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Distortion product otoacoustic emissions: Cochlear-source contributions and clinical test performance

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Abstract

It has been proposed that the clinical accuracy of distortion product otoacoustic emissions (DPOAEs) is affected by the interaction of distortion and reflection sources contributing to the response. This study evaluated changes in dichotomous-decision test performance and threshold-prediction accuracy when DPOAE source contribution was controlled. Data were obtained from 205 normal and impaired ears with L_2 ranging from 0 to 80 dB SPL and $f_2 = 2$ and 4 kHz. Data were collected for control conditions (no suppressor, f_3) and with f_3 presented at 3 levels that previously had been shown to reduce the reflection-source contribution. The results indicated that controlling source contribution with a suppressor did not improve diagnostic accuracy (as reflected by ROC curve area) and frequently resulted in poorer test performance compared to control conditions. Likewise, correlations between DPOAE and behavioral thresholds were not strengthened when using the suppressors to control source contribution. While improvements in test accuracy were observed for a subset of subjects (normal ears with the smallest DPOAEs and impaired ears with the largest DPOAEs), the lack of improvement for the larger, unselected subject group suggests that DPOAEs should be recorded in the clinic without attempting to control the source contribution with a suppressor.

I. INTRODUCTION

Current theories of otoacoustic emission (OAE) generation suggest that there are multiple mechanisms by which otoacoustic emissions are generated (e.g., Shera and Guinan, 1999; Shera, 2004). These mechanisms include nonlinear distortion and coherent reflection. Different types of OAEs may be dominated by either one or both mechanisms. For example, as typically recorded in the ear canal, distortion product otoacoustic emissions (DPOAEs) are believed to include contributions from both a nonlinear-distortion source and a coherent-reflection source (e.g., Talmadge et al., 1998, 1999; Mauermann et al., 1999a; Shera and Guinan, 1999; Stover et al., 1999; Konrad-Martin et al., 2001, 2002).

In the case of DPOAEs, the components from these two sources are generated at different locations on the basilar membrane. The nonlinear-distortion component is believed to arise near the f_2 place, where the primary nonlinear interaction between f_1 and f_2 occurs. The nonlinear interaction of the two primaries produces the $2f_1-f_2$ distortion product that propagates in two directions: basally toward the ear canal and apically toward its tonotopic place on the basilar membrane, where it will be reflected by the coherent-reflection mechanism (Zweig and Shera, 1995). DPOAEs, therefore, contain contributions from disparate locations on the basilar

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membrane. Furthermore, the phases of the nonlinear-distortion and the coherent-reflection components rotate at different rates with respect to one another as a function of frequency. This difference in the rate of phase rotation with frequency results in the two components interacting with each other in a manner that alternates between constructive and destructive interference and produces a quasi-sinusoidal pattern of maxima and minima in DPOAE level as frequency is varied in small increments. The pattern of alternating maxima and minima is typically referred to as DPOAE fine structure or microstructure. While the interaction of the distortion and reflection components is believed to be the primary mechanism responsible for DPOAE fine structure, periodicity in the reflection component alone also has been observed (e.g., Kalluri and Shera, 2001; Mauermann and Kollmeier, 2004; Wilson and Lutman, 2006). The periodicity in the reflection component may contribute to DPOAE fine structure, as well as fine structure observed in other otoacoustic emission types (e.g., stimulus-frequency OAEs, transient-evoked OAEs) and in behavioral thresholds. In the case of DPOAEs, the fine structure in the response is due primarily to the interaction of the distortion and reflection components, with the inherent periodicity in the reflection component adding additional variability to the measure.

The idea that DPOAEs contain contributions from two different cochlear locations generated by two different mechanisms has led a number of investigators to speculate that DPOAE test performance may be affected by the interaction of these sources (e.g., Heitmann et al., 1998; Shera and Guinan, 1999; Shaffer et al., 2003; Mauermann and Kollmeier, 2004; Shera, 2004). This hypothesis can be understood by considering how DPOAE fine structure varies across ears and across stimulus levels. The frequency at which a given maximum or minimum occurs is essentially randomly distributed across ears. For example, when $f_2 = 2$ kHz, one ear with normal hearing may produce a minimum DPOAE level while another normal-hearing ear might produce a maximum level and a third ear may be intermediate between maximum and minimum levels. These differing patterns of fine structure might lead to the erroneous conclusion that the normal-hearing ear producing a minimum at 2 kHz is impaired. Additionally, the frequencies at which maxima and minima occur within an individual ear may shift as level is increased (e.g., He and Schmiedt, 1993, 1997; Heitmann et al., 1996; Johnson et al., 2006b). This shift will influence the slope of the DPOAE I/O function and, therefore, may not only affect predictions of auditory status (i.e., normal versus impaired), but also may affect the accuracy with which behavioral thresholds can be predicted from DPOAE I/O functions (e.g., Boege and Janssen, 2002; Gorga et al., 2003; Oswald and Janssen, 2003). Indeed, Mauermann and Kollmeier (2004) report less variability in thresholds predicted from DPOAE I/O functions across frequency when the reflection-source contribution was reduced or eliminated, although they do not describe the correspondence between these predicted thresholds and measured behavioral thresholds.

