Delays and Growth Rates of Multiple TEOAE Components

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INTRODUCTION

Previous work has suggested that transient-evoked otoacoustic emissions (TEOAEs) elicited at low levels are generated primarily by linear coherent reflection[4]. Recent work has suggested that TEOAEs contain multiple energy peaks with different delays and magnitude growths[2]. This study used time- and frequency-domain analyses to examine these peaks. The purposes of this study were to:

1) **Investigate delays and growth rates of multiple TEOAE peaks as a function of stimulus level.**
2) **Compare results obtained using linear and nonlinear extraction methods.**
3) **Determine if the base of the cochlea is involved in the generation of early TEOAE peaks.**
4) **Investigate the effect of multiple energy peaks on calculation of group delay.**

METHODS

Transient stimuli (1- 4 kHz bandwidth, 2 ms duration) were presented at a rate of 33.3 clicks per second to 18 normal-hearing ears and 2 ears with severe sensorineural hearing loss using an ER-10C probe assembly. Seven stimulus levels were used (45-75 dB peSPL, in 5 dB steps). TEOAEs were extracted using linear and nonlinear double-evoked[5] paradigms. Five ears had synchronous spontaneous OAEs and were excluded from the analysis. To test the hypothesis that early components are generated more basally to later components, three ears were also tested with the addition of ipsilateral highpass masking noise (3.2 – 20 kHz bandwidth), mixed acoustically. To reduce basal stimulation directly related to the bandwidth of the eliciting stimulus, bandwidth of the transient was reduced to 1 – 3 kHz. Noise level was adjusted on an individual basis to reduce the level of the $2f_1$-f_2 DPOAE at 2.5 kHz (f_2=4 kHz, f_2/ f_1=1.22) by $\geq$ 6 dB while maintaining a signal-to-noise ratio (SNR) $\geq$ 12 dB.

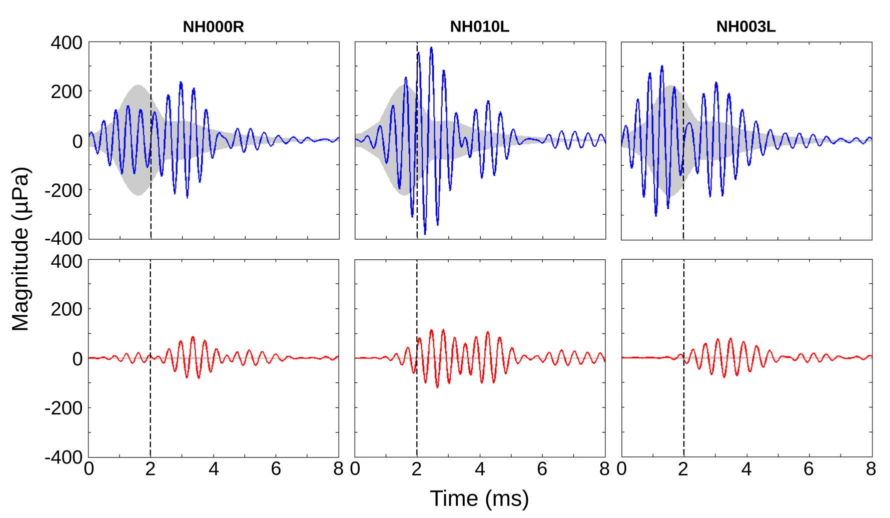

Fig 1. TEOAE waveforms obtained at 75 dB peSPL using linear extraction (top row, blue) and nonlinear extraction (bottom row, red). Waveforms were filtered with 1/3-octave wide FIR filters centered at 2.52 kHz. For linear extraction, waveforms were time-windowed prior to filtering to reduce signal artifact. Data are shown for three normal hearing subjects. Gray shaded regions represent the envelope of the artifact measured in an artificial ear and subject with severe SNHL. Time zero is relative to the stimulus peak. Analysis began at 2 ms (dashed line), as excessive stimulus artifact occurred prior to this time when using linear extraction.

