechanism probably located in the cochlea, responding mechanically to auditory stimulation, and dependent upon the normal functioning of the cochlear transduction process...

It is tempting to suggest that one of the functions of the outer hair cell population is the generation of this mechanical energy."
Historical Overview of OAEs:
Major Events Since Discovery (1)

- 1980s
  - Early studies of newborn hearing screening in UK and Denmark
  - Introduction of ILO 88 “auditory neuropathy”

- 1990s
  - Research on DPOAEs in animals and humans
  - NIH Consensus Conference recommends UNHS in 1993, including use of OAEs
  - New DPOAE systems by major manufacturers in 1994
  - First CPT codes in 1995
  - OAEs in identification of ANSD
  - Automated OAE devices
  - Evidence on clinical applications grows

Historical Overview of OAEs:
Major Events Since Discovery (2)

- 2000 to present
  - Two textbooks on OAEs
  - OAEs recommended by JCIH for screening
  - New applications of OAEs including:
    - Tinnitus
    - Ototoxicity monitoring
    - Noise/music cochlear dysfunction
    - Preschool and school age screening
  - Combination technologies
    - ABR and OAEs
    - Tympanometry and OAEs
  - New CPT codes for OAEs

OAEs: Differences between inner and outer hair cells (1)

<table>
<thead>
<tr>
<th>Inner Hair Cells</th>
<th>Outer Hair Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single row</td>
<td>3 or 4 rows</td>
</tr>
<tr>
<td>N = 3500</td>
<td>N = 12,000 to 20,000</td>
</tr>
<tr>
<td>On spiral lamina</td>
<td>On basilar lamina</td>
</tr>
<tr>
<td>Wine bottle shape</td>
<td>Cylinder (test tube) shape</td>
</tr>
<tr>
<td>No contact bet/ stereocilia</td>
<td>Tallest stereocilia contact tectorial and tectorial membrane</td>
</tr>
<tr>
<td></td>
<td>membrane</td>
</tr>
<tr>
<td>95% of afferents innervate IHC</td>
<td>5% of afferents innervate OHCs</td>
</tr>
</tbody>
</table>

OAEs: Differences between inner and outer hair cells (2)

<table>
<thead>
<tr>
<th>Inner Hair Cells</th>
<th>Outer Hair Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not motile</td>
<td>Motile</td>
</tr>
</tbody>
</table>
Encompassed by support cells  
Central nucleus  
Single layer of endoplasmic cisternae  
Mitochondria scattered  
Efferents from lateral superior olive  
Supported only on top & bottom  
Nucleus at base of cell  
Extensive subsurface reticulum  
Mitochondria along throughout cell  
Efferents from medial superior olive

Site of Generation

- Cochlea: observed delay in OAEs; recordings from BM & auditory nerve.
- Outer Hair Cells: concomitant ablation of OAEs and OHC (e.g., Davis et al., 2002); loss of OAEs due to other insults associated with OHC damage (salicylate, noise, etc.).
- But where in the OHC?

Why does it matter?

- No amplifier: Recordable DPOAEs at high input levels. Good candidate for acoustic amplification.
- No transducer: DPOAEs not recordable. Good candidate for electrical input.

Auditory Anatomy Involved in the Generation of OAEs

- Outer hair cell motility
  - Prestin motor protein
- Stereocilia
  - Motion
  - Stiffness
- Tectorial membrane
- Basilar membrane mechanics
  - Dynamic interaction with outer hair cells
- Stria vascularis
- Middle ear (inward and outward propagation)
- Medial efferent pathways
- External ear canal
  - Stimulus presentation
  - OAE detection

CLINICAL APPLICATION OF OTOACOUSTIC EMISSIONS (OAE): General advantages
CLINICAL APPLICATION OF OTOCOUSTIC EMISSIONS (OAE): Possible disadvantages

- Susceptible to effects of noise
- Affected greatly by middle ear status
- Provide cochlear information only about outer hair cells
- May be abnormal or not detected with normal audiogram
- Are not detectable with hearing loss > 40 dB HL
- Cannot be used to estimate degree of hearing loss
- Not a measure of neural or CNS auditory function
- Not a test of hearing

