Clinical Interpretation of Distortion Product Otoacoustic Emissions (DPOAEs)

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Otoacoustic Emissions

- First described by David Kemp, 1978
- Low level sounds that originate from the cochlea (outer hair cell activity); by-product of normal hearing process
- Propagate through the middle ear and external auditory ear canal
- Measured in the ear canal using a sensitive microphone
Otoacoustic Emissions

- Objective indirect measure of cochlear function, specifically outer hair cell (OHC) function
- Reflect nonlinear and sharply tuned micro-mechanics of the normal hearing process
- Preneural – do not require 8th nerve function
OAEs and Identification of Hearing Loss

- Normal cochlea behaves nonlinearly
  - Source of nonlinearity is the OHC system
  - Healthy, functioning OHCs required for normal hearing
- OAEs are byproducts of normal nonlinear function
  - Loss of OAEs indicates damage to the OHCs
Loss of OAEs

OHC damage

Infer hearing loss is present
OAEs generally present at normal levels in ears with normal hearing, absent or present at reduced levels in ears with hearing loss.

- Many ears with mild hearing loss have OAEs, it is hard to distinguish normal from mild hearing loss.
- Having present OAEs (for typical clinical protocols) generally suggests normal hearing or no more than a mild hearing loss.
- For typical clinical protocols the vast majority of ears with moderate to profound hearing loss have absent OAEs.
Types of OAEs

- Spontaneous
- Evoked
  - Transient Evoked OAEs (TEOAEs)
  - Distortion Product OAEs (DPOAEs)
  - Stimulus Frequency OAEs (SFOAEs)
DPOAE
Stimulus and Response
Typical clinical stimulus conditions

- **Stimulus levels:**
  - $L_1 = 65$ dB SPL, $L_2 = 55$ dB SPL

- **Stimulus frequencies:**
  - $f_2/f_1 = 1.22$
  - $f_2$ often set equal to audiometric frequency. Why?

- Many studies suggest these conditions, particularly $L_1, L_2 = 65, 55$ dB SPL, are most accurate for identifying hearing loss (e.g., Stover et al., 1996; Johnson et al., 2007; 2010).
Goal: Identify Ears with Hearing Loss

How does response from normal ears differ from impaired ears?
Next figure shows DPOAE levels for normal and impaired ears.

- DPOAE level as a function of $f_2$
- Data from normal (left panel) and impaired (right panel) ears are shown
- Parameter is percentage, from 5th to 95th percentiles
- Filled symbols represent the DPOAE levels at the median (50th) percentile
DPOAEs in Normal & Impaired Ears

Gorga et al. (1996)
Overlap Between Normal and Impaired Responses

- No criterion can be selected that completely separates responses from the normal and impaired ears.
  - Some impaired ears produce bigger responses than some normal ears
  - And, some normal ears produce smaller responses than some impaired ears
Development of Template

- Study: Gorga et al. (1997, E&H)
- Data from 1257 normal and impaired ears
- $L_1/L_2 = 65/55$ dB SPL
- All data collected under clinical conditions
- Constructed cumulative distributions
Cumulative distributions & Template Construction
Cumulative distributions & Template Construction
Using the template

Must judge influence of noise

1. If SNR ≥ 6 dB, plot DPOAE level on template, interpret accordingly
2. If SNR ≤ 6, how noisy was the response?
   - If noise falls below the lower lines on the template (impaired region), plot and interpret accordingly
   - If noise falls above the lower lines on the template (impaired region) responses contaminated by noise and can’t be interpreted

Uncertain region

- Diagnosis is uncertain for responses in the shaded region, even if SNR ≥ 6 dB, because responses here could be from either normal or impaired ears.
### Example Case #1

<table>
<thead>
<tr>
<th>f2 frequency</th>
<th>DPOAE level (dB SPL)</th>
<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>8</td>
<td>-10</td>
<td>18</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>-13</td>
<td>16</td>
</tr>
<tr>
<td>4000</td>
<td>2</td>
<td>-10</td>
<td>12</td>
</tr>
</tbody>
</table>
Case 1
Case 1: Results Consistent with Normal Hearing

- Low noise levels even for lower $f_2$’s
- Large DPOAEs
- Positive SNRs at all $f_2$’s
- Levels above 95th percentile for impaired ears
- Results consistent with normal hearing because few impaired ears produce such large responses
<table>
<thead>
<tr>
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<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>8</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>4000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Case 2
Case #2: High Noise Levels = Uninterpretable Responses

