Evaluation of cochlear compression using the generator component of distortion product otoacoustic emissions (DPOAE)

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ABSTRACT:

Our ability to process a wide dynamic range is a result of more amplification of low level sounds and less amplification of high level sounds (cochlear compression). Damage to the cochlear amplifier leads to a reduction of this compression, resulting in a reduced dynamic range. Input/Output (I/O) functions of distortion product otoacoustic emissions (DPOAE) can potentially provide a tool for evaluating cochlear compression. However, DPOAE I/O function structure (pseudo-periodic fluctuations in DPOAE amplitude and phase due to interactions of two components from different sources in the cochlea) introduces variability in estimates of DPOAE I/O functions. Separating the two components reduces this variability (Mauermann and Kolmer, JASA, 118, 2198-2207, 2005). The two components will be represented using logarithmic sweeping primary tones (Long et al., JASA 124, 1613-1626, 2003). The slope of the I/O function of the extracted generator component was estimated by dividing the I/O function into three linear segments. The estimated slope from mid-level stimuli provides an indication of compression. We found a highly significant correlation between the estimated I/O slope and behavioral thresholds from subjects with range of thresholds. Moreover, within each subject, changes in threshold across frequency were highly correlated with the estimated slope, consistent with expectations that increasing hearing loss leads to increased reduction of compression.

Introduction

Cochlear compression:

- Basilar Membrane (BM) velocity at the Characteristic Frequency (CF) is nonlinear and compressive.
- Compression is observed at moderate to high levels.
- Nonlinear compressive cochlear responses enable wide dynamic range of hearing.
- In individuals with hearing loss the dynamic range of hearing is reduced. The lowest detectable level (threshold) is increased, but the uncomfortable loudness level is usually not increased.

Using Distortion Product Otoacoustic Emissions (DPOAE) to evaluate BM linearity

- Direct measurement of BM linearity is invasive and possible only in animals.
- DPOAEs provide a non-invasive frequency-specific test reflecting BM linearity.
- Produced by two tones with frequencies f1 (lower frequency) and f2 (higher frequency) to the ear.
- When two tones are presented simultaneously, additional signals are generated in the healthy cochlea with frequencies not present in the stimulus (due to cochlear nonlinearity), such as 2f1-f2, 2f2-f1, f1-f2, f2-f1.
- The 2f1-f2 DPOAE usually has the largest amplitude when f1/f2 ≈ 1:2, consequently this DPOAE is frequency investigated.

DPOAE components:

- One of the limitations of DPOAE is that, they come from more than one region of the cochlea (see model in Poster 100).
- Separating the components of DPOAE can potentially give more information about cochlear linearity.
- Two major components: A: nonlinear generator component generated at region of maximum overlap of the primaries near f1, and B: linear reflection component near the DPOAE characteristic frequency.
- Constructive and Destructive Interactions of the two components creates maxima and minima in DPOAE level and phase which can be observed when doing high frequency resolution measurements (figure 1).

Method

- Subjects: 30 ears of 21 subjects
- DPOAE:
  - Ls ranging from 25 dB to 75 dB SPL in 10 dB steps.
  - Ls determined by scientists paradigm (Ls = 4 * L1 - 39).
- Logarithmic and descending tones (220Vc from 500Hz to 8kHz), 1:1:1:1:2:2.
- DPOAE level and Phase extracted using Least Square Fit (LSF).
- LSF is like moving narrow-band filter with moving center frequency in time with the changing DPOAE frequency.
- A component with shorter delay will fall within the filter bandwidth and will be detected by the filter.

Hearing Thresholds:

- Bekesy tracking procedure 250 ms on 250ms silence, 4 dB/oct Narrow-band noise (50%-20%)
- Less affected by threshold line structure.
- Frequency range 1 to 10 kHz 4 points per octave.

![Figure 1: DPOAE I/O function structure and separated components (solid lines) and noise floor (dashed lines) for a normal hearing subject for Ls levels of 25, 35, 45, 55, 65, and 75 dB SPL. Note the clear fine structure in the total DPOAE, relatively smooth curves for the generator component and a broader structure in the reflection component. In this subject, the reflection components are lower than the other component and less dependent on primary level.](image1)

The I/O function:

- The I/O function is a plot of DPOAE level as a function of Ls at a specific frequency (figure 2).
- In normal-hearing individuals the I/O function has a steep slope at low levels (high amplification of low level sounds).
- The slope decreases at moderate primary levels (reduced in Jansen and Mulders, 2008).
- The slope of the I/O function may be associated with the response growth in the cochlea and has been used to estimate cochlear compression (Naeve et al. 2009).

![Figure 2: Extraction of the I/O function at a specific frequency from the estimates of DPOAE generator component as a function of frequency shown in Figure 1.](image2)

Estimation of the slope of the I/O function:

- The slope of the I/O function between adjacent levels was calculated.
- The slopes were classified into three regions by evaluating the slopes of each pair of adjacent levels.
- The transition between regions (dotted lines in figure 3) was determined by grouping based on slope similarity.
- The region slope (compression region) is hypothesized to provide an indication of cochlear compression.

![Figure 3: Estimation of the I/O function from DPOAE generator components at a specific frequency (2 kHz). The dotted lines show the estimated slope of each region. The vertical dashed lines shows the transitions between regions.](image3)

Conclusion:

- The slope of the I/O function of uncorrected DPOAE includes rapid changes and in normal adjacent frequencies due to interaction of the two components.
- The generator component level changes slowly with frequency, providing less variable estimates of slope of across frequency.
- This reduced variability produces higher correlations between the slope of the compression area and behavioral thresholds.
- Reduced compression could be a sign of hearing damage. Lower compression (higher slope) is consistent with higher behavioral thresholds.
- The generator component alone may provide more useful estimates of cochlear damage.
- The failure of getting high correlation for reflection component may be due to its proximity to the noise floor.

Results:

The variability in the slopes estimates obtained using the total DPOAE (red line, figure 4) are larger than for the generator component (black line, figure 4) suggesting that the generator component provide more reliable estimates of compression. Even greater variability seem in the reflection component (green line, figure 4) may be due to proximity of this component to the noise floor.

![Figure 4: Estimated slope of the compression region for generator, reflection and uncorrected components as a function of frequency in the region of overlap. The reflection component is plotted as a function of the DPOAE frequency, while the other components are plotted as a function of f0 frequency reflecting the hypothesized cochlear regions responsible for the different components. The generator component varies more slowly with frequency than the other components. Bottom figure shows the psychological measurement for the same subject.](image4)