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The Dependence of the Distortion Product $2f_1 - f_2$ on Primary Levels in Non-Impaired Human Ears

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The optimal intensity relation between the two primaries used to generate Distortion Product Otoacoustic Emissions (DPOAEs) in unimpaired human ears, over a clinically relevant intensity range, was evaluated using a commercially available clinical device. The ILO92 was used to determine the level of the DPOAE at $2f_1 - f_2$ for 16 combinations of primary levels in the range of 40 to 80 dB SPL from 40 unimpaired, young adult ears. Data were collected between 1 and 6 kHz at 1, 1.5, 2, 3, 4, 5, and 6 kHz. The commonly used procedure of dropping data points less than 3 dB above the noise floor was compared to a power subtraction procedure. A multivariate ANOVA was performed to determine main effects of gender, ear, stimulus levels, frequencies, and interactions between stimulus levels and frequencies. An overall increase of DPOAE amplitude with increase in primary level was observed, along with a decrease of the optimal difference in primary levels as L_2 was increased. Although the power subtraction and 3-dB drop paradigms yielded similar results at high stimulus levels, the power subtraction paradigm provided a more realistic indicator of DPOAE level when low level primaries were used. Possible mechanisms responsible for the level dependence of the optimal relationship between primaries and implications for clinical choice of primary levels are discussed.

KEY WORDS: otoacoustic emissions, DPOAEs, primary levels, power subtraction

It has been known since the mid-eighteenth century that simultaneous stimulation of the auditory system with two tones may give rise to the sensation of one or more additional tones (reviewed in Plomp, 1976). Psychophysical research indicated that these sensations were due to the generation of Distortion Products (DPs) in the cochlea. Kemp (1978) recorded these DPs in the ear canal in the form of distortion product otoacoustic emissions (DPOAEs). When stimulated by two pure tones, at frequencies f_1 and f_2 ($f_2 > f_1$), the ear generates several DPOAEs at frequencies different from, but mathematically related to, those of the stimuli. The cubic DPOAE at the frequency $2f_1 - f_2$ has been found to be the most robust in the human ear under specific stimulus conditions ($f_2/f_1 \approx 1.22$). Due to its robust nature, this DPOAE has found increasing use as a clinical tool for identification of cochlear malfunction. The term DPOAE will be used in this paper to refer to the cubic DPOAE unless specified otherwise.

The clinical utility of any DPOAE test depends on its ability to record robust emissions from normal hearing ears, while being appropriately vulnerable to cochlear malfunctions. Several factors—physiological (cochlear and middle ear function), mechanical (probe fit, subject state),

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and stimulus parameters—influence the amplitude of DPOAEs (L_{DP}) recorded from a particular ear. For a clinical test to be successful, stimulus parameters that enable recording of robust DPOAEs from normal hearing ears, but are vulnerable to cochlear injury, need to be identified. The important stimulus parameters under the clinician's control are the levels of f_1 and f_2 (conventionally referred to as L_1 and L_2) and the frequency ratio between the primaries (f_2/f_1).

An f_2/f_1 ratio of approximately 1.22 has been found to generate the highest L_{DP} in human ears (Gaskill & Brown, 1990; Harris, Lonsbury-Martin, Stagner, Coats, & Martin, 1989; Kemp & Brown, 1983; Nielsen, Popelka, Rasmussen, & Osterhammel, 1993). However, findings for the optimal L_1 and L_2 are not as well documented. Several researchers (Hauser & Probst, 1991; Probst & Hauser, 1990) have suggested that L_{DP} is highest when L_1 is about 10 dB greater than L_2 ($L_1 - L_2 = 10$). Psychoacoustic experiments with combination tones support this observation (Helle, 1969). Helle (1969) reported on levels of the combination tones by estimating the level of a cancellation tone required to completely mask the combination tone. He used L_1 from 43 to 83 dB SPL in increments of 10 dB and varied L_2 from 30 to 80 dB SPL in 5-dB steps. Rasmussen, Popelka, Osterhammel, and Nielsen (1993) have reported nearly equal L_{DP} for $L_1 - L_2$ values ranging from 0 to +10. A dynamic relationship between the optimal $L_1 - L_2$ value and the overall intensity of L_1 and L_2 has been suggested by other researchers (Abdala, 1996; Gaskill & Brown, 1990; Whitehead, McCoy, Lonsbury-Martin, & Martin, 1995; Whitehead, Stagner, McCoy, Lonsbury-Martin, & Martin, 1995). Frequency dependence of the optimal $L_1 - L_2$ value (Hauser & Probst, 1991) and the use of different intensity ranges by different researchers further complicate the issue.

A dynamic relationship between the optimal $L_1 - L_2$ value and the overall primary level has been reported (Abdala, 1996; Gaskill & Brown, 1990; Whitehead, McCoy, et al., 1995; Whitehead, Stagner, et al., 1995). Such a relationship can be predicted by the change in traveling wave patterns on the basilar membrane with increasing intensity. It is known that the peak of the travelling wave tends to become broader and move basally as intensity increases. These changes would alter the interaction between the two primaries on the basilar membrane. Thus, as overall primary level increases, the $L_1 - L_2$ value might need to be adjusted to maintain maximal interaction between them. The above researchers have indeed confirmed that primaries with a smaller separation yield larger L_{DP} as the overall level of the primaries increases. Based on these findings, appropriate recommendations have been made for the clinical choice of primary levels. The present study attempts to replicate this dynamic relationship between primary levels over a clinically relevant range of intensities and frequencies.

Different strategies are used to determine presence or absence of DPOAEs. A minimum signal to noise ratio of 3 dB, or one standard deviation of the noise floor, are some of the commonly used criteria. However, the use of such criteria often results in a loss of data points. Although such a procedure is clinically necessary to differentiate between true DPs and noise components, unequal cell sizes resulting from dropping of data points adversely affects statistical test results (see discussion in Method section). We applied a power subtraction procedure first proposed by Nelson and Zhou (1996) to overcome some of the effects of unequal cell sizes. Data were analyzed using both the power subtraction and the 3-dB drop paradigms in order to compare the relative efficiency of the procedures.