- “Large” DPOAEs
- High noise levels
- Low SNRs
- Results are uninterpretable because “large” DPOAEs may be nothing more than noise
- Note that the DPOAE levels were similar to Case #1
<table>
<thead>
<tr>
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<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>-14</td>
<td>-15</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>-18</td>
<td>-17</td>
<td>-1</td>
</tr>
<tr>
<td>4000</td>
<td>-18</td>
<td>-20</td>
<td>2</td>
</tr>
</tbody>
</table>
Case #3: Low SNRs & Low Noise Levels can be Interpreted

- DPOAEs below the lower limits of graph
- Noise levels also are low
- Low SNRs (i.e., DPOAE level was not measured reliably)
- Results are consistent with hearing loss because the reason a response was not measured was NOT due to high levels of noise, but to low level of response.
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<tr>
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<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0</td>
<td>-11</td>
<td>11</td>
</tr>
<tr>
<td>2000</td>
<td>-6</td>
<td>-14</td>
<td>8</td>
</tr>
<tr>
<td>4000</td>
<td>-6</td>
<td>-20</td>
<td>14</td>
</tr>
</tbody>
</table>
Case 4
Case #4: DPOAEs in the region of uncertainty

- DPOAE levels in shaded region
- Noise levels well below DPOAEs
- Positive SNRs, meaning DPOAEs were measured reliably
- Results cannot be assigned to normal or impaired distribution
### Example Case #5

<table>
<thead>
<tr>
<th>f2 frequency</th>
<th>DPOAE level (dB SPL)</th>
<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0</td>
<td>-2</td>
<td>2</td>
</tr>
<tr>
<td>2000</td>
<td>-5</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>4000</td>
<td>-6</td>
<td>-5</td>
<td>-1</td>
</tr>
</tbody>
</table>
Case 5
Case #5: Uninterpretable DPOAEs in Region of Uncertainty

- DPOAEs in shaded region
- Noise levels = DPOAE level
- SNRs approximately = 0
- DPOAEs therefore are not reliable
- Results cannot be interpreted because measured “responses” may be just noise, but this cannot be known
<table>
<thead>
<tr>
<th></th>
<th>DPOAE level (dB SPL)</th>
<th>Noise level (dB SPL)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>-14</td>
<td>-21</td>
<td>7</td>
</tr>
<tr>
<td>2000</td>
<td>-16</td>
<td>-23</td>
<td>7</td>
</tr>
<tr>
<td>4000</td>
<td>-16</td>
<td>-23</td>
<td>7</td>
</tr>
</tbody>
</table>
Case #6: SNRs > 6 dB, Responses in Impaired Region

- Although SNRs all > 6 dB, the DPOAE Levels indicate impaired OHC function, consistent with hearing loss

- Important to evaluate both response level and noise independently, not just the SNR
Bad News - Good News

- **Bad news:**
  - Errors in diagnoses are inevitable when OAEs are used to identify hearing loss.
  - This is true for other tests, not just OAE tests.

- **Good news:**
  - When auditory status is uncertain, it is more likely that we are confusing normal and mild hearing loss.
  - It is much less likely that we are confusing normal hearing with moderate or greater losses.
Multivariate Approaches
Typical Goal of OAE Testing

- Identify auditory status
- Does this ear have normal hearing or impaired hearing?
Predicting Auditory Status: Univariate Approach

- Responses interpreted by looking at information from one frequency

- For example:
  - Is the SNR at 2kHz > 6 dB and was the DPOAE level at 2kHz consistent with normal or impaired hearing?
Predicting Auditory Status: Univariate Approach

- Performance is not perfect, responses from normal and impaired ears can look the same.
- Uncertain region on clinical forms comes from this overlap.
Predicting Auditory Status: Multivariate Approach

- Measurements (DP level, noise) made at several frequencies can be used to predict auditory status at a single frequency.

