Slopes of distortion-product otoacoustic emission growth curves corrected for noise-floor levels

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Distortion-product otoacoustic emission (DPE) input/output (I/O) curves were measured at $2f_1-f_2$ frequencies with spectral-averaging and time-averaging procedures from ten normal-hearing ears. Stimuli were equal-level f_1 and f_2 primary tones with f_2/f_1 ratios of 1.2 and f_2 frequencies at 1200, 2400, and 4800 Hz. Time-averaging procedures lowered noise-floor (NF) levels, compared to spectral averaging, so DPEs could be elicited by stimuli as low as 18 dB SPL in some ears. DPEs were corrected for power summation with NF levels and the resulting DPE I/O curves were fit with sixth-order polynomials. Slopes of fitted I/O curves were specified by the first derivative as a function of the level of the primary tones. Slopes of uncorrected spectrally averaged DPE I/O curves were strongly influenced by the NF level. Slopes of NF-corrected spectrally averaged DPE I/O curves were more representative of the true slope, specified as the slope of the corresponding time-averaged DPE I/O curve well above its NF. True DPE I/O slopes decreased with level from a mean slope near 1.0 dB/dB at 30 dB SPL and below for all three f_2 frequencies. Nonmonotonicities in I/O curves were *not* seen at very low stimulus levels. At moderate stimulus levels and above, nonmonotonicities in individual DPE I/O curves reduced the slopes of individual I/O curves and reduced the average slope across ears. © *1996 Acoustical Society of America.*

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INTRODUCTION

Previous reports of the growth of distortion-product otoacoustic emissions (DPEs) with stimulus level indicated that DPE input/output (I/O) curves were compressive with slopes much less than unity at lower frequencies and increasing to near unity at higher frequencies (Lonsbury-Martin *et al.*, 1990; Harris, 1990). DPEs measured at lower stimulus levels revealed growth slopes closer to unity at all frequencies (Kimberley and Nelson, 1990; Popelka *et al.*, 1993). By contrast, growth of basilar-membrane distortion has been shown to be linear with slopes near unity (Robles *et al.*, 1990; Ruggero *et al.*, 1992). The present research was carried out to clarify these apparent differences in DPE growth slopes between studies.

Two techniques have been used to measure DPEs: *spectral averaging* and *time averaging*. Both techniques perform spectral analysis of a time waveform to reveal DPEs in the presence of higher level primary tones. Averaging of repeated spectra reduces the variance in the background noise, while the narrow bandwidth of the (digital or analog) spectrum analysis reduces the background noise relative to the DPE level. Time averaging of the waveform, prior to spectral analysis, significantly reduces the average noise level but results in a larger noise variance. Reducing the noise floor by time averaging reveals DPEs at much lower stimulus input levels (Kimberley and Nelson, 1990; Popelka *et al.*, 1993) than the spectral-averaging technique (Harris *et al.*, 1989; Gaskill and Brown, 1990; Leonard *et al.*, 1990; Lonsbury-Martin *et al.*, 1990; Smurzynski *et al.*, 1990). These lower level DPEs obtained by time averaging may provide information about cochlear function not revealed by higher level DPEs. Indeed, some investigators have suggested that lower level DPEs provide information about the active gain mechanism in the cochlea, which might not be revealed by higher level DPEs (Norton and Rubel, 1990; Nelson and Kimberley, 1992; Popelka *et al.*, 1993; Mills and Rubel, 1994). Thus some of the differences in DPE I/O slopes among studies might be the result of measuring DPEs at different stimulus levels because of the inherent NF limitations of the measurement procedures employed, and those different slopes might reflect different underlying cochlear mechanisms. To examine this directly, the present study compared DPE growth curves obtained with a spectral-averaging and a time-averaging procedure in the same individual ears.

Such an examination of DPEs across the acoustic dynamic range requires an accurate estimate of DPE levels at the lowest possible stimulus levels, where DPE levels are often close to the background NF level. Whitehead *et al.* (1993) have demonstrated, through DPE simulations, how power summation between true DPE levels and NF levels should result in overestimation of DPE levels at small DPE/NF ratios, which in turn would reduce estimates of DPE I/O slopes at lower stimulus levels. Their simulations implied that true DPE levels could be calculated by power subtraction of measured NF levels from measured DPE levels. Thus some of the differences in DPE I/O slopes among studies might be due to the influence of higher NF levels. A secondary purpose of the present study was to test that notion directly. DPEs obtained with the spectral-averaging procedure at low DPE/NF ratios were corrected for the influence

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of measured NFs. Those corrected DPEs were then compared with time-averaged DPEs from the same ears, which were not influenced by the NF because the time-averaged NFs were considerably lower.

