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Delays and Growth Rates of Multiple TEOAE Components

Shawn S. Goodman, Ian B. Mertes, and Rachel A. Scheperle

Department of Communication Sciences and Disorders, The University of Iowa

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 stimulus 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 basal portion 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.

Keywords: transient-evoked otoacoustic emissions, growth, delay, multiple components, generation mechanisms

PACS: 43.64.Jb, 43.64.Kc, 43.64.Ri

INTRODUCTION

Otoacoustic emissions (OAEs) may be composed of multiple components generated by one or more mechanisms. Distortion-product (DP) OAEs have wave-fixed and place-fixed components generated by distortion and reflection sources, respectively [9, 15]. Stimulus-frequency (SF) OAEs may be generated by an early component having a slowly-rotating phase and a late component with a rapidly-rotating phase [11]. Transient-evoked (TE) OAEs have been shown to have multiple energy peaks with differing time delays and growth rates [1, 4]. Similar findings have been reported for DPOAEs [12] and SFOAEs [2].

In humans, SFOAEs and TEOAEs are believed to be generated by place-fixed coherent reflection, at least at low stimulus levels [6, 8]. At higher stimulus levels, it is possible that TEOAEs may have a distortion component [4, 13, 14].

The purpose of this study was to investigate multiple TEOAE components with regard to time distribution, magnitude growth, and delay as a function of stimulus level. The magnitude growth functions obtained using linear and nonlinear extraction methods were compared. Potential generation mechanisms are discussed in relation to these characterizations.

METHODS

Transient stimuli (1–4 kHz bandwidth, 2 ms duration) were presented to 18 normal-hearing ears at 7 levels (45–75 dB peSPL, in 5 dB steps). Five ears had synchronous spontaneous emissions, and were excluded from analysis. Presentation and recording

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were made using an ER-10C (Etymōtic Research) probe assembly and custom MATLAB software on a PC. Stimuli were presented at a rate of 33.3 clicks per second, and 1000 averages were obtained for each stimulus level. Emissions were extracted using a linear paradigm and a double-evoked nonlinear residual paradigm [7]. For the nonlinear paradigm, suppressor clicks were presented at 12 dB above the probe clicks.

Averaged TEOAE waveforms were filtered with a 1/3-octave wide bandpass finite impulse response filter centered at 2.52 kHz and corrected for group delay. Waveform envelopes were calculated as the magnitude of the analytic signal

$$\text{env} = \sqrt{x^2 + \hat{x}^2}, \tag{1}$$

where $\hat{x}$ is the Hilbert transform of the waveform, x. Envelopes were examined to locate energy peaks. Time zero was defined as the peak of the stimulus. The analysis window began at 2 ms in order to avoid stimulus artifact. The absence of stimulus artifact after 2 ms was verified in an artificial ear and a subject with severe sensorineural hearing loss.

Three ears were also tested with the addition of ipsilateral highpass masking noise. For this condition, the bandwidth of the 2 ms transient stimulus was reduced to 1–3 kHz and was presented at 75 dB peSPL. Masking noise (3.2–20 kHz bandwidth) was mixed acoustically with the transient stimulus. The level of masking noise was adjusted until a $2f_1 - f_2$ DPOAE at 2.5 kHz ($f_2 = 4$ kHz, $f_2/f_1 = 1.22$) was reduced by at least 6 dB while maintaining a 12 dB or greater signal-to-noise ratio. This noise level was used during presentation of transient stimuli. Analysis of these TEOAE waveforms was performed using the same analysis described above.

RESULTS

Figure 1 shows the envelopes obtained for three subjects. Multiple energy peaks are present in all three subjects. Within subjects, peak delays were nearly constant across stimulus level, allowing construction of a level series for each set of peaks having similar delays. In contrast to the stability of individual peaks across level, the delay location of the peaks was variable across subjects.

