DPOAE Suppression Tuning Curves in Normal and Impaired Human Ears

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Underlying Purpose and Clinical Relevance

- Can we provide objective estimates of response growth in ears with hearing loss that will allow us to predict perceptual effects such as loudness growth?
- Can we provide estimates of the "gain of the cochlear amplifier" in humans and determine how much it is reduced by hearing loss?

Importance of Response Growth

- Adult patients with hearing loss sometimes experience abnormal loudness growth. It is reasonable to assume that some infants and children have similar experiences.
- Infants and young children cannot tell us if amplified sound is too loud.
- It could be important to know if infants and young children with hearing loss experience abnormal response growth that might correlate with loudness recruitment.

Cochlear-Amplifier Gain

- Auditory system can code level over a 120dB range
- It does this by providing amplification for low-level sounds (thus improving thresholds), and by providing compression for moderate level sounds (thus increasing the range of sounds that are tolerated).
- Cochlear hearing loss reduces gain at threshold, but also causes a loss of compression for moderate level sounds, resulting in a reduction of the dynamic range

Brief Comments on Auditory Physiology Related to Response Growth, Compression, and Cochlear-Amplifier Gain Best Frequency (BF) Responses Related to the Present Study

- Normal cochlear mechanical responses are compressive at BF, but are more linear (steeper) following a cochlear insult (Ruggero et al., 1991)
- BF single-unit rate-level functions may be steeper in ears with OHC damage (Evans, 1974; Sewell, 1984; Heinz et al., 2003).
- Thus, mechanical and neural responses may grow more rapidly when cochlear damage exists.

Off-Frequency Responses Related to the Present Study

- For low frequencies (relative to BF for a given cochlear place), response grows more linearly, less compressively with level (Rhode, 1971, Ruggero et al., 1997; Sachs & Abbas, 1974; Robles & Ruggero, 2001).
- Response growth for low frequencies relative to the BF for a given cochlear place does not depend on status of outer hair cells.
- For high frequencies (relative to the BF for a given cochlear place), the response grows very slowly with level.

Questions Related to Response Growth

- The data in these papers were collected in animals with induced lesions.
- Does best frequency response grow more rapidly in impaired ears compared to normal human ears?
- Is the frequency-dependent slope of response growth altered by hearing loss in humans?

Can We Evaluate These Cochlear-Response Properties in Humans?

- We cannot make direct mechanical or neural measurements in humans.
- On the other hand, indirect masking/suppression experiments can be used in humans.

Measurements in Humans

- In these indirect measurements, one signal serves as a probe whose level and frequency are fixed. Thus, it presumably results in the same response every time.
- Another stimulus serves as a masker/suppressor, whose level and frequency is varied.
- The response to the masker/suppressor at the cochlear place where the probe is represented is inferred from the changes to the probe response caused by the presentation of the masker/suppressor.

DPOAE Suppression Paradigm

- Probe consists of f_2 and f_1 , each of which is fixed during suppression measurements
- Probe level (L₂) also is fixed during suppression measurements
- Probe response in quiet (control condition) must be of some amount, so that changes in the response due to the presentation of a suppressor can be measured.

DPOAE Paradigm Continued

- Response to the fixed frequency (f₂), fixed level (L₂) probe is measured during the simultaneous presentation of a suppressor.
- Suppressor frequency (f_3) and level (L_3) are varied
- Response to the suppressors is measured as the decrement (amount of suppression) of the probe response as a function of f_3 and L_3 .
- Functions relating decrements to suppressor level can be viewed as measures of response growth to the suppressor at the probe frequency (f_2) place.

Stimulus Conditions

- Measure DP level in quiet (control condition) for a probe stimulus ($f_2 = 4 \text{ kHz}$)
- Measure DP level in presence of suppressors as a function of suppressor frequency (f₃) and level (L₃)
- Determine the extent to which the suppressor decrements the probe response (amount of suppression)
- Compare decrement vs. L_3 functions & suppression tuning curves in normal and impaired human ears

Subjects

- 22 ears of 20 normal-hearing subjects (mean threshold = 5.7 dB HL, SD = 4.4 dB)
- 23 ears of 21 hearing-impaired subjects (mean threshold = 36.3 dB HL, SD = 9.1 dB)
- All subjects had normal middle-ear function
- Subjects with mild-moderate hearing loss were "unusual" in that they produced DPOAE at L_2 levels of 50-70 dB SPL

DPOAE Input/Output Functions in Normal and Impaired Ears

Control Conditions: These are the conditions for which suppression experiments can be conducted. This is because a response of some level is needed in quiet if one is going to measure a reduction in these responses as a consequence of the presentation of the suppressor.