Outer Hair Cells, Otoacoustic Emissions, and Auditory Function

- OHCs and OAEs are highly dependent on blood flow to the cochlea, due to demands of metabolism
- OAEs are pre-neural and, therefore, not affected by retrocochlear auditory dysfunction
- OHC motility contributes to:
  - Enhanced auditory sensitivity
  - Sharper tuning curves (increased frequency selectivity or cochlear tuning)
  - Normal growth of loudness

OAEs after Sound Induced Damage

And in humans...
still from Avan & Bonfils (2004)

Recreational Exposure

Six Reasons Why OAEs Will Never Replace the Audiogram nor Accurately Estimate Hearing Loss
(1-3)

- OAEs measurement is dependent on inward and outward propagation of energy through the middle ear (e.g., abnormal OAEs with normal hearing sensitivity)
- OAEs are more sensitive to cochlear dysfunction than the audiogram (e.g., abnormal OAEs with normal hearing sensitivity)
- OAEs are electrophysiologic measures while the audiogram is behavioral (e.g., normal OAEs with abnormal audiogram)

Six Reasons Why OAEs Will Never Replace the Audiogram nor Accurately Estimate Hearing Loss
(4-6)

- OAEs are produced by OHCs, whereas the audiogram is dependent on IHCs (e.g., normal
OAEs with abnormal audiogram:

- OAEs are pre-neural, whereas the audiogram is dependent on retrocochlear pathways (e.g., normal OAEs with abnormal hearing sensitivity)
- OAEs reflect OHC integrity, whereas the audiogram measures hearing (e.g., normal OAEs with abnormal audiogram)

Otoacoustic Emissions in Audiology Today:
Limitations in use of OAEs by clinical audiologists

Regular Spacing of Spontaneous OAEs

Coherent Reflection Filtering

Classification

Types of OAEs:
Conventional Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Stimulus</th>
<th>Prevalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous</td>
<td>none</td>
<td>&lt; 70%</td>
</tr>
<tr>
<td>Evoked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>transient</td>
<td>click or tone burst</td>
<td>&gt; 99%</td>
</tr>
<tr>
<td>distortion product</td>
<td>two pure tones</td>
<td>&gt; 99%</td>
</tr>
<tr>
<td>stimulus frequency</td>
<td>continuous tone</td>
<td>?? %</td>
</tr>
</tbody>
</table>

Transient Otoacoustic Emissions (TEOAE)

Distortion Product Otoacoustic Emissions (DPOAEs)

Mixed DPOAEs

Improving Predictions Using I/O Functions

- Plot DPOAE pressure (in Pascals not dB SPL).
- Fit linear function to first few points reliably above the noise floor.
- Threshold is the stimulus level that yields 0 Pa DPOAE amplitude per the fitted line.
  (Boege & Janssen, 2002)
Two slope method (Neely et al., 2009) leads to further improvement.

Abnormal OHCs and loudness recruitment
“The phenomenon of loudness recruitment appears to be the psychoacoustic expression of the loss of a large component of outer hair cells and the concurrent preservation of a large component of inner hair cells and type I cochlear neurons.”

Schuknecht HF. Pathology of the Ear (2nd ed). 1993, p. 91

Steps in Analysis of DPOAE Findings
- Perform analysis at all test frequencies
- Verify adequately low noise floor (< 90% normal limits)
- Verify replicability of DPOAE amplitude (+/- 2 dB) from at least two runs
- Is DP - NF difference > 6 dB?
  - Yes? DPOAEs are present
  - No? There is no evidence of DPOAEs
- Is DP amplitude within normal limits?
  - Yes? DPOAEs are normal
  - No? DPAOEs are abnormal (but present)

Ear canal factors influencing OAE measurement
- Non-pathologic
  - probe tip placement, size, or condition
  - probe insertion depth
  - standing waves
  - cerumen or debris
  - vernix casseous (healthy newborn infants)
- Pathologic
  - stenosis
  - external otitis

