

# Delays and growth rates of early and late CEOAE components

Ian B. Mertes      Shawn S. Goodman

Department of Communication Sciences and Disorders, The University of Iowa, Iowa City, Iowa 52242

## INTRODUCTION

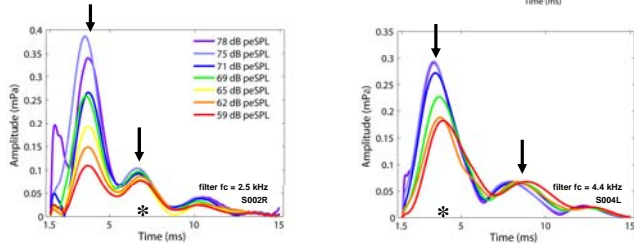
Previous work has suggested that click-evoked otoacoustic emissions (CEOAEs) are primarily generated by linear coherent reflections<sup>1</sup>. Other recent work has suggested that CEOAEs contain two or more components with differing delays and amplitude growths<sup>2</sup>. In previous analyses the growth and relative size of the early component may have been affected by use of a nonlinear extraction technique. Here we report amplitude and latency measurements of early and late components using linear extraction (time windowing).

## METHODS

Band-limited clicks with energy from 2-4 kHz were presented through an ER-10C probe assembly at a rate of 13 per second, using a sampling rate of 200 kHz. Seven stimulus levels were used, from 59 dB to 78 dB peSPL. The number of averages varied from 250 to 2000, according to stimulus level. Responses were obtained from 9 normal-hearing subjects (age 10 to 27 yrs).

**Figure 1.** Recording from a subject's ear after averaging (blue line). The peak of the stimulus impulse was defined as time zero. The CEOAE analysis window (gray region) was ramped on with a Hann window starting at 1.5 ms. Recordings made in an artificial ear coupler (not shown) were used to determine the earliest the analysis window could start while avoiding stimulus artifact.

**Figure 2.** Example of a CEOAE before (gray) and after (blue) filtering with a 1/6-octave bandpass FIR filter (700 taps; filter group delay corrected for). Filter center frequencies varied between 2-4 kHz, and were chosen individually for each subject to achieve good signal-to-noise ratios and to avoid synchronous spontaneous OAEs.



**Figure 3.** The envelopes of the filtered waveforms were calculated as the magnitude of the discrete Hilbert transform. Most envelopes contained two or more distinct peaks (black arrows). Additional peaks were also seen. Amplitudes and latencies were calculated for the first two peaks with latencies greater than 2.5 ms. Peaks occurring earlier than 2.5 ms were suspected of including middle ear effects; later peaks were interpreted as evidence of multiple internal reflections. Expected SFOAE latencies<sup>3</sup> are shown by asterisks.

## RESULTS

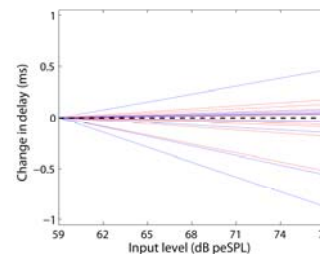
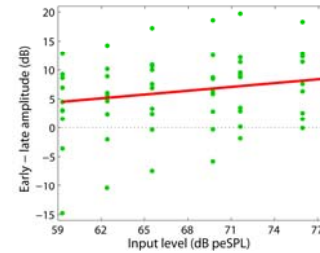
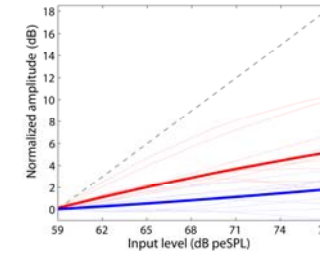
### AMPLITUDE GROWTH WITH STIMULUS LEVEL

**Figure 5.** Amplitude growth functions. For each subject, the peak amplitudes from the early and late components were fitted with quadratic polynomials using a robust least-squares procedure. Growth of the early components (thin red lines) and later components (thin blue lines) are shown for individual subjects. The dashed black line indicates linear growth. To facilitate comparison, the fits were normalized to zero at the lowest input level. The median growth of the early component (thick red line) was significantly less compressive than the growth of the late component (thick blue line) for the four lowest stimulus levels.

