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An alternate approach to constructing distortion product otoacoustic emission (DPOAE) suppression tuning curves[a)]

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Abstract

DPOAE suppression tuning curves (STCs) typically are constructed using suppression criteria of 3 or 6 dB. This paper describes a technique for generating DPOAE STCs using criteria ranging from 3 dB to complete suppression. The criterion effect was examined at various primary levels (f_2 = 4 kHz) in normal-hearing ears. As expected, Q_{ERB} and tip-to-tail differences decreased as probe level (L_2) increased. Q_{ERB} values were not systematically dependent on criterion. For low L_2's, tip-to-tail differences decreased as criterion increased. Given similarities in methodology, DPOAE STCs constructed from completely suppressed responses might be most appropriate for comparison to psychophysical tuning curves.

I. INTRODUCTION

Distortion product otoacoustic emissions (DPOAEs) have been measured using a suppression paradigm. Suppression tuning curves (STCs) constructed from these measures may be compared to tuning curves obtained from other methods, such as psychophysical masking experiments in humans. Because the slope of functions relating amount of suppression to suppressor level varies with suppressor frequency, the shape of the DPOAE STC constructed from these functions might depend on the suppression criterion used to construct it. DPOAE STCs frequently are constructed using suppression criteria of either 3 or 6 dB (e.g., Abdala, 2001; Abdala and Fitzgerald, 2003; Abdala et al., 1996; Brown and Kemp, 1984; Gorga et al., 2002; Gorga et al., 2003; Martin et al., 1998b, 2003). These criteria, however, represent only partial reduction of the DPOAE response and, as such, are not directly analogous to tuning curves generated from psychophysical masking experiments in which the probe is rendered inaudible. In this paper, we propose a method for generating DPOAE STCs, based on the fully suppressed condition, that may be more similar to the conditions from which psychophysical tuning curves are constructed. We also examine the influence of suppression criterion on the shape of the DPOAE STC as described by Q_{ERB} and the tip-to-tail difference.

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II. METHODS

A. Subjects

Data from 22 ears of 20 subjects with normal hearing were included in the analyses presented here. Normal hearing was defined as thresholds ≤ 15 dB HL (re: ANSI, 1996) at 4 kHz. The mean threshold at 4 kHz was 5.7 dB HL.

B. Stimuli

Stimulus generation (and data collection) was accomplished using custom designed software (EMAV, Neely and Liu, 1993) that controlled a sound card (CardDeluxe, Digital Audio Labs) housed in a PC. The stimuli were delivered via loudspeakers housed in an ER-10C probe-microphone system. The probe frequency (f_2) was fixed at 4 kHz with a primary frequency ratio (f_2/f_1) of 1.22. The level of f_2 (L_2) varied in 10-dB steps from 20 to 70 dB SPL. The level of f_1 (L_1) was set according to the equation $L_1 = 0.4L_2 + 39$ dB (Kummer et al., 1998). Seventeen suppressor frequencies (f_3) were used, varying from 1 octave below to 1/2 octave above f_2. The level of the suppressor (L_3) was varied in 5-dB steps from 5 to either 85 or 90 dB SPL, depending on f_3.

C. Data collection

For each L_2, DPOAE levels were measured first in response to the primaries presented alone (the control condition). Next, the primaries were presented in the presence of a fixed suppressor frequency (f_3) that varied in level. This process was repeated until the f_3-level sequence had been repeated for each of 17 f_3's and each of 6 L_2's.

D. Analysis

Following data collection, DPOAE levels were converted to decrements (amount of suppression) by subtracting the level measured during each suppression condition from the level measured during the control condition. Mean decrement-versus-L_3 functions for 3 f_3's (one below, one approximately equal to, and one above probe frequency, f_2) are shown as solid lines in the upper panel of Fig. 1. In this figure, $f_2 = 4$ kHz and $L_2 = 40$ dB SPL. Because we were interested in constructing DPOAE STCs for a range of suppression criteria, including the condition where the response is fully suppressed, the maximum amount of decrement was calculated for each L_2. The signal-to-noise ratio (SNR) in the control condition (28 dB at this L_2) defines the maximum measurable amount of suppression and was used to define the point at which the response was suppressed to the noise floor. In the top panel of Fig. 1, the upper horizontal line is equivalent to the control-condition SNR when $L_2 = 40$ dB SPL. The lower horizontal line in the same panel indicates the point at which the response had been decremented (suppressed) by 3 dB.