The purpose of the investigation reported in this paper was to verify the optimal relationship between L_1 and L_2 over a clinically relevant intensity range. Previously reported research has suggested a dynamic relationship between overall primary levels and primary level separation. This paper attempts to confirm those findings and extend them over a range of clinically relevant frequencies and intensities. A secondary goal of this paper was to compare two methods of data analysis. The commonly used "3-dB drop" method was compared to a novel power subtraction procedure first reported by Nelson and Zhou (1996).

Method

Participants

Data were collected from 40 ears of 20 healthy young adults (10 men, 10 women), ages ranging from 18 to 30 years. All participants had normal hearing sensitivity (thresholds ≤ 10 dB HL; ANSI 1996) at octave and mid-octave audiometric frequencies between 250 and 8000 Hz. In addition, the participants had (a) no anatomical abnormalities of the outer ear and the tympanic membrane, as indicated by visual otoscopy; (b) normal middle ear function, as indicated by a single peaked tympanogram at 226 Hz, with peak compensated static acoustic admittance between .35 and 1.75 mmho and presence of ipsilateral and contralateral acoustic reflexes at stimulus levels less than 100 dB HL; (c) no history of chronic noise exposure, acute acoustic trauma, ear infections in the previous six months, or ototoxic drug medication; (d) no history of familial hearing loss; and (e) no Stimulated Spontaneous Otoacoustic Emissions (SSOAEs) recordable with the ILO88 system in the test frequency range (1–6 kHz). Participants with SSOAEs in the test frequency range were not chosen to avoid possible interactions between SSOAEs and DPOAEs.

Instrumentation

The GSI-10 Clinical Audiometer and the GSI-1723 Immittance Meter were used for screening participants. SSOAE detection was done using the ILO88 Otodynamic Analyzer. DPOAE measurements were done using the ILO92 DP Advanced Laboratory System Otodynamic Analyzer in a sound treated audiometric test booth. It should be noted that lack of recordable SSOAEs with the ILO88 system does not guarantee the absence of low level Spontaneous Otoacoustic Emissions (SOAEs). Researchers using custom designed equipment have reported a significantly greater prevalence of SOAEs in normal hearing ears than researchers using the ILO88 system (Talmadge, Long, Murphy, & Tubis, 1993). The ILO88 and the ILO92 systems were controlled by an IBM compatible personal computer with an 80486 CPU running at 33 MHz.

Calibration

System distortion was evaluated using a hard walled cavity (approximately 1.3 cm^3 in volume) prior to data collection. Three measurements were averaged to estimate system distortion. The highest distortion of –9.1 dB SPL was recorded for an f_2 of 5000 Hz (L_1 = 80; L_2 = 65 dB SPL). These are the highest stimulus levels used in the experiment. Under most stimulus conditions, system distortion was lower than –15 dB SPL.

The "checkfit" procedure was administered on every ear prior to the experimental protocol. In the checkfit procedure, a standard feature of the ILO92 system, two broadband clicks are delivered alternately by the two output transducers. Sixteen such averages are stored in an array and used during stimulus delivery to balance and normalize the stimulus level at the entrance of the ear canal (Engdahl & Kemp, 1996). It should be noted that calibration at the entrance of the ear canal does not ensure a constant stimulus level at the tympanic membrane (Siegel, 1995). The experimental protocol was administered without disturbing the probe assembly after checkfit was performed.

Stimulus Parameters

DPOAE data were obtained for 16 combinations of L_1 and L_2. Four combinations had equal L_1 and L_2 values ($L_1 - L_2 = 0$) of 40, 50, 60, and 70 dB SPL, respectively. L_2 was fixed at the above mentioned levels, and L_1 was increased in 5-dB steps to an $L_1 - L_2$ value of 15 dB. Because the maximum output of the ILO92 is 80 dB SPL, an adjustment had to be made for the 15-dB difference condition at an L_2 of 70 dB SPL. L_1 and L_2 were set at 80 and 65 dB SPL, respectively, to maintain a difference of 15 dB between the primaries.

The f_2/f_1 ratio was held at a constant 1.22. Recordings were obtained from 1000 to 6000 Hz at f_2 frequencies of 1, 1.5, 2, 3, 4, 5, and 6 kHz. Averaging of the DP data was done in the time domain. Sixteen averages were done on each data point with each epoch lasting 80 ms. This resulted in an averaging time of 1.3 s for each data point. Three sweeps were allowed through the frequency range for each $L_1 - L_2$ combination.

Data Analysis

The ILO92 software uses a fast-Fourier-transform (FFT) algorithm with a frequency resolution of 12.2 Hz to calculate all DP terms. The noise floor was estimated from the 10 Fourier components adjacent to, but not including, the DP frequency and was reported in terms of one and two standard deviations of the average noise floor. The average noise floor can be easily calculated from the standard deviation values.

Detection of DPOAEs is limited by the noise floor. Signal processing paradigms that lower the noise floor allow the detection of smaller DPOAEs. Spectral analysis with a narrow bandwidth lowers the level of background noise relative to the DP level, and averaging over repeated spectra reduces the variance in the noise floor. Significantly lower noise floors can be obtained through averaging in the time domain (Nelson & Zhou, 1996; Popelka, Osterhammel, Nielsen, & Rasmussen, 1993; Whitehead, Lonsbury-Martin, & Martin, 1993). Consequently, most DPOAE instruments use time averaging. When a signal is averaged in the time domain, the level of the noise floor is inversely proportional to the time of averaging; that is, longer averaging time results in lower noise floors. Indeed some instruments set a desired signal to noise ratio as the criterion and average the signal until the desired ratio is achieved. Such a procedure could be time consuming, especially at low frequencies where physiological and environmental noise are significant. However, it should be noted that all instruments that use a predetermined signal to noise ratio as a criterion to stop data collection also have a preset upper time limit to make the procedure time efficient. An alternative procedure that would allow detection of smaller DPOAEs without compromising data collection time is worth considering.