- Why do this?
  - Normal at one frequency, likely normal at other frequencies.
  - Impaired at one frequency, likely impaired at other frequencies.
Predicting Auditory Status: Multivariate Approach

- Need to know which frequencies help most in prediction
- How?
  - Use logistic regression
Logistic Regression

- Specifies which variables and associated coefficients most accurately separate a normal from an impaired ear
  - Variables = DPOAE levels and noise values at different $f_2$ frequencies
  - Coefficients = multipliers for the variables
- Generates an equation that transforms DPOAE and noise levels into LF score.
  - LF score can be used to predict auditory status.
Simplified (!) example of LR equation

\[ LF_{4000} = (0.068 \times DP_{2000} + 0.038 \times DP_{3000} + 0.172 \times DP_{4000}) + (-0.087 \times N_{3000} + -0.082 \times N_{4000} + -0.051 \times N_{6000}) \]

- LF score is not a physical variable like DP level or noise but can be used to make decisions about auditory status
- Use LF templates to make decisions.
LF score (on ordinate) is a dimensionless number derived from logistic regression.
Multivariate Approach

- Gorga et al. (1999, 2005)
  - First to use a multivariate analysis with DPOAEs
  - New approach improved test accuracy
    - Dependent on degree of hearing loss and frequency
    - Never produced more uncertainty
    - Improvements seen in two different studies with different subjects
Does the Gorga et al. multivariate approach translate to a different clinic, different equipment, and pediatric only data set?

Tested this question using data from our clinic at KUMC.
Methods: Subjects & Inclusion Criteria

- Subjects selected from KUMC Audiology Clinic pediatric data
  - 24 subjects (n=47 ears)
  - Ages: 6 months to 16.5 years
- Inclusion criteria:
  - DPOAEs
  - Behavioral audiometric data (VRA, CPA, conventional)
  - Normal tympanometry
Methods: Behavioral & DPOAE Data

- Data extracted from our pediatric clinic records:
  - **Behavioral air conduction thresholds** from 1-4 kHz (interpolated at 1.5 & 3 kHz)
    - Each threshold was classified as normal (≤ 20 dB HL) or impaired (>20 dB HL)
  - **DPOAE and noise levels** from 1-6 kHz
    - DPOAEs classified as normal, uncertain, or impaired using BTNHR template
DPOAE and noise levels were converted to LF scores using the Gorga et al (2005) equations.

Example of the LF score computation at 4kHz:

\[ LF_{4000} = (0.068 \times DP_{2000} + 0.038 \times DP_{3000} + 0.172 \times DP_{4000}) + (-0.087 \times N_{3000} + -0.082 \times N_{4000} + -0.051 \times N_{6000}) \]

LF score was classified as normal, uncertain, or impaired by comparing to template.
Methods: Determining Accuracy

Truth (behavioral threshold) = Impaired
Methods: Determining Accuracy

- What was considered an “error”?
  - If DPOAE decision differed from behavioral threshold decision
    - N vs. I, I vs. N, uncertain vs. N or I
  - If LF decision differed from behavioral threshold decision
    - N vs. I, I vs. N, uncertain vs. N or I
  - If DPOAE was uninterpretable due to high noise levels/poor SNR
Results: Decision Univariate DPOAEs vs. LF Score

Correct

Test Condition
- 1500 Hz
- 2000 Hz
- 3000 Hz
- 4000 Hz

Proportion of Ears
- 0.0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0

DP Level
- LF Score

*p = 0.003
*p = 0.039

Errors

Test Condition
- 1500 Hz
- 2000 Hz
- 3000 Hz
- 4000 Hz

Proportion of Ears
- 0.0
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0

DP Level
- LF Score

*p = 0.003
*p = 0.039
Results: LF Only Errors

Rare for the LF score to make an error when univariate DPOAE had been correct
Discussion

- Increase in the number of correct decisions when using LF score vs. the univariate DPOAE
- Few cases where the LF score caused an error and the traditional approach did not
- Large contribution to improved decisions with LF scores was from cases where the univariate DPOAE was uninterpretable due to high noise levels and the LF score made a correct decision
Discussion

- Original formulas developed with the Biologic system generalized to the ILO system
- Multivariate approach does not require any more participation from the patient! It’s all data analysis after the fact.
Limitations

- Limited data for logit function equation
  - To compute all frequencies, you need DP emission and noise values for 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz
  - Do not typically collect DP\textsubscript{8000} or N\textsubscript{750}
    - Extrapolation of DP\textsubscript{8000} from DP\textsubscript{6000}
    - Did not use equations requiring N\textsubscript{750}
- Small sample size (n=47 ears); but consistent with other larger studies
Overall Conclusions

- BTNRH templates provide an evidence-based approach to interpreting DPOAE data based on a very large data set.
- It is important to look at both DPOAE level and noise levels when interpreting DPOAEs.
- Multiple studies (BTNRH and KUMC) suggest that the multivariate approach improves DPOAE test accuracy.
References