Before generating DPOAE STCs, the decrement-versus-L_3 functions were transformed according to the following equation:

$$D=10 \quad \log\left(10^{\mathrm{decr}/10}-1\right). \tag{1}$$

When D = 0, the decrement is 3 dB. This equation served to linearize the functions and allowed points with high SNRs (i.e., decrements between 1 and 3 dB) to be included in the generation of a linear model for the data. The transformed data were then fit with a linear equation with the constraint that only decrements ≥ 1 dB were included in the fit and that there must be at least 3 L_3's producing decrements greater than 1 dB. Additionally, only functions including at least one condition for which at least 3 dB of suppression occurred were transformed with a linear equation. The r^2 values resulting from these fits ranged from 0.8 to >0.99 with 86% greater than 0.9. Those r^2 values falling below 0.9 were equally divided between low- and high-frequency suppressors. The linear equations were subsequently solved for decrements ranging from 3 dB to the fully suppressed condition (i.e., the point when the decrement equals the SNR in the control condition). DPOAE STCs were generated using these different suppression criteria.

These approaches to data analysis are also illustrated in Fig. 1. In the upper panel, the linear fits to the transformed data are shown as dashed lines. The open symbols represent 3-dB decrements (calculated from these linear fits) for the three suppressor frequencies shown in the figure. The closed symbols represent the corresponding complete-suppression condition. In the lower panel, these points are re-plotted as a function of frequency. The lines shown as tuning curves represent spline fits to these data, in combination with the data from the other 14 suppressor frequencies. The STCs that were generated using decrement criteria of both 3 dB and complete suppression are shown. It is important to note that, for some conditions (especially when $f_3 > f_2$), it was not always possible to fully suppress the DPOAE response, even when L_3 = 85 or 90 dB SPL. However, using the approach described above, it was possible to extrapolate to the L_3 that would be expected to fully suppress the response. In the lower panel, points above the horizontal, dashed line represent extrapolated values of L_3. The greatest difference in the STCs constructed from the 3-dB and fully suppressed criteria was observed when $f_3 > f_2$, less when $f_3 \approx f_2$, and least when $f_3 < f_2$.

III. RESULTS

A. Suppression tuning curves

Mean DPOAE STCs are shown in Fig. 2, with data for a different L_2 shown in each panel. DPOAE STCs are shown for suppression criteria ranging from a decrement of 3 dB to the fully suppressed condition (in 6-dB increments). In each panel, the lowest curve represents the DPOAE STC constructed from the 3-dB criterion and the highest curve represents the fully suppressed condition. In each panel, the circles shown on the upper- and lower-most curves indicate f_3's where the decrement-versus-L_3 function met the linear-fit inclusion criteria. Even for the highest L_2 (70 dB SPL), where it was more difficult to suppress the response, linear-fit inclusion criteria were met for 10 suppressor frequencies. At lower L_2's, the inclusion criteria were met for more suppressor frequencies. Data falling above the dashed, horizontal lines represent extrapolated values of L_3, as described above. As the criterion progressed from minimum (3-dB decrement) to maximum suppression, there was a systematic upward shift in the STC. At low L_2's, there tended to be a greater shift at the tip than on the low-frequency tail of the tuning curve. This effect was less evident at higher L_2's. Additionally, the low- and high-frequency slopes of the STC's changed as the suppression criterion was varied. As the suppression criterion increased, the slope of the high-frequency flank became steeper while the slope of the low-frequency flank became shallower.