The observed L_{DP} is the result of a power summation between actual DP levels and measured noise levels. The power subtraction paradigm (Nelson & Zhou, 1996) presents a computational method of obtaining estimates of the levels of near-threshold DPOAEs that are free from the influence of the noise floor. Nelson and Zhou (1996) showed that the power subtraction paradigm can remove the apparent elevation of near threshold DPOAE obtained using spectrally averaged L_{DP}. This was done by comparing the corrected spectrally averaged L_{DP} to the time averaged L_{DP}. The ability of power subtraction to isolate L_{DP} from the influence of the noise floor does not depend on the type of averaging. However, such a procedure is likely to be more effective on spectrally averaged data because the noise floor is already lowered to a great extent when data are averaged in the time domain. We analyzed the data using both the power subtraction and the 3-dB drop paradigms in order to compare the relative efficiency of the procedures.

The 3-dB drop paradigm differentiates between presence and absence of emissions. In a clinical setting, criteria to determine the presence of emissions are important. However, the use of such criteria results in the elimination of data points near the noise floor. Several data points may be eliminated under poor signal to noise conditions, which in turn leads to overestimation of L_{DP}. In contrast, a more realistic estimate of L_{DP} is desired when evaluating the impact of stimulus parameters on L_{DP}. The power subtraction paradigm (Nelson & Zhou, 1996) was applied to the DP terms and compared to the 3-dB drop paradigm to evaluate the efficacy of the two paradigms.

Equation 1 was used to calculate corrected L_{DP} (DPc), where DPm and NF represent the measured L_{DP} and noise floor, respectively.

$$\text{DPc (in power)} = 10^{0.1\text{DPm}} - [1/(1 - 10^{-0.1(\text{DPm} - \text{NF})})] \qquad (1)$$

It should be noted that the above correction, although it prevents substantial overestimation of L_{DP}, does not provide the most accurate measure. Accuracy is compromised by the use of an estimate of the noise floor value from FFT bins adjacent to the DPOAE bin. Such an estimation could result in noise floors higher than L_{DP}. DPc calculated on such measurements returns negative values. All such values for DPc in the current data set were replaced by the value of the noise floor. It should be noted that, although the detection of DPOAEs is limited by the noise floor, DPOAEs smaller in amplitude would be detected if the noise floor could be lowered (Nelson & Zhou, 1996). The noise floor thus imposes a bound on the DPOAE level. Consequently, replacing the value of DPc with the value of the noise floor artificially elevates the average L_{DP} to some extent. The use of drop criteria, such as the 3-dB drop paradigm, includes only the most robust values of L_{DP} in the average, elevating the estimate even more. It is clinically essential to determine whether or not valid DPOAEs are present. Consequently, the power subtraction paradigm in its present form would not be appropriate clinically because it does not have any mechanism to determine the presence or absence of DPOAEs. However, when data from several ears are averaged to establish norms or describe normative behavior, the power subtraction technique provides a better estimate.

Researchers who have employed the correction in the past have reconverted DPc from power to amplitude immediately after the correction (Nelson & Zhou, 1996; Whitehead et al., 1993). Amplitude distributions are one sided, whereas power distributions are two sided, ranging from –infinity to +infinity. Moreover, when measured at low signal to noise ratios, amplitudes tend to approximate a Rayleigh distribution rather than a Gaussian distribution. Thus, a power distribution provides a better fit to the requirements of statistical tests. Based on the above arguments, statistical analyses were performed on DPc values expressed in power.

To facilitate comparison with previously reported research, DPc values were reconverted to amplitude using Equation 2, following the completion of statistical operations.

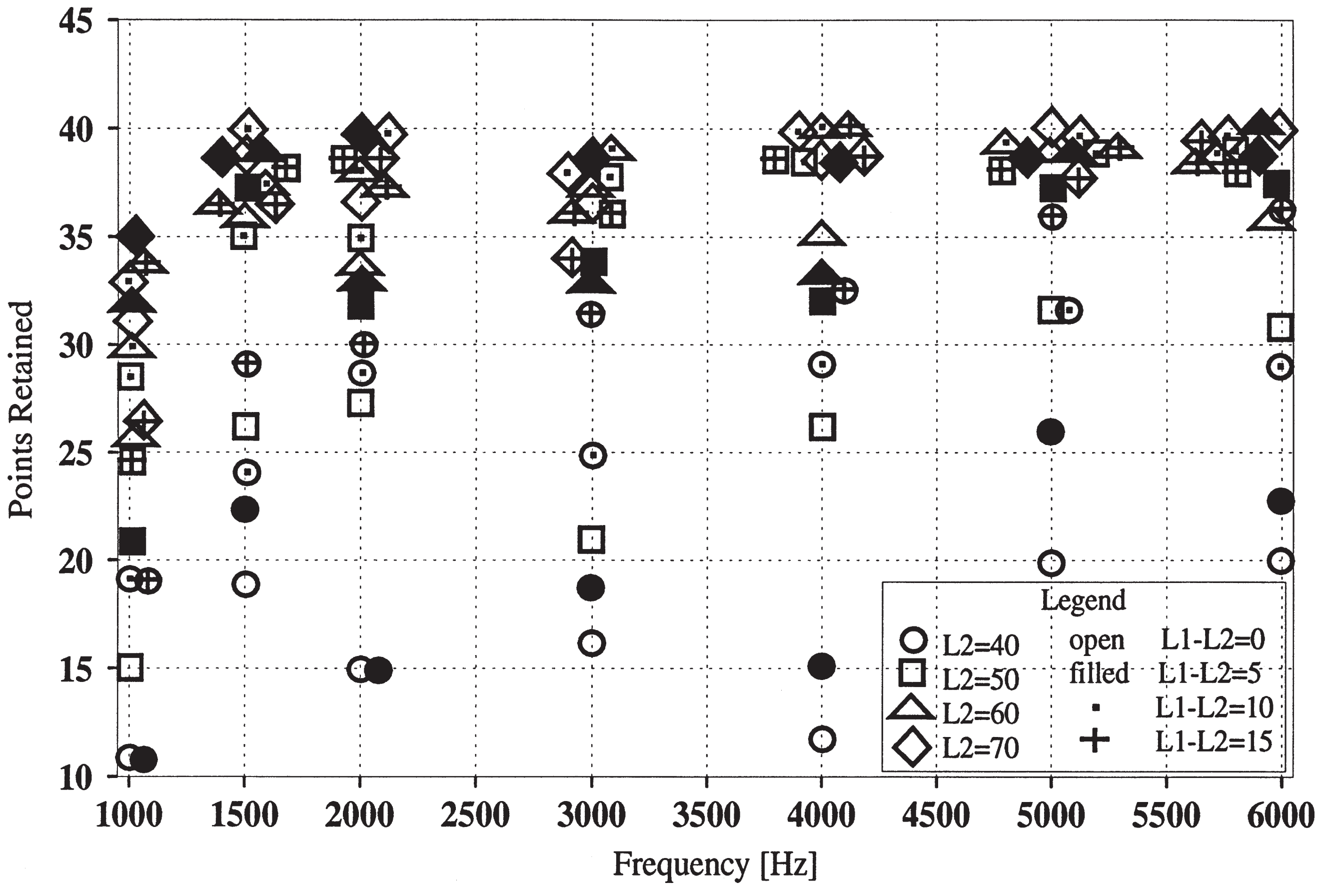
$$\text{DPm (in dB SPL)} = 10 \times \log 10\ (\text{DPc}) \qquad (2)$$