The speculation that multiple-source contributions and the resulting fine structure affect DPOAE test performance has both intuitive and theoretical appeal; however, this hypothesis has not been directly tested. There is indirect evidence that source interactions and the resulting fine structure may not play a large role in limiting DPOAE test performance. For example, Dhar and Shaffer (2004) and Shaffer and Dhar (2006) failed to find a statistically significant correlation between behavioral threshold and DPOAE level for moderate-level stimuli, even when attempting to reduce or eliminate the contribution from the reflection source. However, these data were collected in a small group of normal-hearing subjects and, therefore, are not well suited to testing hypotheses regarding the influence of source contribution on test performance, which would require data for both normal and impaired ears. Additionally, both Dhar and Shaffer (2004) and Johnson et al. (2006b) reported that DPOAE fine structure was not observed in the majority of normal-hearing ears in the vicinity of 4 kHz, suggesting that it is unlikely that uncontrolled source interaction plays a major role in limiting test performance when testing at or around 4 kHz. While the Dhar and Shaffer (2004), Johnson et al. (2006b),

and Shaffer and Dhar (2006) data cast doubt on the hypothesis that fine structure contributes to diagnostic errors, they do not directly address the question of whether uncontrolled source interaction influences DPOAE test performance. Additional data from both normal and impaired ears are necessary to answer this question.

There are several methods by which the sources contributing to the DPOAE can be controlled. In one approach, DPOAE responses are recorded for many closely spaced frequencies. The response is then transformed to the time domain by computing an inverse fast Fourier transform (IFFT). The long-latency components (thought to be generated by the reflection source) are mathematically eliminated from the response and the response is then converted back into a frequency representation by computing a fast Fourier transform (FFT). This method, often referred to as time windowing, has been shown to be effective at eliminating the fine structure in DPOAE responses (e.g., Stover et al., 1996b; Kalluri and Shera, 2001; Knight and Kemp, 2001; Konrad-Martin et al., 2001; Mauermann and Kollmeier, 2004), and represents the gold-standard approach for restricting the DPOAE source contribution to the distortion source. While effective at separating source contributions, this approach is not suitable for clinical applications because it is necessary to record DPOAE responses for many closely spaced frequencies in order to have sufficient precision to compute the IFFT; the associated increase in test time makes this approach impractical in the clinic.

An alternate approach, selective suppression, involves presenting a third tone, a suppressor, in combination with the primary stimuli used to elicit the response. The suppressor is chosen to have a frequency close to the $2f_1$ - f_2 frequency in order to reduce or eliminate the contribution from the reflection source. With appropriately chosen suppressor levels, this technique also has been shown to reduce fine structure in DPOAE responses (e.g., Heitmann et al., 1998; Kalluri and Shera, 2001; Konrad-Martin et al., 2001; Johnson et al., 2006b). While the suppression technique has been shown to produce more variable reductions of fine structure compared to time windowing (e.g., Kalluri and Shera, 2001; Johnson et al., 2006b), it is possible to implement this technique under clinical conditions because the suppressor and primary stimuli are presented simultaneously, and, therefore, the technique does not require additional test time. When making DPOAE measurements with neonates, infants, and young children (clinical populations with whom DPOAE testing is frequently used), limiting test time is important. Because the suppression technique can be implemented without increasing test time, it is ideally suited for use when examining the influence of cochlear-source contribution on DPOAE test performance. The application of the suppression technique requires knowledge of the combinations of stimulus and suppressor levels that result in optimal effects, which may also depend on stimulus frequency.

In a previous study, we investigated the effect of a broad range of suppressor levels on DPOAE fine structure for stimulus levels ranging from 20 to 80 dB SPL (Johnson et al., 2006b). From this work, we were able to determine the suppressor levels resulting in optimal reduction of fine structure for each stimulus-level condition. Optimal suppressor level was defined as the suppressor level that resulted in the maximum reduction in fine structure with minimum influence on overall level. The purpose of the present study was to evaluate changes in DPOAE test performance and threshold-prediction accuracy when optimal suppressors were used to limit DPOAE cochlear-source contribution. We hypothesized that auditory status would be more accurately identified when cochlear-source contribution was controlled (i.e., when the suppressor was presented in conjunction with the primary stimuli) because the variability in DPOAE level resulting from fine structure would be eliminated. It was also hypothesized that behavioral threshold would be more accurately predicted from DPOAE I/O functions when cochlear-source contribution was restricted to the distortion source because non-monotonicities and/or other irregularities in the I/O functions would be reduced as well.