B. Q_{ERB} and Tip-to-Tail Difference

The upper panel of Fig. 3 plots the Q_{ERB} values for the mean DPOAE STCs as a function of the suppression criterion used to construct the DPOAE STC. The lower panel plots the tip-to-tail difference for the same conditions, where the tip was defined as the lowest L_3 on each curve and the tail was defined as the L_3 when f_3 = 2 kHz (an octave below f_2). Within both panels, the parameter is L_2. Q_{ERB} is defined as the best frequency (BF) divided by the equivalent rectangular bandwidth (ERB). For any filter, the corresponding ERB is the bandwidth of the rectangular filter with the same BF response that passes the same total power. Q_{ERB} values for low probe levels were larger (indicating sharper tuning) than Q_{ERB} values for higher probe levels. The criterion used to construct the DPOAE STC had little systematic influence on Q_{ERB}. Across all criteria, the tip-to-tail difference decreased as L_2 increased, going from a maximum of about 45-48 dB for L_2 = 20 dB SPL down to approximately 16 dB for L_2 = 70 dB SPL. For L_2 = 20-50 dB SPL, the tip-to-tail difference decreased as the DPOAE response was more fully suppressed. At higher L_2's, the suppression criterion did not influence the tip-to-tail difference.

IV. DISCUSSION

With the exception of the tip-to-tail differences at $L_2 \leq 50$ dB SPL, the criterion used to construct the DPOAE STC had little influence on measures of cochlear tuning derived from the DPOAE STC (e.g., Q_{ERB}). Given the variation in the slopes of the decrement-versus-L_3 functions across suppressor frequency (see Fig. 1), it was expected that the shape of the DPOAE STCs constructed using different suppression criteria would change. Indeed, there are several reports in the literature that estimates of tuning became sharper as the criterion for constructing the DPOAE STC was varied from minimal suppression to greater amounts of suppression (e.g. Kummer et al., 1995;Martin et al., 1998a;Taschenberger and Manley, 1998). In the present data, the slope of the high-frequency side of the DPOAE STC increased as the response was more fully suppressed; however, this effect had little influence on estimates of tuning (Q_{ERB}) around the tip of the STC.

Tip-to-tail differences on DPOAE STCs previously have been viewed as measures related to "cochlear-amplifier gain" (Mills, 1998; Pienkowski and Kunov, 2001), and have been shown to decrease as probe level increases (Gorga et al., 2002, 2003). The decrease in gain, based on these measures, is a consequence of differences in growth of response to on- and low-frequency suppressors. The observations in the present study, in which tip-to-tail differences decreased as the response is more fully suppressed, is a consequence of the same underlying processes. That is, growth of response to suppressors below probe frequency (f_2) was more rapid, compared to suppressors close to f_2. As the criterion increases, this frequency-dependent difference in response growth results in a decrease in the difference between the L_3 required to produce the criterion amount of suppression for on- and low-frequency suppressors.

In our view, the most important result was the demonstration of an approach that enabled us to construct DPOAE STCs from any suppression criteria, including the fully suppressed condition. Because decrement-versus-L_3 functions were well described by linear fits to transformed data, it was possible to extrapolate to suppressor levels that were above the levels that could be produced by the hardware. Assuming this extrapolation was appropriate, this enabled us to extend the dynamic range of our measurements. Furthermore, by using the entire decrement-vs.-L_3 function to develop a linear model, reliable estimates of L_3 were possible for all conditions, including those for which the response was close to the noise floor (i.e., those conditions approaching the fully suppressed condition).

While there was little systematic influence of criterion on estimates of Q_{ERB} from DPOAE STCs, criterion did influence estimates related to cochlear-amplifier gain, particularly at the low to moderate L_2's that are similar to the levels used to construct psychophysical tuning curves. Furthermore, constructing DPOAE STCs based on the fully suppressed criterion may be methodologically more similar to conditions under which psychophysical tuning curves are constructed. In psychophysical tuning-curve experiments, the probe frequency and level are fixed and the level of the masker is varied until the probe is "at threshold" or just audible. Contrast this condition with the DPOAE condition, in which the response is only partially suppressed. The need to present probe and suppressor simultaneously complicates comparisons to other measurements that describe only the "excitatory" pattern of response. However, the completely suppressed response may be a more appropriate criterion for constructing DPOAE STCs when comparisons will be made with tuning curves constructed from threshold measurements such as psychophysical masking experiments.