Previous researchers have attempted to eliminate noise contamination of data by dropping all data points less than 3 dB higher than the noise floor from the data pool. Such criteria are clinically important to determine presence of DPOAEs. The current data set was also analyzed using the 3-dB drop paradigm. However, empty data cells pose problems for statistical analysis on any data. Statistical tests were performed on the "power subtraction" data set only. It should be noted that although commercial statistical packages have procedures to compensate for missing data points, in most cases the missing data points are replaced by the mean. In some cases a different *N* is used for different conditions. Both those strategies compromise the validity of the statistical results. Using mean values to substitute for missing data results in an artificial elevation of the measure, and using different *N* values for different conditions compromises the orthogonality of the results. The problems produced by missing data increase as the proportion of the data dropped increases. Figure 1 displays the number of data points retained after the 3-dB drop paradigm. Circles represent data for $L_2 = 40$, whereas squares, triangles, and diamonds represent data for L_2 = 50, 60, and 70, respectively. Open symbols stand for the $L_1 - L_2 = 0$ condition for each L_2, and $L_1 - L_2 = 5$, 10, and 15 conditions are represented by filled symbols, symbols with a "+" and those with a "." respectively. Less than 50% of data points (out of a maximum of 40) were retained for some stimulus conditions. Given the severity of the problem, we did not feel that we could legitimately use this data set for statistical analysis. Qualitative comparisons were made between the two data sets.

Results

Results of a repeated measures analysis of variance (SAS Institute, 1995) administered on the "power subtraction" data set are reported in Table 1. The a priori

Figure 1. Number of data points retained for different stimulus conditions and frequencies following the 3-dB drop paradigm. Circles represent data for $L_2 = 40$, and squares, triangles, and diamonds represent data for $L_2 = 50$, 60, and 70 respectively. Open symbols stand for the $L_1 - L_2 = 0$ condition for each L_2, and $L_1 - L_2 = 5$, 10, and 15 conditions are represented by filled symbols, symbols with a "+" and those with a "." respectively. Overlapping data points are shifted on the *x* axis for ease of viewing.



level of significance was set at 0.01. The main effects of primary level, frequency, and gender on the dependent variable L_{DP} were statistically significant. The only non-significant effect was that of ear. There was a significant interaction between primary level and frequency.

Mean L_{DP}s generated by different primary levels are displayed in Figure 2, part a. The contour functions for each L_2 (40, 50, 60, & 70 dB SPL) are plotted separately, with an averaged noise floor for each panel. Each panel has four contour functions of L_{DP} plotted against f_2 frequency with $L_1 - L_2$ values of 0, 5, 10, and 15 dB as the parameter.

Table 1. ANOVA results for L_{DP}.

Source of variation	*df*	SS	MS	*F*	*p*
Between subjects					
Gender	1	6292.84	6292.84	27.70	0.0001
Within subjects					
Ear	1	670.55	670.55	2.95	0.0859
Levels	15	247773.27	16518.25	72.71	0.0001
Frequency	6	50874.50	8479.08	37.32	0.0001
Freq × Levels	90	88591.30	984.35	4.33	0.0001

The results of the ANOVA suggest a significant interaction between primary levels and frequency. However, examination of Figure 2, part a, reveals that the primary combination generating the highest L_{DP} in each panel remains relatively unaffected by frequency. The primary combination of 55–40 generated the highest L_{DP} in the $L_2 = 40$ panel for all test frequencies. In the subsequent panels of $L_2 = 50$, 60, and 70, primary combinations of 65–50, 70–60, and 75–70 were the best combinations respectively. The best combination does not change with frequency for a given L_2. The only exception is observed at 4000 Hz for $L_2 = 70$. L_{DP} contour plots exhibit a divergent pattern in all L_2 panels with the contours being closer to each other at the lower frequencies. Another observable trend is that the degree of divergence and the distance between the contour functions decrease as L_2 increases. Hence, functions for the $L_2 =$

70 panel are spaced closer to each other than functions for the L_2 = 40 panel.