I. METHODS

A. Subjects and procedures

DPE I/O curves were measured from ten ears of five normal-hearing subjects. Three of the subjects were women and two were men. Ages ranged from 25 to 35 with a mean of 28 years. None of the subjects had a history of hearing loss or noise exposure. All ears were examined with an otoscope and any excessive cerumen was removed. Prior to measuring DPEs, auditory thresholds at 800, 1000, 1200, 1600, 2000, 2400, 3200, 4000, and 4800 Hz were obtained from each with a three-alternative forced-choice (3AFC) adaptive procedure. During measurements of auditory thresholds, 500-ms tone bursts were delivered through the same ER-2 insert earphones used to measure DPEs. The 3AFC adaptive procedure employed a one-up/two-down stepping rule and a 2-dB step size to estimate 71% correct thresholds (Levitt, 1971). The average of the levels visited on the last 6 out of 12 reversals was taken as threshold. All the ears exhibited thresholds that were better than 10 dB HL at all test frequencies.

DPEs were measured at $2f_1-f_2$ frequencies with $f_2/f_1=1.2$. Equal-level stimulus tones at f_1 and f_2 were presented at levels from 18 to 78 dB SPL in 6-dB steps. The DPEs were measured in three frequency regions: $2f_1-f_2=800$ Hz ($f_1=1000$ Hz, $f_2=1200$ Hz); $2f_1-f_2=1600$ Hz ($f_1=2000$ Hz, $f_2=2400$ Hz); $2f_1-f_2=3200$ Hz ($f_1=4000$ Hz, $f_2=4800$ Hz). During DPE measurements a subject was seated comfortably in a double-wall sound-treated room (IAC) and was instructed to remain as quiet as possible for the duration of each test. In a single experimental session, a subject remained in the sound booth continuously for the following three measurements without removing the earphone/microphone assembly: (1) auditory thresholds at f_1, f_2, and $2f_1-f_2$; (2) a DPE I/O curve with spectral averaging; (3) a DPE I/O curve with time averaging. Breathing and movement artifacts were minimized in the present study by warning subjects when a recording run was about to begin and when it was completed. This was accomplished with lights inside the sound booth, which enabled them to limit their movements to periods between recordings. For each of the experimental conditions, one test and three retests were completed on different days in all but one subject (RRX), who only participated in two retests.

B. Spectral-averaging and time-averaging procedures

The instrumentation used to obtain spectrally averaged DPEs was the same used by Nelson and Kimberley (1992). A computer (IBM PC/AT) digitally synthesized two stimulus tones at f_1 and f_2 with the aid of a digital signal processor (TMS32010 on a Sky321-PC board). The digital signals were output at a sample rate of 20 kHz through two 14-bit digital-to-analog converters, were low-pass filtered at a cutoff frequency of 9.4 kHz with a slope of 24 dB/oct (Frequency Devices 730-BT-4), and were then routed through programmable attenuators (Wilsonics) and impedance-matching transformers to separate insert earphones (ER-2). The acoustic outputs of the insert earphones were introduced into the closed ear canal via separate plastic tubes housed in a microphone assembly (Etymotic ER-10) fitted with a foam tip. The microphone recorded the acoustic signals, which were routed through a low-noise preamplifier (ER10-72) into a signal analyzer (HP3561A) controlled by the computer. The dynamic range of this recording system was about 80 dB.

The signal analyzer applied a Hanning window to the signal input and performed a fast Fourier transformation (FFT) using a bin size of 4.7 Hz. Ninety-nine spectral averages were taken to reduce noise variance. DPE level was measured at $2f_1-f_2$ and the NF level was specified by the FFT bin 20 Hz ($+$ or -2.35 Hz) below the DPE frequency. Each spectrally averaged DPE/NF measurement required about 15 s.