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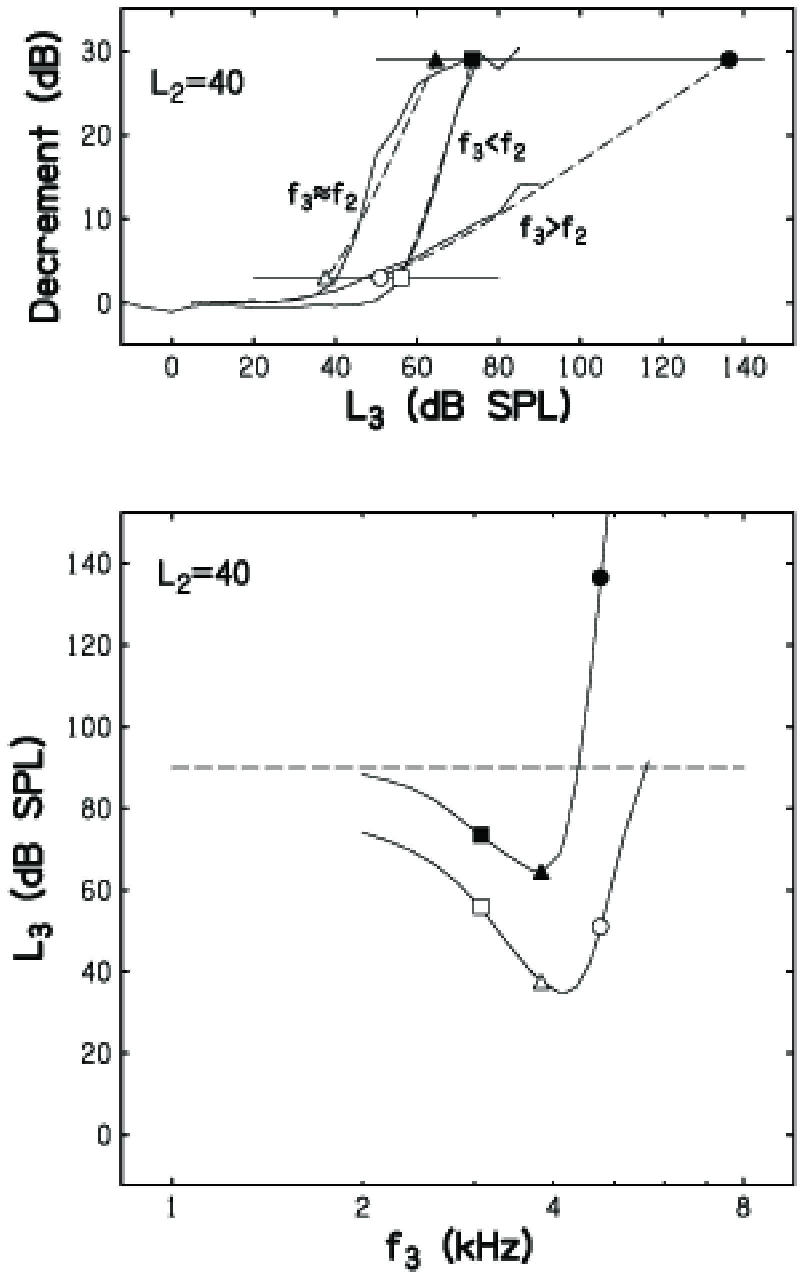

Fig. 1.

Illustration of the approach to data analysis. In both panels, the probe frequency (f_2) = 4kHz and the probe level (L_2) = 40 dB SPL. Upper panel: Mean decrement-versus-L_3 functions for 3 f_3's are shown as solid lines. The upper horizontal line represents the maximum amount of decrement and was determined by calculating the SNR in the control condition (28 dB in this example). This horizontal line, therefore, represents the point at which the response is fully suppressed into the noise floor. The lower horizontal line represents the point at which the response has been suppressed by 3 dB. The dashed lines represent the linear fits to the transformed data (as described in the text). The linear fits were solved for a range of decrements. The 3-dB decrement points are shown in the figure as open symbols for three different suppressor frequencies. The corresponding fully suppressed points are shown as closed symbols. Lower panel: Mean DPOAE STCs plotted as suppressor level (L_3) versus suppressor frequency (f_3) for two different suppression criteria, 3 dB (lower curve) and complete suppression (upper curve). The symbols plotted on the STCs correspond to the symbols displayed in the upper panel. The points on the upper curve above the horizontal, dashed line represent extrapolated values of L_3 (see text for more details).