Control Condition Responses

- SNR provides an estimate of the dynamic range that can be used during suppression experiments.
- Probe responses (control conditions) had dynamic ranges (SNRs) of 20 to 35 dB for probe levels (L_2) from 20 to 70 dB SPL in normal-hearing ears.
- Probe responses had dynamic ranges (SNRs) of 15 to 25 dB for probe levels from 50 to 70 dB SPL in impaired ears.
- Thus, DPOAE suppression can be measured for probes of 20-70 dB SPL in normal ears and 50-70 dB SPL in impaired ears.

Normal DPOAE Decrement (Amount of Suppression) vs. L₃ Functions

Measures of response growth to the suppressor, at the place of the probe, as a function of suppressor level and frequency



Response Growth: Normal

- Left-most functions in each panel represent data for $f_3 \approx f_2$, and show the lowest thresholds.
- As one moves to the right in each panel, f_3 becomes increasingly distant from f_2 and threshold increases.
- Slopes of decrement functions are steep when $f_3 < f_2$. Slopes are shallow when $f_3 > f_2$.
- Pattern is similar to what would be predicted from mechanical and neural responses in lower animals with normal cochleae.

DPOAE Decrement (Amount of Suppression) vs. L₃ Functions in Impaired Ears

Measures of response growth to the suppressor, at the probe place, as a function of suppressor level and frequency



Response Growth: Impaired

- Same convention is used here as was used for decrement vs. L₃ functions in normal ears.
- Threshold increases as f_3 becomes more and more distant from f_2 .
- There seems to be less dependence of slope on frequency, compared to similar data from normal ears.

Estimating the Slope of Decrement vs. L₃ Functions

Estimates of the Rate of Response Growth

Fitting the Data

- Data transformation: $D = 10 \log (10^{dec/10} 1)$. When D = 0, decrement = 3 dB.
- Individual data points were weighted by their SNR, with high SNRs getting larger weighting.
- Points with SNRs < 3 dB were not included in fits.
- Only points that monotonically increased (i.e., decrement increased with L₃) were included in fits.



Examples of Fits to Transformed Data for low-, on- and highfrequency suppressors relative to probe frequency (f_2 , $f_2 = 4$ kHz)

- In the previous slide, open circles represent the original measured decrements.
- Triangles represent the transformed data.
- Filled small circles represent not included in the fit because of the SNR < 3 dB.
- Line represents the fit.
- Slopes of these lines were used to estimate rate of response growth.

Slopes of Decrement vs. L₃ Functions

Each panel shows data for a different probe level (L_2)

Solid line: Data from subjects with normal hearing Dotted line: Data from subjects with hearing loss



Rate of Response Growth: Slopes of Decrement vs. L₃ functions

- Slopes were steepest when $f_3 < f_2$ and shallowest when $f_3 > f_2$.
- This was true for all probe levels (L_2) .
- This was true in both normal and impaired ears.
- Ears with hearing loss showed slightly less difference in slope between low and high frequency suppressors, compared to ears with normal hearing.

Summary of Response Growth

- Indirect estimates of response growth are possible in normal & impaired human ears
- Response growth patterns in normal ears consistent with mechanical and neural data from animal studies
- Ears with hearing loss show less steep low frequency slopes, perhaps because measurements rely on estimates of relative response growth to probe and suppressor.

Tuning & Cochlear-Amplifier Gain in Normal Animal Cochleae

- Normal cochleae show sharp tuning around the tip of frequency threshold curves (FTC).
- Low-frequency tail occurs at a higher level, but remains relatively flat as frequency moves lower.
- Difference between threshold at the tip and threshold on the tail of the FTC provides a measure related to "cochlear amplifier gain" (Mills, 1998; Pienkowski and Kunov, 2001).

Tuning & Cochlear-Amplifier Gain in Impaired Animal Cochleae

- Tuning around the tip may broaden when cochlear damage exists
- The extent to which tuning broadens, however, may depend on magnitude of OHC damage or the amount of hearing loss, which are related (Dallos and Harris, 1978; Gorga and Abbas, 1981; Liberman and Dodds, 1984).
- Data from these same studies show reduced tip-totail differences, suggesting that cochlear-amplifier gain has been reduced.

Questions Related to Tuning in Normal and Impaired Human Ears

- How does mild-moderate hearing loss affect DPOAE suppression tuning curve shape?
- Do DPOAE STCs show reduced tuning when hearing loss exists?
- Is the tip-to-tail difference (cochlearamplifier gain) reduced as a consequence of cochlear hearing loss?