The ER-10 microphone voltages were calibrated in a 2-cc cavity terminated by a half-inch condensor microphone (B&K 4134). Before the measurement of each DPE I/O curve, a transfer function of the external ear canal was obtained at 70 dB SPL. Stimulating tones were then presented at sound-pressure levels adjusted for differences in the frequency-response characteristics of each subject's ear canal. Distortion products at $2f_1-f_2$ were measured in a 2-cc cavity for each pair of stimulus tones used in the experiment. Those levels were always at or below the noise floor of the recording system.

The same instrumentation was used for the time-averaging procedure. The signal analyzer arithmetically averaged 99 time records of the ear-canal acoustic response before executing the FFT. The averaging time window was 320 ms in duration and was synchronized to the envelope frequency of the two stimulus tones (f_2-f_1). Each time averaged DPE/NF measurement required about 30 s.

C. Noise-floor correction of DPE levels

To correct for the influence of the measured noise floor, we assume that the measured DPE level (DPm) is a simple power summation of the true DPE level (DPt) in question and the measured NF level, which is equivalent to the NF in the FFT bins close to the DPE frequency. This power summation is expressed by a simplified version of Eq. (1) from Whitehead *et al.* (1993):

$$\mathrm{DPm}=10\log(10^{0.1\ \mathrm{DPt}}+10^{0.1\ \mathrm{NF}}). \tag{1}$$

From this, the true DPE level can be derived by simple power subtraction of the measured NF level from the measured DPE level:

$$\mathrm{DPt}=10\log(10^{0.1\ \mathrm{DPm}}-10^{0.1\ \mathrm{NF}}). \tag{2}$$

Because the measured DPE level is the power sum of the true DPE level and the measured NF level, as shown in Eq. (1), the measured DPE level is always greater than or equal to the measured NF level. Therefore, with simple algebraic manipulation of Eq. (2), a corrected DPE level (DPc) can be

TABLE I. Noise-floor (NF) correction factors for estimating true DPE levels.

DPm-NF(dB)	0.5	1	2	3	4	5	6	7	8	9	10	15	20
ΔL (dB)	9.64	6.87	4.33	3.02	2.20	1.65	1.26	0.97	0.75	0.58	0.46	0.14	0.04

estimated from the difference between the measured DPE level and the measured NF level:

$$\mathrm{DPc}=\mathrm{DPm}-10\log[1/(1-10^{-0.1\ (\mathrm{DPm}-\mathrm{NF})})]. \tag{3}$$

The second term in Eq. (3) contains the amount of influence the background noise has on the true DPE, which is the amount by which the measured DPE level should be corrected to estimate the true DPE level. This can be expressed as a correction factor (ΔL) in decibels. To simplify the above equation, let ΔL stand for the logarithm term in Eq. (3), that is,

$$\Delta L=10\log[1/(1-10^{-0.1\ (\mathrm{DPm}-\mathrm{NF})})]. \tag{4}$$

Then the corrected DPE can be found by applying a correction factor ΔL, which depends upon the level difference between the measured DPE level and the measured NF level:

$$\mathrm{DPc}=\mathrm{DPm}-\Delta L, \tag{5}$$

To make the conversion simple, without calculations using Eq. (3), one may consult the correction values in Table I. We can see clearly from Table I, that when the difference between the measured DPE and the NF level is 15 dB or more, the effect of the noise on the true DPE is negligible. When the difference is less than 15 dB, one can use the correction factors in Table I to estimate true DPE levels. When the difference was less than 3 dB, we chose not to apply the correction factors because the true DPE was theoretically below the NF, and simply set the DPE level to the NF level. This resulted in an increase, by one or more steps, in the stimulus level required to realize a valid DPE.

II. RESULTS AND DISCUSSION

A. NF corrections of DPE levels

The effects of applying the NF correction to measured DPE levels are demonstrated in Fig. 1. Figure 1(a) shows uncorrected DPE I/O curves at $f_2=2400$ Hz obtained from subject KHT(L) with both the spectral-averaging and the time-averaging procedures. Notice that the spectrally averaged DPEs (circles) were essentially the same as the time-averaged DPEs (inverted triangles) for stimulus levels at 60 and 66 dB SPL. As stimulus levels decreased below 60 dB SPL, spectrally averaged DPE levels approached their corresponding measured NF levels (× symbols). For stimulus levels between 60 and 30 dB SPL, time-averaged DPEs continued to decrease with decreasing stimulus level as the spectrally averaged DPEs merged gradually into the noise floor, revealing a progressive discrepancy between spectrally averaged and time-averaged DPEs. The gradual slope in the spectrally averaged I/O curve, as measured DPE levels approached NF levels, was the result of power summation between the NF and the true DPE. This becomes evident by comparison with the NF-corrected spectrally averaged I/O curve in Fig. 1(b).