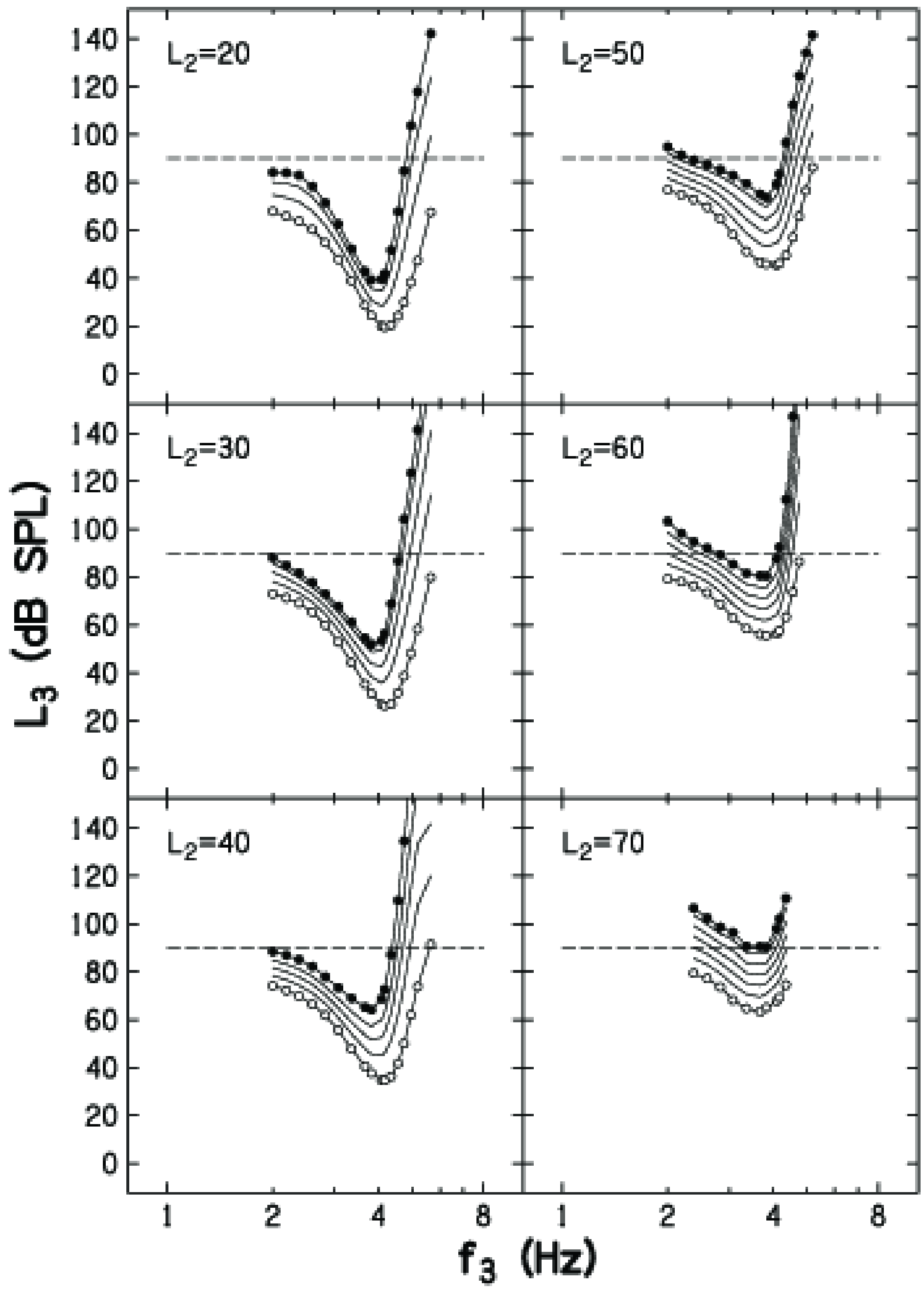

Fig. 2.