Table 2 reports and ranks L_{DP}s generated by each experimental primary combination. The rank of each primary combination within its L_2 panel (from highest to lowest L_{DP} generated) is also listed (Table 2, Column 5). The table also reports the results of a Scheffé test of multiple comparisons (Table 2, Column 1). The Scheffé is one of several tests specially designed to compare multiple means without compromising the confidence interval. The Scheffé letter groupings can be used to compare the mean L_{DP}s generated by any two primary combinations. L_{DP}s generated by any two primary combinations sharing the same letter grouping were not found to be significantly different from each other (α = 0.05). For example, the mean L_{DP} generated by the primary combination of 60–60 was not statistically significantly different from those generated by combinations of either 50–50 (common grouping "F") or 75–60 (common grouping "D").

Examination of Table 2 reveals that the highest mean L_{DP} was generated by the primary combination 55–40 for L_2 = 40. However, the mean L_{DP} generated by this primary combination was not significantly higher than the L_{DP} generated by any other combination of this panel. At L_2 = 50, the combination 65–50 generated the highest L_{DP}, which was significantly higher than those generated by any other combination of this panel. For the plots of L_2 = 60 and 70, the combinations of 70–60 and 75–70 generated the highest L_{DP} respectively. The mean L_{DP}s generated by both of these combinations were significantly higher than those generated by other combinations of their respective panels.

Table 2. Scheffé's test for mean DPOAE levels generated by different primary combinations. Means identified by the same letter are not significantly different.

Scheffé grouping	Mean	Primary	L_2 Gr	Rank in Gr
A	25.84	75–70	70	1
B	17.34	80–70	70	2
B	16.17	70–70	70	3
B	15.81	70–60	60	1
C	9.09	65–60	60	2
D C	8.43	75–60	60	3
D C E	7.02	65–50	50	1
D F C E	6.71	80–65	70	4
G D F C E	4.95	60–50	50	2
G D F E	2.66	60–60	60	4
G F E	1.46	55–50	50	3
G F E	1.46	55–40	40	1
G F	0.58	50–40	40	2
G F	0.49	50–50	50	4
G	0.18	45–40	40	3
G	0.14	40–40	40	4

Note. Alpha = 0.05; *df* = 4366; MSE = 227.6085; Critical Value of *F* = 1.66868; Minimum Significant Difference = 6.3791.

The main effects of gender and frequency on L_{DP} were also significant. L_{DP} in female ears was found to be significantly higher than in male ears. Mean L_{DP}s at 1500 and 5000 Hz were significantly larger than those recorded at other frequencies. The lowest L_{DP} was recorded at 3000 Hz.

In an independent analysis, all data points less than 3 dB above the noise floor were dropped from the data pool. Mean L_{DP} for all primary combinations calculated from this data pool are plotted in Figure 2, part b. The overall divergent pattern of the functions seen in Figure 2, part a, is observable. However, the range of L_{DP} in these functions is limited when compared to data processed using the power subtraction method. Figure 1 displays the number of data points retained for each primary combination after dropping those less than 3 dB higher than the noise floor. As few as 11 out of a possible 40 points were retained for some conditions (low intensities and frequencies).

Discussion

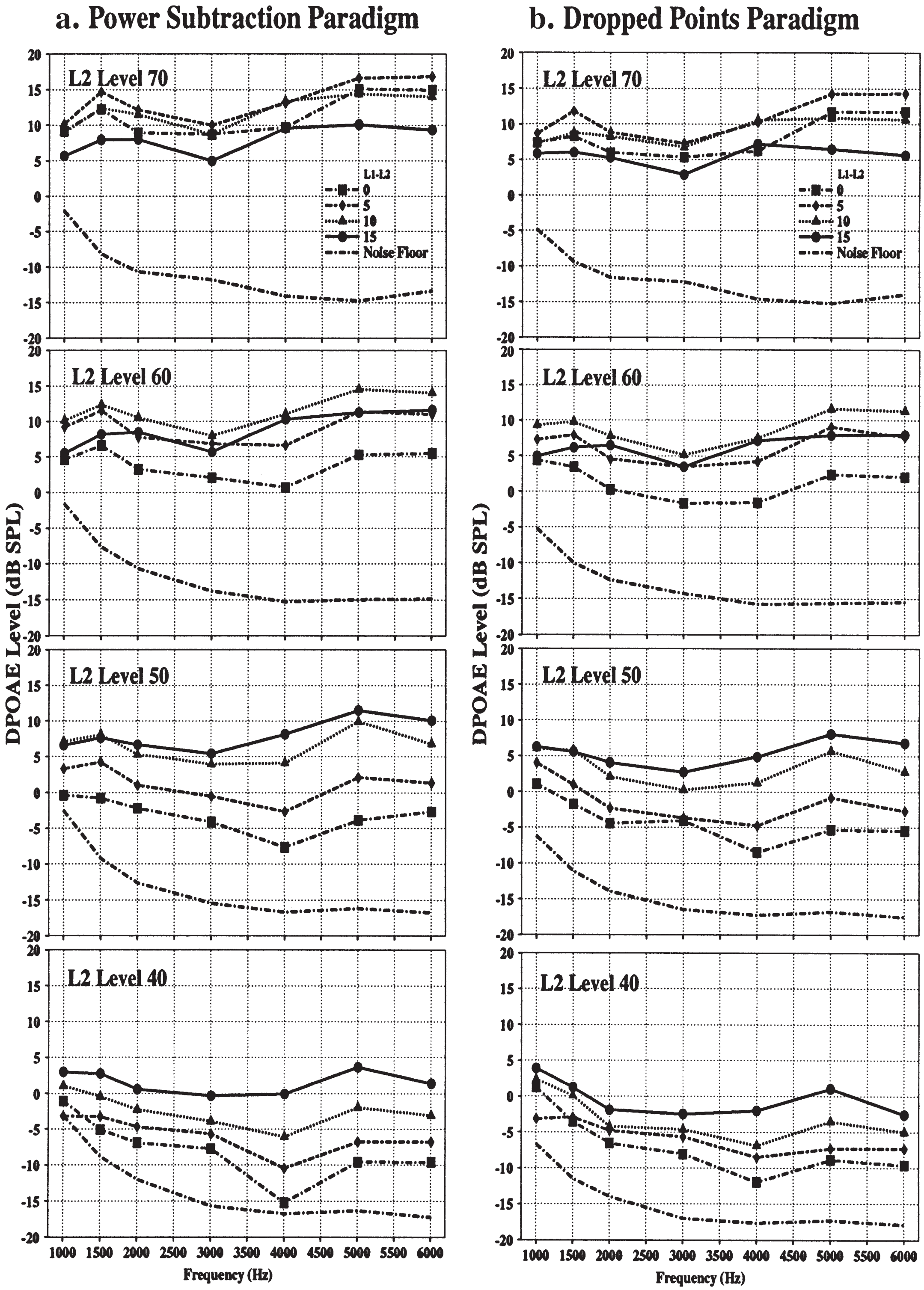
The results obtained in this study are in general agreement with other reports of similar research. L_{DP}s reported in the literature vary between 60 to 30 dB below the primaries (Gaskill & Brown, 1990; Hauser & Probst, 1991; Rasmussen et al., 1993; Popelka et al., 1993). L_{DP}s reported in the present study are within the above range.