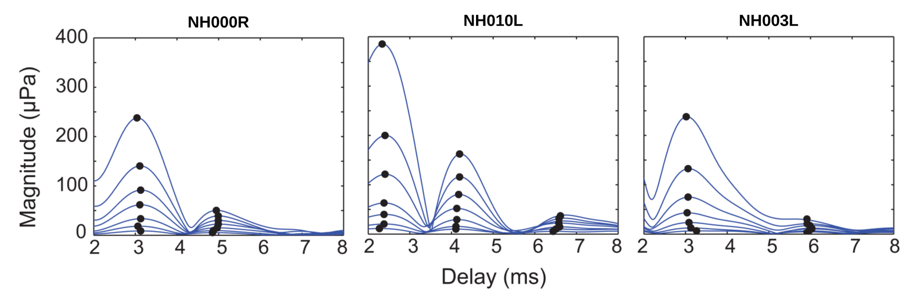

Fig 2. Time domain analysis of data obtained from the subjects shown in Fig 1 (linear extraction). Envelopes were obtained from the magnitude of the analytic signal. Each envelope corresponds to one of seven stimulus levels. Filled circles show locations of envelope peaks. Most subjects had two peaks, though some had one or three peaks. At the highest stimulus level, the majority of peaks had a $\geq$ 6 dB signal-to-artifact ratio (see Fig 1), with larger ratios at lower stimulus levels (not shown). The locations of the envelope peaks were used to examine changes in magnitude and delay with stimulus level.

RESULTS

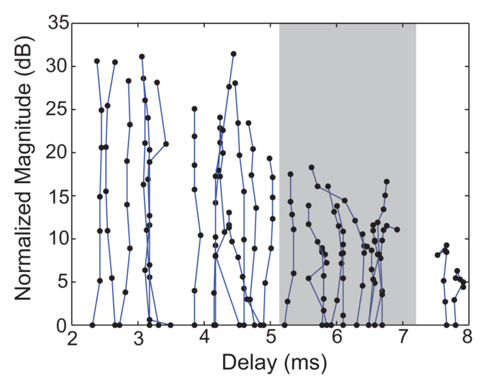

Fig 3. Level series of envelope peaks obtained by linear extraction (25 series, 13 ears). The level series of each energy peak (see Fig 2) is represented by a single line. For each series, responses to the lowest stimulus level were normalized to 0 dB. Small filled circles show the normalized response magnitude at each stimulus level. The gray shaded region shows the 95% confidence interval of expected SFOAE latency[6]. **Delay:** Most lines are nearly vertical, indicating constant delay across stimulus level. Peak delays are spread across 2 – 8 ms, with the exception of two gaps. Peaks after 7 ms may be due to multiple internal reflections. **Growth:** The length of lines indicates magnitude growth. There appears to be an orderly progression of growth with delay, demonstrating that growth becomes increasingly compressive with increasing delay.

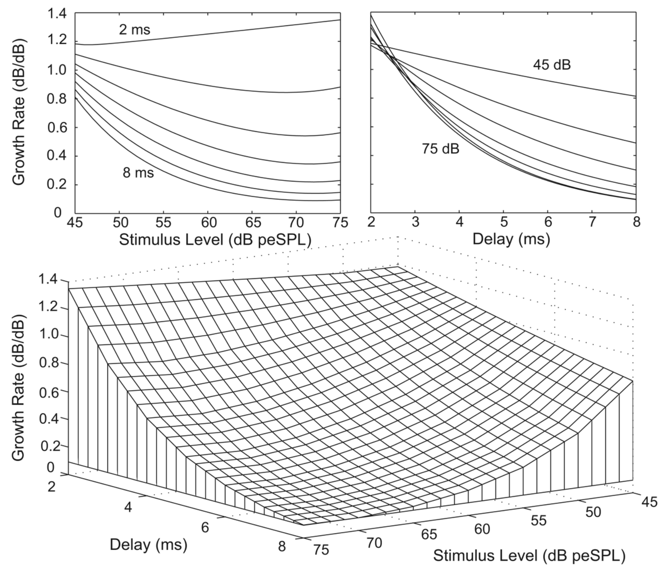

Fig 4. Growth rates as a function of stimulus level and peak delay (linear extraction). The normalized magnitudes of each level series were fit with an exponential function. The fits were then differentiated to determine growth rates (dB/dB). Linear growth is indicated by a value of 1. Top panels display growth rates as a function of stimulus level (left) and peak delay (right). Each line in the top left panel represents a peak delay (2 – 8 ms, top to bottom). Each line in the top right panel represents a stimulus level (45 – 75 dB peSPL, top to bottom). The bottom panel shows the data combined in a three-dimensional surface plot.