In Fig. 1(b), the same I/O curves are shown, but the measured DPEs have been corrected for the influence of measured NF levels by applying Eq. (3). For stimulus levels between 48 and 66 dB SPL, NF-corrected spectrally averaged DPEs agreed well with corresponding time-averaged DPEs. Since the time-averaged DPEs were not influenced by the NF, because they were more than 20 dB above their NF (+ symbols), the NF-corrected spectrally averaged DPEs were considered to be valid estimates of true DPE levels. For stimulus levels below 48 dB SPL, the NF-corrected spectrally averaged DPEs were less than or equal to the NF. They were not considered to be valid estimates of true DPE levels and were set to corresponding NF levels to indicate such. Below 48 dB SPL, time-averaged DPEs continued to decrease with stimulus level even though spectrally averaged DPEs were buried in the NF. In this example, valid spectrally averaged DPEs were obtained down to 48 dB SPL, while valid time-averaged DPEs were obtained with stimulus levels as low as 30 dB SPL.

From this comparison in one subject, it appears that the assumption underlying the proposed NF correction of measured DPE level is reasonable, i.e., that measured DPE levels are the result of power summation between true DPE levels and measured NF levels. Therefore, DPE I/O curves from all

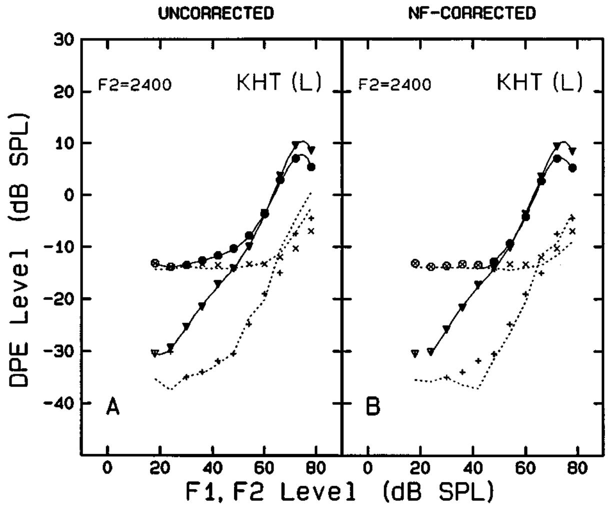

FIG. 1. DPE I/O curves obtained with spectral averaging (circles) and time averaging (inverted triangles) from subject KHT(L). Solid curves show sixth-order polynomial fits to DPE I/O curves. Associated background noise floors (NFs) for the I/O curves are indicated by the × symbols for spectral averaging and the + symbols for time averaging.[1] *Panel A:* Uncorrected DPE levels at $2f_1-f_2$ as a function of the SPL of the equal-level primary tones f_1 and f_2. Unfilled symbols show DPEs that were less than or equal to the NF and were, consequently, set to the level of their corresponding NF. Dotted curves are the levels of $2f_1-f_2$ distortion measured in a 1-cc cavity. *Panel B:* NF-corrected DPE levels for the same curves in panel A. The NF correction accounts for power summation between true DPE levels and background NFs. Dotted curves are the NF levels measured in a 1-cc cavity.