L_1 – L_2 Relationship

Results of the Scheffé test suggest a dynamic relationship between the optimal $L_1 - L_2$ value and L_2. The primary combinations 55–40 and 65–50 generated the highest L_{DP} for L_2 = 40 and 50, respectively. At these L_2 values, the optimal difference between the primaries was 15 dB. However, the optimal difference decreased to 10 dB for L_2 = 60 because the combination 70–60 generated the highest L_{DP}. The optimal difference further decreased to 5 dB for L_2 = 70 because the combination 75–70 generated the highest L_{DP}. Thus, the optimal difference between the primaries reduces as L_2 increases.

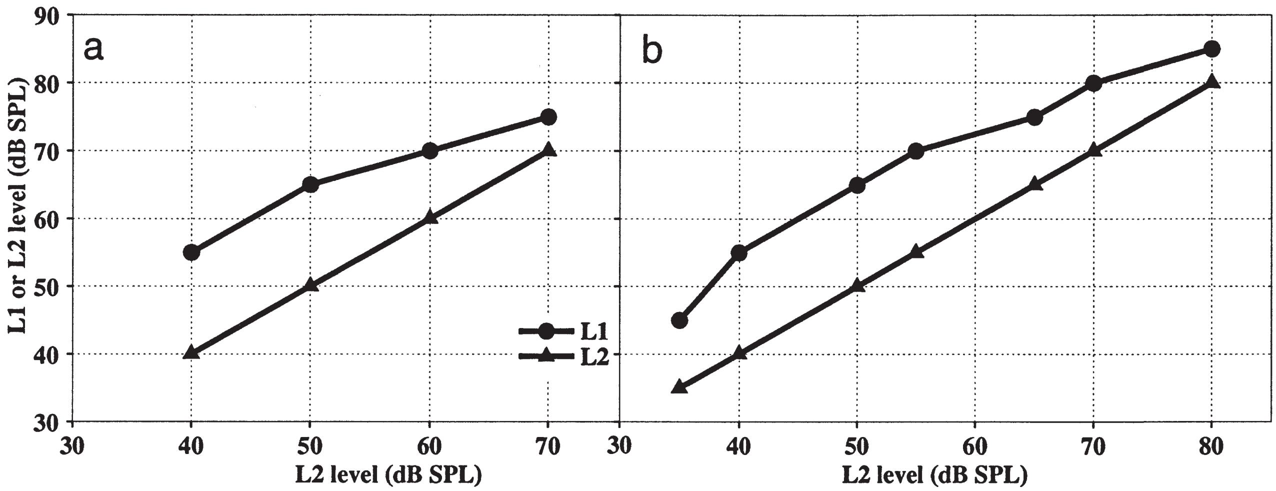
These results are in close agreement with previous results (Abdala, 1996; Gaskill & Brown, 1990; Whitehead, McCoy, et al., 1995; Whitehead, Stagner, et al., 1995). Gaskill and Brown (1990) reported results for L_2 between 25 and 60 dB SPL. They reported an optimal level difference of 23.2 dB for L_2 = 25. The optimal level difference was reduced to 5.2 dB for L_2 = 60. Figure 3 displays the above mentioned relationship as found in

Figure 2. L_{DP} generated by different primary combinations at four L_2 groups. Part a = Data set processed by application of the power subtraction paradigm to isolate L_{DP} from possible effects of the noise floor. Part b = Data set processed after dropping all data points less than 3 dB above the noise floor.



this study (Figure 3, part a) together with similar results reported by Whitehead, Stagner, et al. (1995) (Figure 3, part b). L_2 is reported on the *x* axis, and the *y* axis represents L_1 and L_2 required to generate the largest L_{DP} for a given L_2. The parameters are L_1 and L_2. Both plots show a convergent pattern suggesting that the

Figure 3. Optimal relationship between L_1 and L_2 levels. Part a = Results of this study. Part b = Results from Whitehead, Stagner, et al. (1995). Converging L_1 and L_2 lines in both plots confirm dynamic relationship between optimal $L_1 - L_2$ and the overall level of the primaries.



optimal difference between the primaries decreases as L_2 increases. The application of a statistical test to determine significant differences between L_{DP} generated by different primary combinations is unique to this study. As shown in the Scheffé groupings (Table 2), the best combination for each L_2, except $L_2 = 40$, generated significantly higher L_{DP}s than the other combinations for that L_2. The increase in L_{DP} for unequal level primaries over equal level primaries was much larger than that reported by Whitehead, McCoy, et al. (1995). Recently, Boege, Janssen, Kummer, and Arnold (1998) have made a similar suggestion in the selection of primary level separation. They suggest the following relationship between L_1 and L_2:

$$L_1 = 0.4L_2 + 39 \text{ dB}$$

This computational technique results in primary level separations that are within 5 dB of those reported in this paper for L_2 levels less than 65 dB SPL. The above formula suggests that L_2 should be higher than L_1 for $L_2 > 65$ dB SPL. However, the results of this study suggest the use of $L_1 > L_2$ for L2 as high as 70 dB SPL.