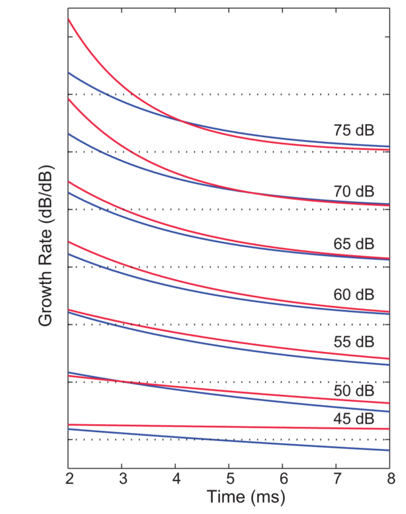

Fig 5. Growth rates for each stimulus level obtained using linear (blue lines) and nonlinear (red lines) extraction. Dotted lines represent linear growth. For early peaks elicited at high stimulus levels, nonlinear extraction showed more expansive growth relative to linear extraction. There were fewer differences between extraction methods for early peaks elicited at lower stimulus levels and for later peaks at all stimulus levels. Overall, the choice of extraction method has the largest effect on growth rates for early peaks elicited at high stimulus levels.

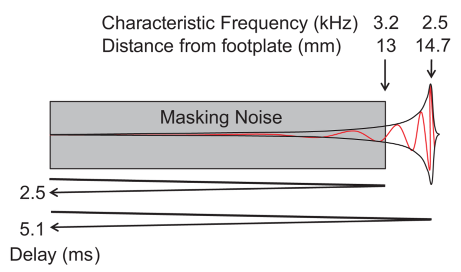

Fig 6. Schematic of the highpass masking condition. A traveling wave is shown for a 2.5 kHz stimulus. Masking noise is shown by the gray box. Arrows represent two locations on the basilar membrane: the place corresponding to the lower cutoff frequency of the noise, and the peak of the traveling wave. Approximate round-trip delay for a 2.5 kHz SFOAE reflected from each location is shown at the bottom[1,3,6]. Because emissions generated basal to the peak of the traveling wave will have gone through fewer phase rotations, travel times can be much faster than emissions generated at the peak. In this scenario, it is possible for a 2.5 kHz component to be reflected from the 3.2 kHz place, and have a round-trip delay of 2.5 ms. Our results are consistent with the possibility that early components are generated by a place-fixed reflection mechanism occurring apical to the 3.2 kHz place.

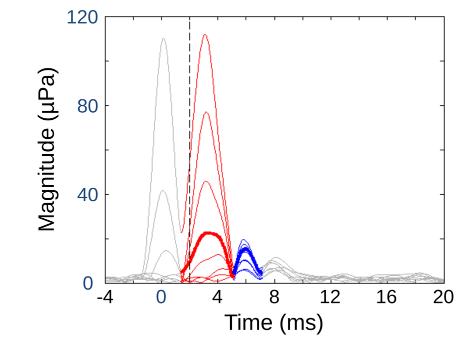

Fig 7. Early (red) and late (blue) components as a function of time across different levels for subject NH007L using nonlinear extraction. The response to a stimulus of 65 dB peSPL (thick lines) was specifically examined because the two energy peaks were approximately equal in magnitude at this input level.

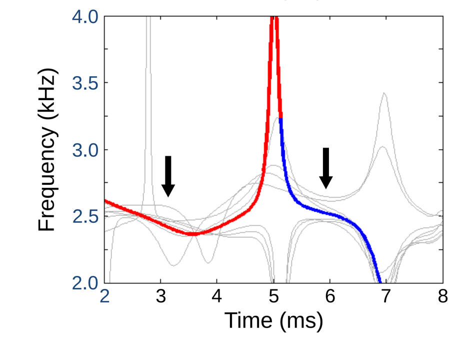

Fig 8. Instantaneous frequency of early (red) and late (blue) energy peaks corresponding to thick lines in Fig 7. Gray lines show instantaneous frequency for responses at other stimulus levels. Instantaneous frequency was calculated as the derivative of the analytic signal phase (unwrapped) with respect to time. Both energy peaks appear to have similar frequency content. Black arrows show the time locations of the envelope peaks.