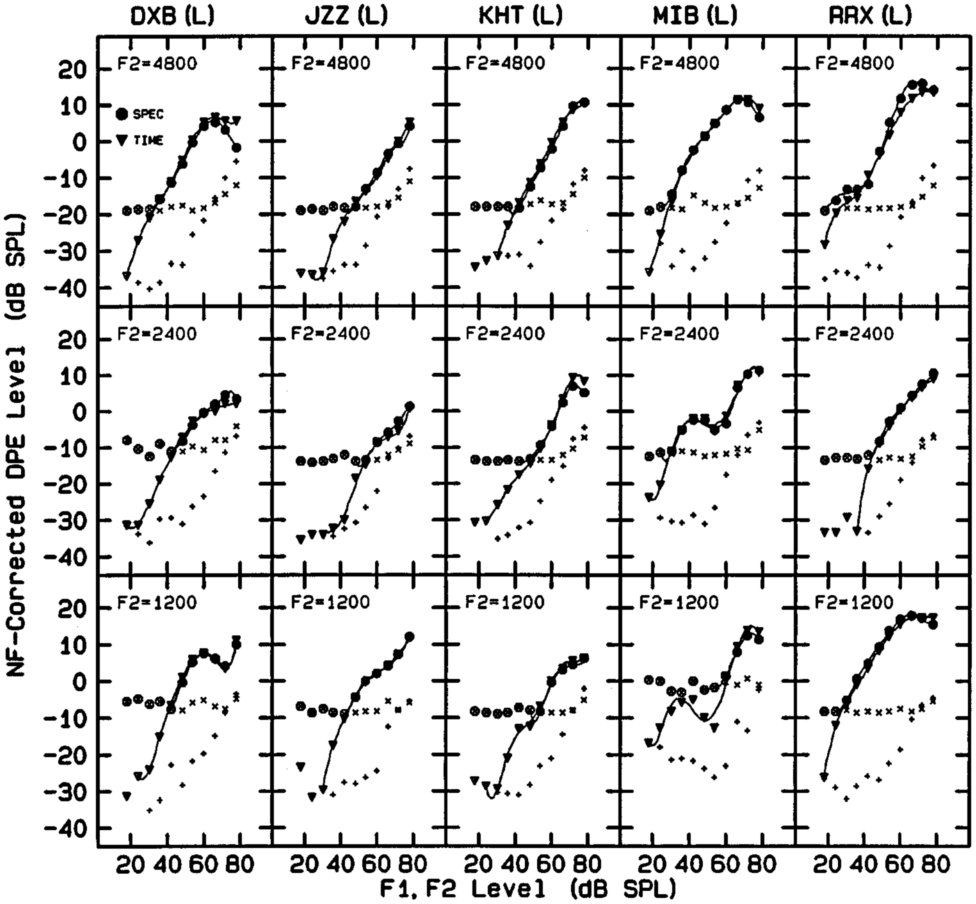

FIG. 2. DPE I/O curves for spectral averaging (circles) and time averaging (inverted triangles) from the left ears of all five subjects. All DPEs are corrected for their associated NFs, which are shown by × and + symbols for spectral and time averaging, respectively. Unfilled symbols show NF-corrected DPEs that were less than or equal to the NF. Solid curves show sixth-order polynomial fits to NF-corrected DPE I/O curves. Each column of panels shows I/O curves from a single subject, with curves for different frequency regions in different rows of panels.

ten ears were corrected by applying Eq. (3) so the generality of the NF correction could be evaluated across ears.

NF-corrected DPE I/O curves obtained from the left ears of the five subjects are shown in Fig. 2 to demonstrate characteristics of I/O curves seen in individual ears. Results for different ears are shown in each column of panels and results for different f_2 frequencies are shown in each row of panels. At stimulus levels sufficient to elicit valid spectrally averaged DPEs (uncorrected DPEs more than 3 dB above the noise floor), there was excellent agreement between NF-corrected spectrally averaged and time-averaged DPEs. For all but a few ears the two measurements were within a couple dB of one another up to stimulus levels of 78 dB SPL. Once measured DPE levels were corrected for low DPE/NF ratios, both methods essentially produced the same results. At moderate stimulus levels, any differences between uncorrected spectrally averaged and time-averaged curves were essentially removed by the NF-correction process.

At the highest stimulus levels there was a tendency for the DPE levels obtained under spectral averaging to be smaller than those obtained with time averaging. This effect is particularly evident for stimulus levels of 72 and 78 dB for KHT(L) in Fig. 1. Of the 30 DPE I/O curves measured, 11 of them demonstrated noticeably greater saturation at the highest stimulus levels under spectral-averaging than under time-averaging conditions. We have no adequate explanation of this tendency, although we have ruled out auditory fatigue or adaptation because the time-averaging procedure, which produced higher DPE amplitudes, took longer to accomplish than the spectral-averaging procedure.