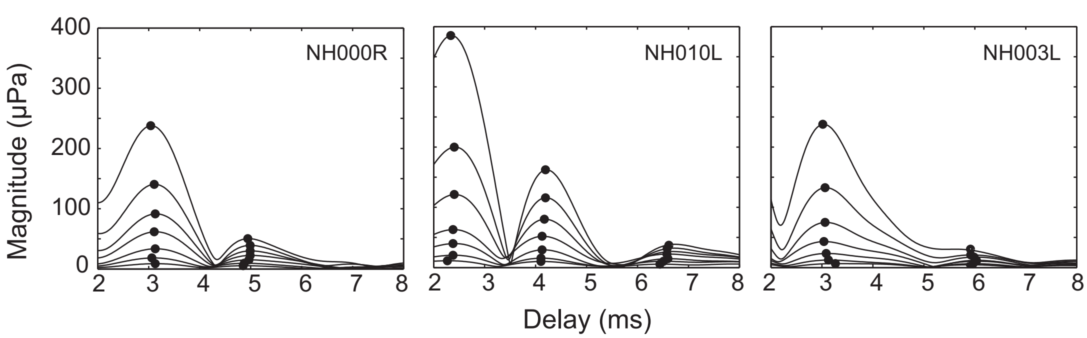

FIGURE 1. TEOAE envelopes (linear extraction mode). Each panel shows data from a different subject. Each envelope corresponds to one of seven stimulus levels (45–75 dB peSPL). TEOAE peaks, identified using a peak-picking algorithm, are shown by small dots. Level series were constructed for each energy peak for all ears and are plotted in Fig. 2.

The magnitudes of early peaks grew faster with stimulus level than later peaks.

Figure 2 shows the level series of all ears tested. Each level series is represented by a single line. Peak magnitudes were expressed in dB SPL and normalized so that the lowest magnitude was zero. Most of the lines are nearly vertical, indicating constant delay across stimulus level. Although a few of the lines have a slope, indicating increasing or decreasing delay with stimulus level, no systematic trend was seen. Given that each line shows the peak magnitudes across all seven stimulus levels, shorter lines represent more compressive growth than longer lines. The orderly arrangement of line length demonstrates that growth becomes increasingly compressive with longer delays. Note that peak delays are spread evenly across the range of 2–8 ms, with the exception of a gap at 7 ms and a smaller gap at 3.5 ms. 7 ms is the expected upper limit of SFOAE delays for 2.5 kHz tones [10]. Peaks with delays longer than 7 ms likely represent multiple internal reflections. It is uncertain whether a true gap exists around 3.5 ms. If so, it might separate peaks into "early" and "late" components; however, more data might show the distribution to be essentially continuous.

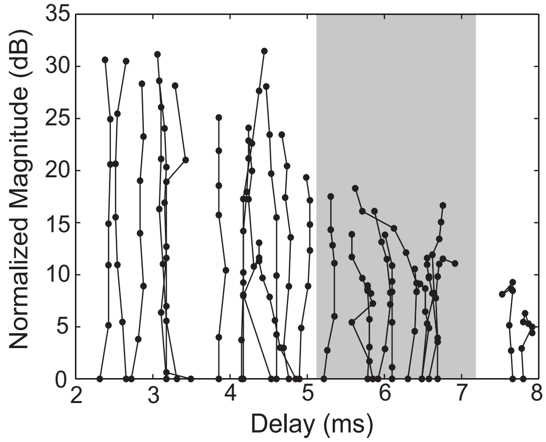

FIGURE 2. Normalized peak magnitudes and delays (25 series, 13 ears) obtained by the linear extraction paradigm. Each level series is represented by a single line. Small filled circles (obtained from the peak picking operation shown in Fig. 1) on the lines show the magnitude at each of the seven stimulus levels. The gray shaded region shows the 95% confidence interval of expected SFOAE latencies [10].

A quantitative description of growth rates is shown in Fig. 3. Growth rates were determined as follows: Each level series was fit with an exponential function of the form

$$y = ae^{bx} + ce^{dx}, \quad (2)$$

where x is stimulus level in dB peSPL. The resulting fits were differentiated to obtain the growth rates (dB per dB). The growth rates of the individual level series were then used to obtain the fits shown in Fig. 3. For each stimulus level, growth rates as a function of peak delay (top right panel) were determined using an exponential fit of the form

$$y = ae^{bx}, \quad (3)$$

where x is delay in ms. For integer delays between 2 and 8 ms, growth rates as a function of stimulus level were determined using an exponential fit [Eq. (2)]. Combining these two functions (bottom panel) shows that growth is most compressive for peaks with long delays elicited by high stimulus levels. Growth is expansive for peaks with short delays elicited by low stimulus levels.