Clinical application of otoacoustic emissions (OAE): Trouble-shooting
- Minimizing the effects of noise on OAE recordings
  - eliminate extraneous noise sources in test room
  - close door to test room
  - insert probe deeply
  - secure probe cord
  - instruct patient to remain quiet and still (if feasible)
  - position test ear away from equipment
  - modify protocol (to frequencies > 2000 Hz)

Ventilation tubes and OAEs
- Tilanus. Stenis, Snik.(1995). Otoacoustic emission measurements in evaluation of the effect

**AUDIOGRAM & DPOAEs:**
Pre-ventilation tubes (5 y.o. girl)

**AUDIOGRAM & DPOAEs:**
Ventilation tubes (4 mos. later before APD eval.)

**Non-factors in OAE Interpretation**
- Non-Factors
  - diurnal effects (time of day)
  - genetics
  - body temperature
  - body position
  - anesthetic agents (w/ normal middle ear status)
  - state of arousal (attention to stimulus)

**Six Reasons Why OAEs Will Never Replace the Audiogram nor Accurately Estimate Hearing Loss**
(1-3)
- OAEs measurement is dependent on inward and outward propagation of energy through the middle ear (e.g., abnormal OAEs with normal hearing sensitivity)
- OAEs are more sensitive to cochlear dysfunction than the audiogram (e.g., abnormal OAEs with normal hearing sensitivity)
- OAEs are electrophysiologic measures while the audiogram is behavioral (e.g., normal OAEs with abnormal audiogram)

**Six Reasons Why OAEs Will Never Replace the Audiogram nor Accurately Estimate Hearing Loss**
(4-6)
- OAEs are produced by OHCs, whereas the audiogram is dependent on IHCs (e.g., normal OAEs with abnormal audiogram)
- OAEs are pre-neural, whereas the audiogram is dependent on retrocochlear pathways (e.g., normal OAEs with abnormal hearing sensitivity)
- OAEs reflect OHC integrity, whereas the audiogram measure hearing (e.g., normal OAEs with abnormal audiogram)

**Functional Role of Auditory Efferents**
- Protection from noise.
- Disrupted function in neuropathy.
- Role in learning and learning disability.
- Signal detection and localization in noise.
CAS leads to reduction in SOAE magnitude and increase in SOAE frequency

- The direction of change in SOAE level and frequency reflects changes in BM vibration magnitude and phase.
- Slow effects are minuscule if any.
- Changes in SOAE frequency shows an "intermediate effect."
- Absence of slow effects detracts from role in protection from noise trauma.

Tuning of MOC Efferents

- Contralateral tones near 750 Hz appear to be most effective in inhibiting SOAEs of all frequencies.
- Cat MOC fibers have a second lobe of sensitivity at a lower frequency.
- These data would suggest that this secondary lobe is dominant in humans (and the primary tuning peak is absent).
- Could be a difference due to anesthesia. Then we could be witnessing the effect of the entire cortico-fugal system in the human, versus the olivocochlear system in cats.

Distortion Product OAEs

General Methods
- 8 normal-hearing young adults.
- Best estimate of middle ear muscle reflex > 90 dB SPL.
- DPOAE recorded using stimulus tones swept in frequency between 1 and 4 kHz.
- Broad band noise (0.1 - 10 kHz) presented in contralateral ear at 60, 70, and 80 dB SPL.
- +CAS conditions bracketed by two -CAS conditions.

Greater reduction in CF component could explain DPOAE enhancement in valleys.
The magnitude of the CF component is reduced more than the magnitude of the overlap component on efferent stimulation (also observed by Abdala et al., 2009).

Efferent stimulation also causes fine structure patterns to shift toward higher frequencies. (Mauermann & Kollmeier, 2004; Sun, 2005, 2008; Purcell et al., 2008, Abdala, 2009)

Change in slope of CF component phase.
Change in slope of CF component phase.

CF component phase changes more than overlap component phase on efferent activation.

Clinical Considerations
Stuck at one frequency
Following a peak
Tracking frequency shift
Practically speaking...

- Efferent modulation of OAEs can be complex with changes in both magnitude and phase.
- Both clinicians and scientists appear to be interested in the phenomenon and its reliable measurement.

Questions?