From this analysis, it appears that the NF correction suggested by Whitehead *et al.* (1993), and implemented here in individual ears, is a valid way of obtaining a better estimate of the true DPE level at low DPE/NF ratios. From a theoretical view point, perhaps such a NF-correction procedure should be used routinely.

B. Spectrally averaged versus time-averaged DPE I/O curves

The major differences between spectral-averaging and time-averaging procedures were the improved NFs achieved by time averaging. As indicated in Table II, the average NFs in ear canals for spectral averaging ranged between −6.6 dB SPL for $f_2 = 1200$ Hz and −18.2 dB for $f_2 = 4800$ Hz. With time averaging, the average noise floors ranged between −27.0 and −35.5 dB SPL for the same frequency regions.[1] The average improvement was 19.2 dB, which is about what

TABLE II. Mean noise-floor (NF) levels (in dB SPL) averaged over the lowest four stimulus levels tested.

	$F2=1200$ Hz			$F2=2400$ Hz			$F2=4800$ Hz			
	Spec	Time	$S-T$	Spec	Time	$S-T$	Spec	Time	$S-T$	Ave($S-T$)
NF (cavity)	−9.7	−30.7	21.0	−13.9	−35.7	21.8	−18.6	−38.2	19.6	20.8
NF (ear canals)	−6.6	−27.0	20.4	−12.0	−31.7	19.7	−18.2	−35.5	17.3	19.2
s.d. across ears	2.9	4.2		2.4	2.6		0.3	2.2		
Ears−cavity	3.1	3.7		1.9	4.0		0.4	2.7		

was expected from 99 averages [$10\log(N)=19.9$ dB, with $N=99$]. The major source of noise for these measurements appears to be the electronics and acoustics of the instrumentation, since the average NFs in real ear canals were only a few dB higher than in the calibration cavity (see Table II). This suggests that the technique employed in this study, of visually indicating to a subject when the recording run began and ended, was successful at minimizing breathing, swallowing, and movement artifacts during recording.

As demonstrated in Fig. 2, the improved NFs achieved by time averaging revealed measurable DPEs in response to lower stimulus levels than possible with spectral averaging. DPEs were recordable well below the spectrally averaged NF from all ten ears at every frequency. In the majority of the individual I/O curves (27 out of 30), the low-level portion of the curve (at stimulus levels below 40 dB SPL) was relatively *linear* without the same evidence of nonmonotonicities seen at moderate and high stimulus levels.

Three exceptions were obvious among the 30 I/O curves examined. The I/O curve for RRX(L) at $f_2=4800$ Hz (shown in Fig. 2) and the I/O curves at 2400 and 4800 Hz for MIB(R) (not shown) demonstrated partial saturation at stimulus levels below 40 dB SPL. These could reflect the influence of nearby spontaneous otoacoustic emissions (Wier *et al.*, 1988), which were not measured in the present study. However, their effect is restricted to low stimulus levels and would tend to flatten the obtained growth slopes, which were rather steep in these three ears. Nevertheless, the lack of obvious nonmonotonicities at low stimulus levels (<40 dB) in 27 of the 30 I/O curves provides qualitative evidence that DPEs for low-level stimuli revealed by time averaging are more linear with stimulus level than those elicited by higher stimulus levels.

C. Slopes of DPE I/O curves

A more quantitative evaluation of linearity can be achieved by examining slopes of DPE I/O curves as a function of stimulus level. As illustrated by the solid curves in Fig. 2, each of the NF-corrected DPE I/O curves (spectrally averaged or time averaged) was fit with a sixth-order polynomial. Such a high-order polynomial was used to preserve moderate discontinuities in the curves. The curve-fitting procedure included those NF-corrected DPEs that were more than 0.25 dB above their corresponding NF levels. In addition, in order to anchor the polynomial fit, the curve fit included the first NF level as the I/O curve rose out of the background noise. The first derivative of that fit was then calculated to specify the slope of the I/O curve as a function of stimulus level.