Previous work has described growth rates for TEOAEs extracted using a nonlinear paradigm [4]. Because nonlinear paradigms cancel any linear growth of the TEOAEs,

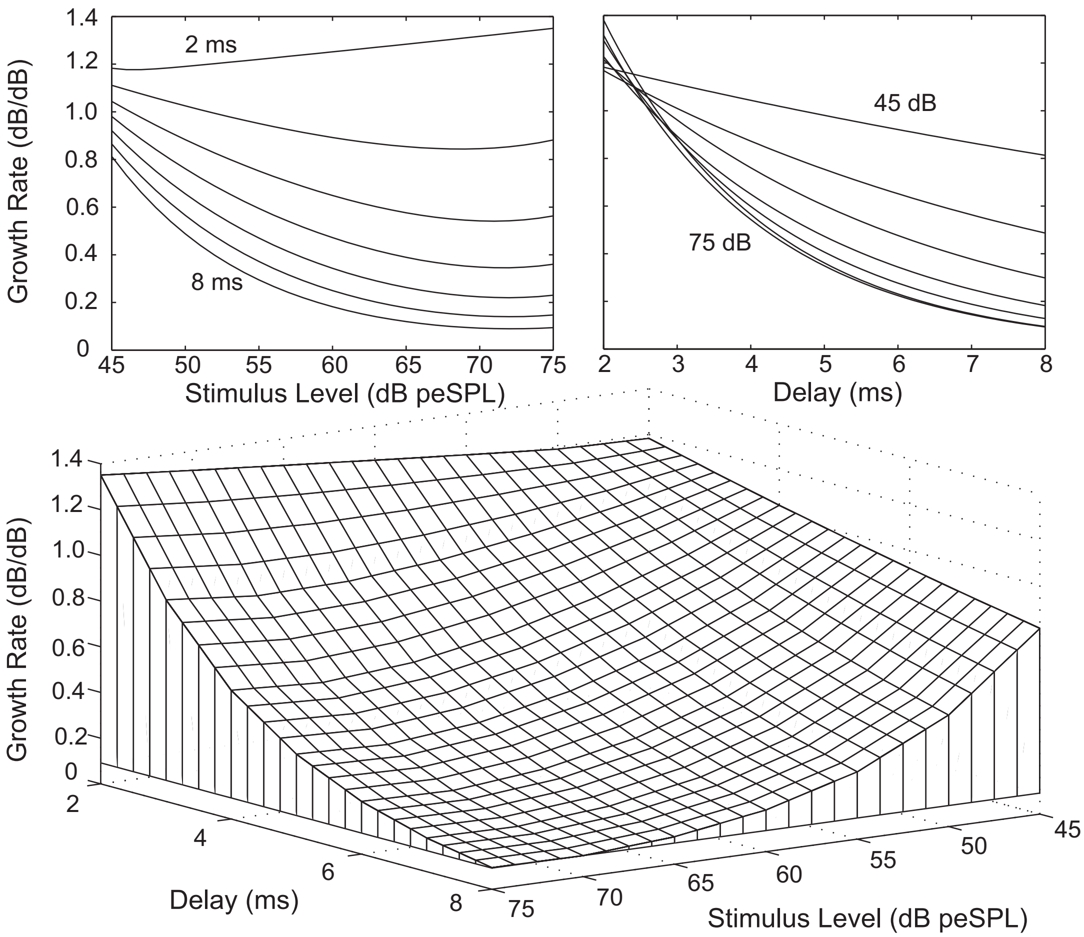

FIGURE 3. Growth rates as a function of peak delay and stimulus level (linear extraction mode). Linear growth is indicated by a value of 1. The top panels display growth rates as a function of stimulus level (left) and peak delay (right). Each line in the top left panel represents a peak delay (2, 3, 4, 5, 6, 7, or 8 ms, from top to bottom). Each line in the top right panel represents a stimulus level (45, 50, 55, 60, 65, 70, and 75, from top to bottom). The bottom panel shows the data combined in a three-dimensional surface plot.

it was of interest to compare growth rates obtained using both nonlinear and linear paradigms. Figure 4 shows a comparison of growth rates obtained using the two paradigms. Overall, growth rates were higher when using nonlinear extraction. At high stimulus levels, nonlinear extraction showed more expansive growth of early peaks, while both extraction methods showed similar compressive growth for later peaks. At lower stimulus levels, the growth rates of early peaks were similar between the two methods. The constant expansive growth across time demonstrated by the nonlinear extraction at the lowest stimulus level may be an artifact arising from poor signal-to-noise ratio. Taken together, these data show that extraction method has the largest effect on growth rates for peaks early in time elicited by higher stimulus levels.

DISCUSSION

Our data show the following:

1. TEOAEs at a given frequency region are composed of multiple energy peaks.
2. Across ears, these peaks appear to be distributed nearly continuously in time.
3. Within ears, peak delays are generally constant across stimulus level.
4. Growth rates of peaks decrease (growth is more compressive) with increasing delay and increasing stimulus level.