Some researchers have reported a nondynamic relationship between the optimal level difference and the overall primary level (Hauser & Probst, 1991; Rasmussen et al., 1993). However, closer examination of these studies reveals methodological differences that can account for the reported differences. Hauser and Probst (1991) reported an optimal difference of 10 dB. However, these researchers collected data for primaries up to 55 dB SPL. At these levels an optimal difference of 10 dB is in agreement with the present results. Rasmussen et al., (1993) reported equal primary levels to be optimal. This observation can be a direct result of the use of high primary levels. Indeed data reported by these researchers were collected at $L_2 = 75$. Thus, it is evident that data apparently in contradiction with the present results can be explained on the basis of methodological differences between the studies.

The change in the optimal level difference with overall stimulus level is best understood by taking into account basilar membrane vibration patterns. DPOAEs have been proposed to be a result of nonlinear mechanical interaction between the traveling waves of f_1 and f_2 (Kemp, 1986). Results from studies involving suppression of DPOAEs suggest that the f_2 region on the basilar membrane plays a dominant role in the generation of DPOAEs (Brown & Kemp, 1984; Harris & Glattke, 1992; Kummer, Janssen, & Arnold, 1995). Thus, the highest L_{DP} should be generated when the primary traveling waves have comparable vibrational amplitudes at the f_2 region. Comparable vibrational amplitudes of the two traveling waves at the f_2 region can be achieved only when L_1 is higher than L_2 because the f_1 characteristic place is apical to that of f_2. The above argument explains the need to have L_1 higher than L_2 in order to generate high L_{DP}.

The changing pattern of traveling waves with increasing intensity (Gaskill & Brown, 1990) may further explain the change in optimal level differences. As intensity increases, the peaks of the waves tend to become broader and shift toward the base of the cochlea. The vibrational amplitude due to f_1 becomes more pronounced at the f_2 place as intensity increases. At such intensities, the relative increase in the vibrational amplitude of f_2 necessary to achieve optimal interaction between the two waves is smaller. Thus, at higher intensities, smaller differences between the primaries are necessary to produce high L_{DP}s.

Primary levels ideal for clinical use should generate large L_{DP}s in normal hearing ears and should be vulnerable to cochlear insult. Results from the present study indicate that unequal level primaries should be used when the goal is to record the highest possible L_{DP} from a given ear. It is also suggested that the overall level being used is deterministic in selecting the optimal difference between the primaries. Figure 3 can be used to choose an appropriate level separation depending upon the L_1 or L_2 in use. It is also evident from Figure 2 that the appropriate level separation is not affected by the test frequency. Hence, the same level separation can be used across the test frequency range. The results presented here are limited to normal hearing ears; therefore, the issue of vulnerability of L_{DP} with cochlear injury cannot be directly addressed. However, Whitehead, McCoy, et al. (1995) have reported DPOAEs to be more vulnerable to cochlear injury when unequal level primaries were used. It should be noted that a majority of the data reported by the above authors were obtained from noise-exposed rabbits. A subset of the data was from humans with sloping or notched high-frequency hearing losses. Results of preliminary experiments conducted by the Otoacoustic Emissions Research Group at Purdue University involving salicylate-induced temporary insult to the cochlea have similar indications. L_{DP} showed little or no change when recorded with equal or high level primaries, whereas L_{DP}s recorded with unequal level primaries were reduced significantly (Rao, Long, Narayan, & Dhar, 1995). In this study, volunteer adults with normal hearing consumed 12 doses of 375 mg of aspirin over three days. The participants' cochlear status was monitored using a Bekesy tracking procedure, DPOAEs, and Transient Evoked Otoacoustic Emissions. Sutton, Lonsbury-Martin, Martin, and Whitehead (1994) conducted a similar study on adults with normal hearing exposed to noise. Their results suggest that lower L_2 and unequal primary combinations were most sensitive to changes in cochlear status. However, these authors used very limited combinations of primary levels and only one primary level difference ($L_1 - L_2 = 25$). The most systematic searches to find the most clinically appropriate primary combination have been conducted by Kimberley, Hernadi, Lee, and Brown (1994) and Stover, Gorga, Neely, and Montoya (1996). Kimberly et al., (1994) suggested the use of L_1 and L_2 of 60 and 50, respectively. Data were collected between 1000 and 6000 Hz and only at moderate primary levels in that study. Stover et al., (1996) overcame these limitations by reporting on data collected between 500 and 8000 Hz. They suggested the use of L_1 and L_2 values of 65 and 55. However, even this study is not entirely conclusive because only one primary level difference ($L_1 - L_2 =10$) was used. Thus, it is evident that the use of moderate overall levels and unequal primaries might be most appropriate clinically. However, more detailed and systematic research is required in this area to evaluate the roles of overall primary levels and primary level differences in detecting cochlear pathology.

It should also be noted that it might be advantageous to choose primaries depending upon the specific demands of the test. If different primary levels and separations are found to be differentially vulnerable to cochlear insult, the required sensitivity and specificity of a particular test might govern the choice of primary levels. Most vulnerable primary levels can be chosen when sensitivity is of primary importance. Relatively less vulnerable primary levels can be chosen when specificity is of greater importance.

Gender and Frequency Effects

Gender was found to have a significant effect on L_{DP}. L_{DP}s recorded from female ears were significantly larger than those recorded from male ears. This is consistent with several previous reports (e.g., Lonsbury-Martin, Martin, & Whitehead, 1997).