Mean derived slopes, averaged across the ten normal-hearing ears, are plotted in Fig. 3 as a function of stimulus level. The mean slopes obtained from time-averaged DPE I/O curves are shown in Fig. 3 by the filled squares. At 30 dB SPL, the mean slopes were just above 1.0 dB/dB, indicating that DPE amplitude grew linearly with overall level of the equal-amplitude primary tones. By 40 dB SPL the mean slope began to decrease slightly, reflecting the occurrence of nonmonotonicities in individual I/O curves. Above 50 dB SPL, the mean slope decreased further, until at 1200 and 4800 Hz the slope approached zero, reflecting the frequent occurrence of saturation and rollover in individual I/O curves.

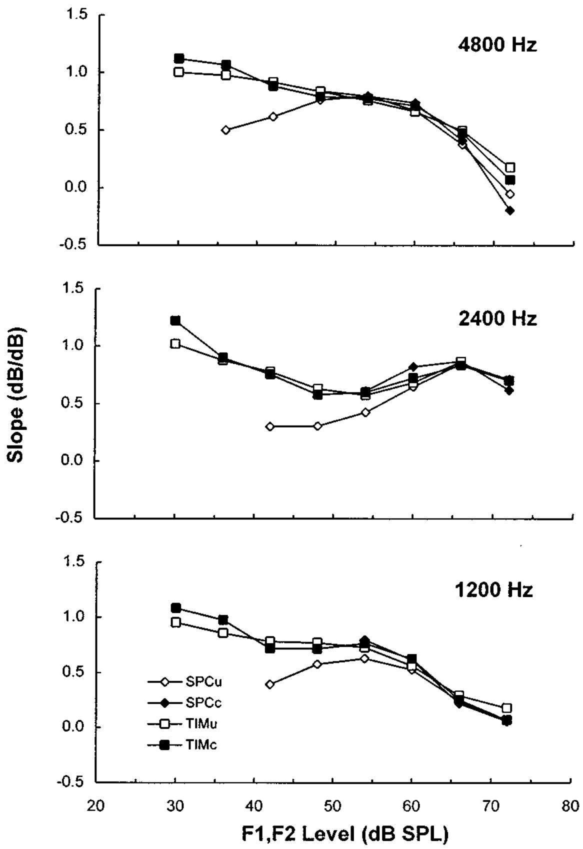

FIG. 3. Mean slopes of DPE I/O curves from ten ears as a function of the level of the equal-level primary tones. Slopes were taken from the first derivative of sixth-order polynomial fits to DPE I/O curves. Diamond symbols show slopes derived from spectrally averaged DPE I/O curves. Square symbols show slopes derived from time-averaged DPE I/O curves. Unfilled symbols indicate slopes derived from DPEs that were not corrected for background noise levels. Filled symbols indicate slopes obtained from NF-corrected DPEs. Different panels show slopes at different f_2 frequencies.

At the lower stimulus levels (42–54 dB SPL at 1200 and 2400 Hz, and 36–48 dB SPL at 4800 Hz), the mean slopes for uncorrected spectrally averaged DPE I/O curves (unfilled diamonds in Fig. 3) were appreciably flatter than the true slopes (filled squares). As predicted by the simulations reported by Whitehead *et al.* (1993), low DPE/NF ratios in the spectrally averaged data flattened these I/O slopes. When the NF correction was applied to the spectrally averaged DPE I/O curves (filled diamonds) it reduced DPEs at low DPE/NF ratios so the stimulus level at which valid DPEs could be measured was increased, and the resulting derived slopes were essentially the same as the true slopes (filled squares).

Notice also that the true slopes of DPE I/O curves for low-level stimuli did not change appreciably with test frequency; they were close to 1.0 at all three frequencies. This is contrary to reports by other investigators who employed spectral averaging (Lonsbury-Martin *et al.*, 1990; Harris, 1990). Previously reported increases in I/O slopes with test frequency also reported decreasing NFs at higher test frequencies, which suggests that the frequency effect on I/O slopes reported in the past was at least partly due to a progressively decreased influence of background noise with increased test frequency. The NF correction used here should reduce that frequency effect if applied to spectrally averaged data with its inherent higher NF levels. However, the higher NFs associated with spectral averaging still restrict DPE measurements to moderate stimulus levels and above, where more frequent nonmonotonicities in individual I/O curves are more likely to reduce slope estimates, as is the case in the present data.