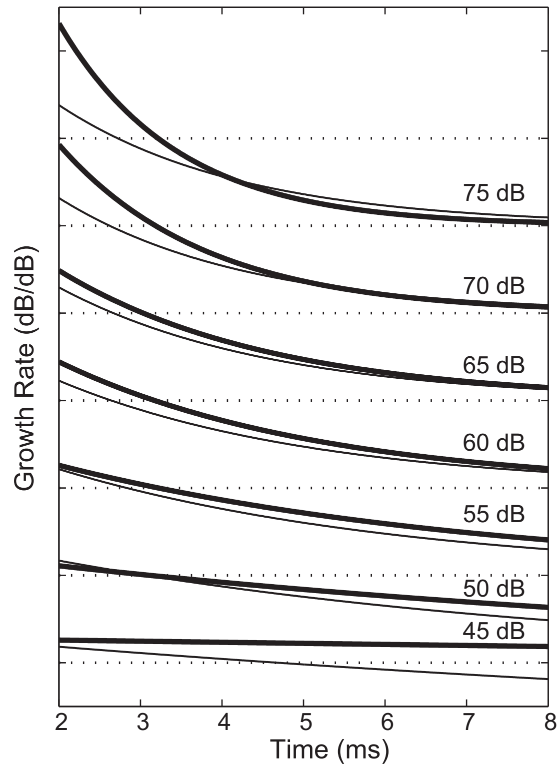

FIGURE 4. Growth rates obtained using linear (thin lines) and nonlinear extraction (thick lines). The stimulus level for each set of responses is shown. Dotted lines represent linear growth.

TEOAEs, in a manner similar to SFOAEs, are thought to be generated by a coherent reflection mechanism located near the peak of the traveling wave [6]. TEOAE peaks occurring early in time, however, must be generated from a different place and/or by a different mechanism. As a preliminary investigation into the generation of early peaks, we repeated our measurements in three subjects with the addition of highpass masking noise. The presence of masking did not affect the magnitudes or delays of the peaks compared to responses obtained without noise. This suggests that the early components were not influenced by $2f_1 - f_2$ distortion products (see Methods section), though it does not rule out the presence of other distortion sources. We also calculated group delay for early and late peaks (not shown). Although the phases of early peaks rotated less rapidly than late components, rotations were consistent with the peak delays generated by a reflection source, which is not consistent with a wave-fixed distortion generation mechanism.

It has also been suggested that early components arise from basal sites in the tail region of the traveling wave. Our results do not support that early peaks arise from the most basal regions of the cochlea. A schematic of the masking paradigm is shown in Fig. 5. A possible explanation for the generation of early TEOAE energy peaks is place-fixed reflections from locations somewhat basal to the peak. The expected lower limit of round-trip delay for a 2.5 kHz SFOAE was 5.13 ms [10]. Using a cochlear model from Geisler [3], the number of cycles to the peak of the traveling wave was 5, and the number of cycles to the location corresponding to the masking cutoff frequency was 2.5. Travel times were approximated by dividing the total number of cycles to the peak by the forward SFOAE delay, yielding the delay per cycle. Because components generated basal to the peak of the traveling wave will have gone through fewer phase rotations, their travel times can be much faster than components generated very near the peak. In this scenario, it is possible for a 2.5 kHz component being reflected from the 3.2 kHz place to have a round-trip travel time of approximately 2.5 ms, which is consistent with our data. The increasingly linear growth of earlier components is also consistent with generation sites basal to the peak of the traveling wave.

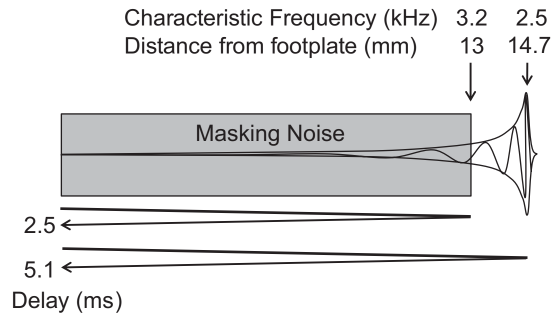

FIGURE 5. Schematic of masking condition. Traveling wave shown for 2.5 kHz stimulus. Masking noise is shown by the gray box. Distance from stapes calculated using Greenwood map [5].

ACKNOWLEDGMENTS

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COMMENTS AND DISCUSSION

Christopher Shera: A very nice analysis. Any thoughts on how to understand the gap at 7 ms? That is, thoughts on why there should never be a maximum in the time-domain waveform near the expected SFOAE delay time?

Sarah Verhulst: Have you investigated the spectra of the waveforms after you band-pass filter the recorded TEOAE with the 1/3rd octave wide filter? I am wondering whether there was only one frequency component in those waveforms or whether there were multiple evoked components. In case of multiple evoked components, have you considered a possible relation between the beating frequency of the evoked components and the delay of the envelope peaks?