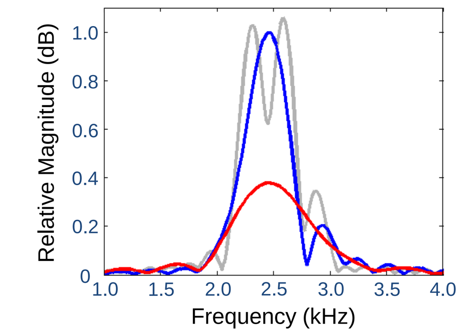

Fig 9. Relative magnitudes of early (red) and late (blue) energy peaks as a function of frequency, calculated as the DFTs of each waveform separately. The gray line shows magnitude of the DFT across both waveforms. Note the notch in the combined magnitude (gray) near 2.5 kHz, which suggests a phase interaction between energy peaks at this frequency.

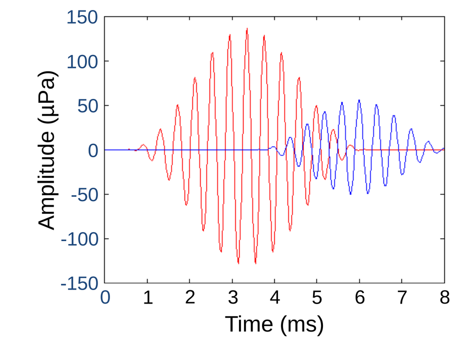

Fig 10. A model of interaction. The phases at 2.5 kHz were obtained at the peak of each component using a least-squares fitting procedure. Model envelopes were chosen to be consistent with those shown by the thick lines in Fig 7. The two energy peaks were found to be out of phase at 2.5 kHz, resulting in partial cancellation where the waveform envelopes overlapped. Further analysis of the model yielded results similar to those in Figs 8 and 9 (not shown).

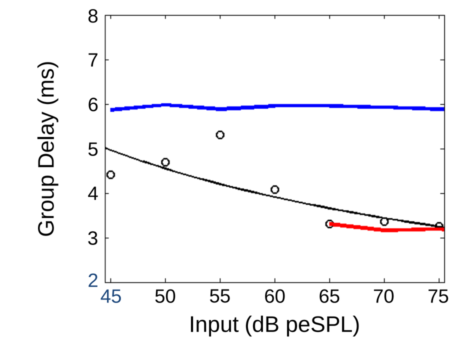

Fig 11. Delay as a function of input level. The peaks of early (red) and late components (blue) are approximately constant. Black circles show group delay calculated from the phase gradient (including both energy peaks). The black line shows a fit using a power function. The change in phase gradient does not appear to represent actual changes in delay. Rather, it is consistent with different growth rates of early and late components.

CONCLUSIONS

1) **TEOAE peak delays are generally constant across stimulus level. Growth is most compressive at the highest stimulus levels for energy peaks having the longest delays.**
2) **Nonlinear extraction shows more expansive growth than linear extraction, specifically for short-delay energy peaks evoked by high stimulus levels.**
3) **Place-fixed reflections from locations somewhat basal to the traveling wave peak could potentially account for the growth and delay of early energy peaks.**
4) **Early and late energy peaks can be out of phase with each other, resulting in partial cancellations and misleading group delay values when analyzed together, e.g. via DFT.**

ABSTRACT

Bandpass-filtered transient-evoked otoacoustic emissions (TEOAEs) show multiple energy peaks with time delays that are invariant with level and growth rates that vary with delay and level, suggesting that multiple generation mechanisms may be involved at moderate and high stimulus levels. We measured delays and magnitude growths of multiple TEOAE energy peaks and compared the results obtained from linear and nonlinear extraction methods. To test the hypothesis that early components are generated at the base of the cochlea, delays and growth rates were also measured in the presence of highpass masking noise for a subset of subjects. No effect of the highpass masking was seen. The results are discussed in terms of potential generation mechanisms of the multiple energy peaks.

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