DPOAE Suppression Tuning Curves (STC) from Individual Subjects

Top panel: Normal-hearing subject **Bottom three panels:** Data from individual subjects with heairng loss

Parameter within each panel: Probe level (L2)

Notations within each panel: Q_{10} , Q_{ERB} , tip-to-tail difference



Data From Individual Subjects

- Sharpness around the tip (Q_{10}, Q_{ERB}) decrease as probe level (L_2) increases.
- Tip-to-tail differences (cochlear-amplifier gain) decreases as probe level increases
- These trends were present in both the normal ear and the ears with hearing loss

Mean DPOAE STCs from Normal (solid lines) & Impaired (dotted lines) Human Ears



Shapes of DPOAE STCs

- On average, DPOAE STCs from normal and impaired human ears look similar.
- There is a tendency for the low-frequency tail to occur at a lower level in impaired ears, compared to similar data from normal ears.

Constant SPL vs. Constant SL

- Impaired ears had mean behavioral thresholds at 4 kHz that were 30 dB higher than normal ears.
- Impaired ears produced DPOAEs in quiet that differed from normal ears at the same SPL, but did not differ when shifted by 30 dB (i.e, when SL was held constant).
- By collecting data in normal ears over a wide range of levels, we can compare normal and impaired results at the same SPL or at the same SL.

Q₁₀ and Q_{ERB} as a Function of Audiometric Threshold

Does tuning around the best frequency decrease as threshold increases?



Effects of Audiometric Threshold on Q

- Paradoxical increase in both Q values as audiometric threshold increases. However, the data were variable and the effect was observed only for the constant SPL condition.
- On balance, the data suggest that there is little change in tuning around the tip for hearing loss not exceeding 50-55 dB HL.

Mean Q values as a Function of Probe Level (L₂)



Summary of Tuning Properties

- Normal ears and ears with mild-moderate hearing loss show essentially the same tuning around the best frequency of DPOAE STCs
- The lack of an effect of hearing loss on tuning at the tip probably relates to extent of cochlear damage. Since these subjects all produced DPOAEs, there must have been some surviving OHC's in their cochleae. This hypothesis would be consistent with data from animal studies

An Alternative Explanation

- Suppression regions in FTC's of normal ears extend beyond their excitatory regions.
- DPOAE STC's in normal ears outline the wider suppression areas.
- DPOAE STC's in impaired ears might be outlining what may be an excitatory region that is broader than the normal excitatory region
- But, by including both excitatory and suppressive regions, normal and impaired ears appear to produce similar Q's.

Previous Tip-To-Tail Differences Related to the Present Study

- Threshold differences between the tip and tail of mechanical or DPOAE tuning curves are reduced following treatment with furosemide (Ruggero and Rich, 1991; Mills, 1998)
- Tip-to-tail differences on neural tuning curves are reduced when permanent cochlear damage occurs (Dallos and Harris, 1978; Gorga and Abbas, 1981; Liberman and Dodds, 1984)

Questions Related to Tip-to-Tail Differences in Humans

- Can tip-to-tail differences, based on DPOAE suppression measurements, be used to provide an indirect estimate related to "cochlear-amplifier gain" in humans?
- How does hearing loss affect these estimates of "cochlear-amplifier gain"?

Tip-To-Tail Differences (Cochlear-Amplifier Gain) as a Function of Audiometric Threshold

Does threshold elevation decrease cochlear-amplifier gain?



Cochlear-Amplifier Gain in Relation to Audiometric Threshold

- Gain decreases as threshold increases.
- Effect is observed when comparisons are made between normal and impaired human ears at the same SPL and at the same SL.
- Effect is largest when comparisons are made at the same SL.

Mean Estimates of Cochlear-Amplifier Gain

- Top panel: suppressor level (L3) needed for 3 dB of suppression as a function of probe level (L2) in normal ears
- Middle panel: L3 needed for 3 dB of suppression as a function of L2 in impaired ears.
- Parameter in top two panels: suppressor frequency (f3)
- Bottom panel: tip-to-tail differences as a function of L2.
- Parameter in bottom panel: auditory status



Summary of Estimates of Cochlear-Amplifier Gain

- "Gain" decreases as level increases in both normal and impaired ears
- Added to this level effect on "gain" is an effect of hearing loss, which further reduces "cochlear-amplifier gain"

Overall Summary

- We can estimate response growth, but the measurements are limited to hearing losses not exceeding about 50 dB HL
- We can estimate changes in "cochlear amplifier gain", but again, measurements are limited to ears with no worse than about 50 dB HL thresholds
- It remains unknown if these objective measures relate to perceptual consequences of hearing loss, such loudness recruitment or abnormal growth of masking

Long-Term, Pie-in-the-Sky Goals

- Predict perceptual consequences of hearing loss from objective measurements in humans
- Use these data to select hearing-aid characteristics, such as compression threshold and compression ratio, for infants and young children.