Mean DPOAE STCs. Each panel represents data for a different L_2. Within each panel, STCs are shown for suppression criteria ranging from 3 dB (open symbols) to complete suppression (closed symbols) in 6-dB increments. As in Fig.1, points falling above the horizontal, dashed lines do not represent measured suppressor levels, but rather are values extrapolated from the linear fits to the transformed decrement-versus-L_3 functions.

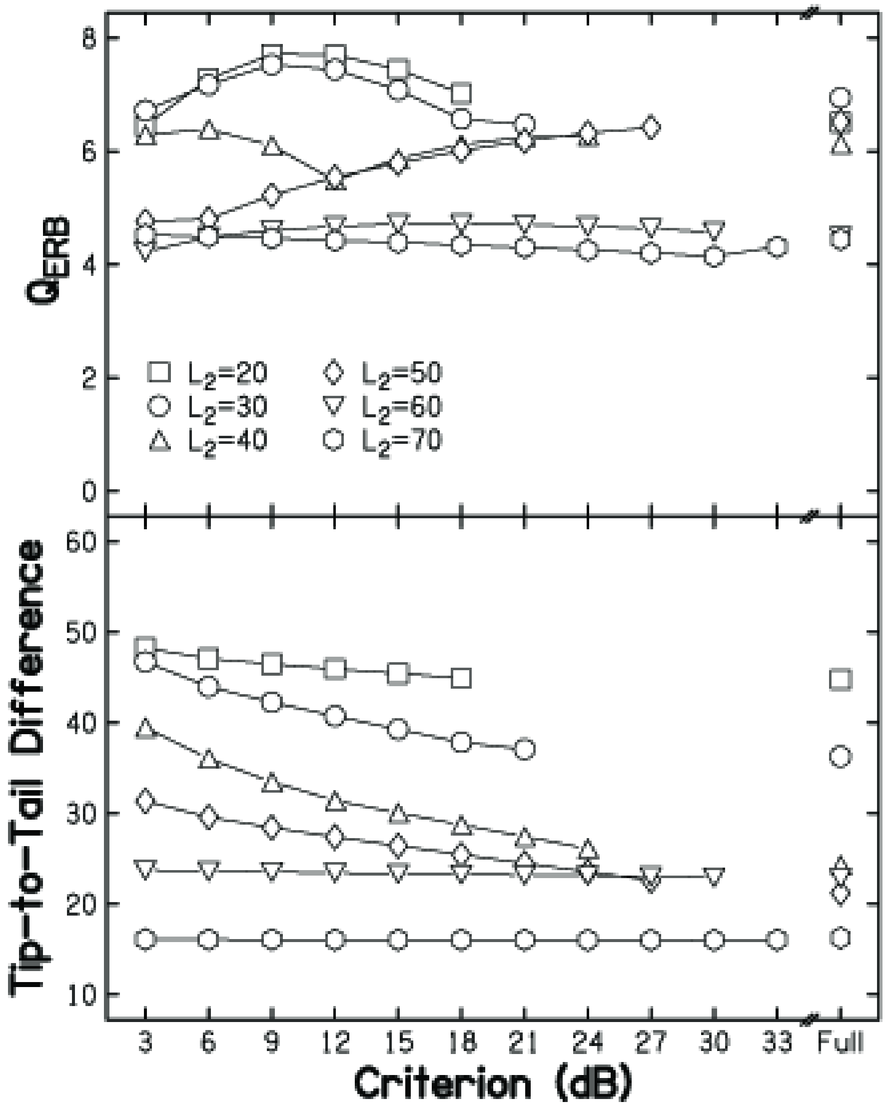

Fig. 3.

Q_{ERB} (upper panel) and tip-to-tail difference (lower panel) as a function of suppression criterion (dB). In both panels the parameter is L_2.