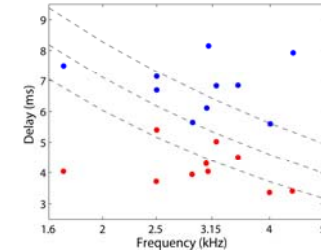
**Figure 6.** Peak amplitude difference between early and late components. Dashed line denotes no difference in amplitude. Values that fall above the dashed line indicate the early component is larger in amplitude. The red line shows a linear fit to the data. Over the range of levels tested, the early component was generally larger in amplitude and that difference increased with stimulus level.

### CHANGE IN DELAY WITH INCREASING LEVEL

**Figure 7.** Change in envelope peak delay as function of stimulus level. For each subject, the 7 peak delays from the early and late components were fit with a line using a robust least-squares procedure. Changes in delay of the early components (thin red lines) and later components (thin blue lines) are shown. To facilitate comparison, the fits were normalized to zero at the lowest input level. Dashed black line indicates no systematic change in delay. Negative change indicates that delay decreased with increasing level. The mean slopes of the components were not significantly different from zero, indicating a general level-invariance for the delay of both components.



**Figure 8.** Peak latency as function of emission frequency. Red dots show early components and blue dots show late components. The dashed lines show the mean and 95% confidence interval values previously reported for low-level SFOAEs<sup>3</sup>. Given that multiple peaks were present in many filtered CEOAE envelopes, use of the descriptors "early" and "late" is potentially misleading. At lower filter center frequencies, the latencies of the early component tend to be shorter than expected if CEOAEs and SFOAEs share the same generation mechanism. At higher filter center frequencies the "late" component may be a multiple internal reflection.



## DISCUSSION

These measurements indicate significant responses occurring within the first 5 ms after the onset of an impulse stimulus. In many previous analyses the relative size of this component may have been reduced by the choice of analysis window and by nonlinear extraction techniques. Based on the latencies and the compressive growth functions, the responses shown are thought to be OAEs. However, there is potential for middle-ear muscle reflex and medial olivocochlear reflex contributions to the measured responses. Future work will examine ways of separating cochlear responses from other contributors.

Both early and later components grow compressively, but the early component grows less compressively, especially at lower stimulus levels. This finding is consistent with Goodman et al.<sup>2</sup>, who reported that the compressiveness of CEOAE growth increases with latency.

The envelope peaks of the early and late components appear to be invariant with level, consistent with some previous reports<sup>2,4</sup>. Many studies reporting CEOAE delay use the slope of the unwrapped phase. If portions of both early and later components are included in the FFT analysis, the resulting delay is expected to correspond to the energy-weighted average of the two components. Because the earlier component grows less compressively, inclusion of the early component when calculating group delay can make it appear as if emission latency decreases as stimulus level increases.

## CONCLUSIONS

- In the range of 2-4 kHz, a CEOAE component occurs within the first 5 ms after stimulus onset. The amplitude of this early component is dependent on stimulus level, and can be large relative to the later-occurring component.
- Both early and later components grow compressively, but the early component grows less compressively, especially at lower stimulus levels.
- The envelope peaks of the early and late components are invariant with level.

## ABSTRACT

Click-evoked otoacoustic emissions (CEOAEs) contain early- and late-delay components. Many CEOAE measurements reduce the early component through time windowing or nonlinear residual techniques. Growth rates and time delays of both components were measured as a function of stimulus level using time windows that retained the early component. Band-limited clicks (2-4 kHz) were presented at 7 levels (59-78 dB peSPL) to normal-hearing subjects. CEOAE envelopes were analyzed using 1/6-octave bandpass filters and Hilbert transform magnitudes. Early peaks had larger amplitudes and grew less compressively than late components. Envelope delays were invariant with level.

## CONTACT

ian-mertes@uiowa.edu

shawn-goodman@uiowa.edu

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<http://www.uiowa.edu/~comsci/research/arl/ARLhome.html>

## REFERENCES

1. Kalluri & Shera (2007). *JASA*
2. Goodman et al (2009). *JASA*
3. Shera, Guinan, & Oxenham (2002) *PNAS*
4. Carvalho et al. (2003). *JASA*