Test frequency also had a significant effect on L_{DP}. Closer examination of the contour plots in Figure 2 reveals two peaks in the general areas of 1.5 kHz and 5 kHz, with a minimum around 3 to 4 kHz. Whitehead, McCoy, et al. (1995) have reported similar maxima around 1.3 and 5 kHz. A trough around 3 kHz was also observed in the data reported by the above researchers. Additionally, these researchers reported a second trough between 6 and 7 kHz. However, data were not collected beyond 6 kHz in this study, thus precluding the possibility of observing a second trough. The above configuration of peaks and troughs could be a result of middle and outer ear influence on DPOAEs.

The interaction between primary levels and frequency was significant. Hauser and Probst (1991) found a similar interaction. These authors reported reduction in primary level separation necessary to generate the largest L_{DP}, with increasing frequency and overall primary level. The results of the present study show a clear effect of increasing overall primary level, but the level separation generating the largest L_{DP} remained constant across frequency. The only exception was observed at 4000 Hz for $L_2 = 70$. There are several fundamental differences in the methodologies of the two studies. Hauser and Probst (1991) used spectral averaging to analyze their data, higher L_1 levels (65 & 75 dB SPL), and a greater range of L_2 levels (20 to 90 dB SPL). In addition, they considered the geometric mean of the two primaries as the generation region of DPOAEs. However, it is not readily apparent that these methodological differences accounted for the differences in the observed interaction between frequency and primary level.

Range of DPOAE Levels

An overall divergent pattern of intensity-frequency contour functions was observed with the functions being closer together at low frequencies. Whitehead, Stagner, et al. (1995) have reported a qualitatively similar trend. The range of L_{DP} reported in this study is greater than that reported by the above researchers. Two methodological differences between the two studies could have resulted in the difference in observed range of L_{DP}. Comparison of parts a and b of Figure 2 reveals a greater range in data points when the power subtraction method is used. This is expected because dropping data points closer to the noise floor effectively elevates the lower limit of L_{DP}, which results in an artificial elevation of the calculated mean. Second, the range of L_{DP} can vary as a function of the intensities of the primaries. Comparison of the four panels of Figure 2, part a, shows that the greatest range of L_{DP} is obtained for the $L_2 = 40$ panel. Higher L_2 panels exhibit progressively smaller ranges. Thus, the greater range of L_{DP} observed in this study could be a result of use of lower level primaries. The observation that lower primaries yield larger L_{DP} range could be a reflection of greater involvement of the active processes of the cochlea at lower intensities. This supports the use of lower level primaries in clinical tests of DPOAEs when the objective of the test is to identify intactness of the active processes of the cochlea.

Power Subtraction Versus 3-dB Drop

A power subtraction paradigm (Nelson & Zhou, 1996) was used to isolate L_{DP} from the influence of the noise floor. Such a paradigm has been used previously on data averaged in the spectral domain. However, the basic utility of the paradigm remains intact even when applied on data averaged in the time domain.

Different criteria, such as a minimal signal to noise ratio of 3 dB, have been used to determine the presence of DPOAEs. The power subtraction paradigm would allow for detection of DPOAEs closer to the noise floor. In the present application, the value of the noise floor had to be used to replace L_{DP} when L_{DP} was lower than the noise floor. L_{DP}s lower than the noise floor are recorded because the noise floor is merely an estimate calculated from bins adjacent to the DPOAE bin. When the noise floor is estimated in the same bin as the DPOAE, the power subtraction paradigm can be applied in its full scope. Under these conditions, it would be possible to estimate true L_{DP} because the measured L_{DP} would always be a power summation between the true DPOAE level and the noise floor. The power subtraction paradigm provides an advantage when L_{DP}s have to be subjected to statistical analysis. Figure 1 reports the number of points retained in the data pool after application of the 3-dB drop paradigm. There are very few conditions in which all 40 points were retained, with the sample size being extremely low for certain primary combinations at the lower frequencies. Different sample sizes destroy the orthogonality of the error terms in the ANOVA model, thereby complicating administration and interpretation of results. Moreover, dropping several data points results in an overestimation of L_{DP} because only the larger L_{DP} are included in the average. The above reasons make the power subtraction paradigm a better choice when data from several participants are being averaged to derive normative values. However, the power subtraction paradigm is not clinically applicable in its present form because it fails to distinguish between presence and absence of DPOAEs. The applicability of the power subtraction paradigm would increase if noise floor estimates were obtained from the DPOAE bin and not those surrounding it. Under those circumstances, the measured L_{DP} would always be a summation of the noise floor and the true DP level. Application of the power subtraction paradigm would then isolate the true DP level from the influence of the noise floor. When used with data collection schemes, such as preset signal to noise ratio stopping values, this paradigm can enable detection of DPOAEs smaller in amplitude.

Summary

This study was designed to identify the optimal level difference between the primaries at different clinically relevant primary intensities. The results indicate:

1. The primary level difference required to generate the largest DPOAEs from normally hearing ears varies with the overall level of primaries being used. The level difference of choice decreases as L_2 increases. The level difference generating the largest L_{DP} is at least 15 dB for $L_2 = 40$; whereas for $L_2 = 70$, the required difference is only 5 dB for the parameters used in this study.
2. The primary level difference generating the largest L_{DP} remains unaltered across the frequency range tested.
3. The power subtraction paradigm provides a more precise estimate of L_{DP} under poor signal to noise conditions than the 3-dB drop paradigm. However, this paradigm is not clinically applicable in its present form. Combinations of using the power subtraction paradigm with sophisticated data collection strategies such as predetermined signal to noise stopping values should be explored.
4. Further research needs to be conducted to determine relative vulnerability of different primary combinations to cochlear insult. It should also be noted

that new knowledge is being gained about mechanisms shaping the amplitude of DPOAEs. An example is the effect of the efferent nervous system on DPOAEs (Liberman, Puria, & Guinan, 1996). As such new discoveries are made, clinical parameters may need to be re-evaluated.

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