The present finding that I/O curves for low-level stimuli are more linear than are curves for moderate-level or high-level stimuli is consistent with results reported by Popelka *et al.* (1993), who also employed time averaging. They fitted their *group mean* I/O curves with second-order polynomials, which allowed them to specify slopes from the first derivative as a function of stimulus level, as done here for *individual* I/O curves. For geometric center frequencies of the two primary tones at 2000 and 4000 Hz their results showed mean slopes at stimulus levels of 15 dB SPL that were around 1.0, with a clear decrease in the slope of the group mean I/O curve as stimulus level increased. At 75 dB SPL the slopes for those two frequencies were around 0.7. Although they only reported the slopes of group mean DPE I/O curves, they also mentioned that nonmonotonicities in individual I/O curves tended to occur at higher stimulus levels (above 40 dB SPL). This seems consistent with the present findings that slopes of individual I/O curves were close to 1.0 at low stimulus levels, and that nonmonotonicities in individual curves tended to reduce the *average* slope at moderate and high stimulus levels. This also suggests that the typical slope for I/O curves obtained below about 40 dB SPL is close to 1.0, and that at stimulus levels above 40 dB there is no typical I/O slope because of the frequent occurrence of nonmonotonicities in individual I/O curves (saturation, partial saturation, notches, and rollover).

The low-level linearity observed in these time-averaged DPE I/O curves is similar to the $2f_1-f_2$ basilar-membrane response recently reported by Robles *et al.* (1990) and Ruggero *et al.* (1992) in chinchillas. They showed that basilar-membrane response at $2f_1-f_2$ grew linearly with stimulus level up to moderate primary levels (about 50 dB SPL), where response saturation occurred. The basilar-membrane preparation records responses from a localized site along the membrane, in this case at a place most sensitive to $2f_1-f_2$ frequencies. This suggests that linear low-level DPEs recorded from the ear canal might reflect the operating characteristics of the basilar membrane in the localized region of the cochlea corresponding to $2f_1-f_2$ frequencies. This might be different from the cochlear regions presumably responsible for DPE generation at moderate and high stimulus levels, which appear to originate from more basal regions excited by the two primary tones. So far, the nonmonotonicities and notches seen in DPE I/O curves for moderate and high stimulus levels have not been seen in basilar-membrane responses. The basilar-membrane response, as reported thus far, simply tends to saturate at moderate and high levels. Therefore, DPEs recorded in the ear canal in response to moderate and high stimulus levels could be reflecting addition and cancellation of responses from multiple regions of the basilar membrane excited by the two primary tones.

III. CONCLUSIONS

Comparisons of NF-corrected spectrally averaged and time-averaged DPE I/O curves, at f_2 frequency regions of 1200, 2400, and 4800 Hz from ten normal-hearing ears, yielded the following conclusions.

At low DPE/NF ratios, measured DPE levels are the result of power summation between true DPE levels and measured NF levels. The I/O growth slope is flattened by the NF at low DPE/NF ratios. An NF correction can be applied to measured spectrally averaged DPE levels to derive better estimates of true DPE levels.

Time averaging lowers the background noise floor and reveals DPEs at stimulus levels as low as 18 dB SPL. The largest DPE elicited by 18-dB primaries was at −22 dB SPL, only 40 dB below the level of the primaries.

DPEs elicited by low-level stimuli (<40 dB SPL) demonstrate steeper growth rates (near unity) than those elicited by higher level stimuli, independent of f_2 frequency. DPE I/O curves for lower level stimuli exhibit fewer nonmonotonicities (saturation and notches) than seen at higher stimulus levels. From this it appears that DPEs elicited by low-level stimuli behave somewhat differently than those elicited by higher level stimuli, which may have implications about their origin within the cochlea.

Low-level DPE I/O curves are similar to those for basilar-membrane vibration at $2f_1-f_2$, with linear low-level segments followed by nonlinear compressive segments at higher stimulus levels (Robles *et al.*, 1990; Ruggero *et al.*, 1992).

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[1] The steady rise in the time-averaged noise floor seen in the figures was due to the constant 80-dB dynamic range of the HP3561A wave analyzer. For example, at stimulus levels below about 50 dB SPL the dynamic range is sufficient to yield NFs at -30 dB SPL. Above 50 dB SPL the NF rises with a slope of 1.0. With this recording system, that was also the limit of intermodulation distortion in the calibration cavity.

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