We have chosen the suppression technique to explore these questions because, as previously described, it can be implemented under clinical conditions where maximizing test efficiency is important. Additionally, while we acknowledge that fine structure exists in behavioral thresholds, in addition to OAE responses (e.g., Elliott, 1958; Long, 1984; Zwicker and Schloth, 1984; Zwicker, 1986; Long and Tubis, 1988a,b; Furst et al., 1992; Kapadia and Lutman, 1999; Lutman and Deeks, 1999; Horst et al., 2002; Mauermann et al. 2004), it typically is not measured during clinical assessments where only fixed octave and inter-octave frequencies are tested. Therefore, because our primary goal is evaluating the influence of cochlear-source contribution on the clinical test performance of DPOAE responses, we have not focused on the influence of behavioral-threshold fine structure on diagnostic errors when DPOAEs are measured.

II. METHODS

A. Subjects

Data were obtained from 98 ears of 56 subjects with normal hearing and 107 ears of 60 subjects with sensorineural hearing losses. Normal hearing was defined as pure-tone behavioral thresholds ≤ 20 dB HL (re: ANSI, 1996) for the octave and inter-octave frequencies between 0.25 and 8 kHz. For purposes of counting the number of normal versus impaired ears participating, an ear was considered hearing impaired if one or more pure-tone behavioral thresholds were > 20 dB HL for the same frequency interval. The majority of these ears (102/107) had behavioral thresholds exceeding 20 dB HL at 2 and/or 4 kHz. A sensorineural hearing loss was defined as air-bone gaps < 15 dB at the octave frequencies of 0.5 through 4 kHz and normal 226-Hz tympanograms. Please note, however, that when evaluating the accuracy of the dichotomous decision, the classification of normal versus impaired was made on a frequency-by-frequency basis (see below). Both normal-hearing and hearing-impaired subjects were required to have normal 226-Hz tympanograms prior to each data-collection session.

Efforts were made to recruit subjects whose hearing losses were primarily sloping in configuration. The reason for this emphasis was, in part, due to the observation that DPOAE responses from ears with sloping high-frequency hearing losses are more likely to include contributions from the reflection source (Konrad-Martin et al., 2002; Stover et al., 1999) and, thus, corresponding fine structure (Mauermann et al., 1999b). Additionally, in order to maximize the likelihood that the impaired ears would produce several points on the DPOAE I/O function, only ears with pure-tone behavioral thresholds ≤ 60 dB HL at 2 and 4 kHz were included.

B. Procedures

1. Equipment and Calibration—Custom-designed software (EMAV; Neely and Liu, 1993) was used for data collection. This software controlled a 24-bit soundcard (CardDeluxe, Digital Audio Labs) housed in a PC. Separate channels of the soundcard were used to generate the two primary tones (f_1 and f_2), which were then mixed acoustically in the ear canal. When a suppressor (f_3) was presented along with the primaries, it was generated on the same channel as f_2 . In the experimental paradigm used for data collection, f_2 and f_3 have a larger frequency separation than f_1 and f_3 . By generating f_2 and f_3 on the same channel, we ensured that intermodulation distortion products due to interactions between f_2 and f_3 did not occur at the same frequency as the DPOAE response ($2f_1 - f_2$).

An ER-10C (Etymotic Research) probe-microphone system was used for stimulus presentation and response recording. Because the ER-10C had been modified to remove 20 dB of attenuation

from each channel, we were able to achieve primary and suppressor levels as high as 80 dB SPL in each subject's ear canal.

Prior to data collection, stimuli were calibrated (in the ear canal) in sound pressure level at the plane of the ER-10C probe. Concerns have been raised regarding *in situ* pressure calibration (Siegel, 1994; Siegel and Hirohata, 1994; Neely and Gorga, 1998), although similar concerns apply to all pressure-calibration methods. While it is the current standard of practice for DPOAE measures, *in situ* pressure calibration may introduce variability into the measure as a result of the calibration, particularly at 4 kHz. We acknowledge this potential source of error and have attempted address this by collecting data on subjects ($N = 205$) with a range of different ear canal dimensions.

Measurement-based stopping rules were used during data collection, such that averaging continued until the noise level was ≤ -25 dB SPL or 32 sec of artifact-free averaging was achieved, whichever occurred first. Measurement-based stopping rules may increase test time but have the advantage of producing more consistent and lower noise levels across subjects because averaging time is increased whenever the noise level exceeds -25 dB SPL. Noise level was estimated from the $2f_1$ - f_2 frequency bin. This was accomplished by alternately storing 0.25-sec samples of the recorded response in one of two buffers. The buffers were summed to provide an estimate of the DPOAE level and were subtracted to provide an estimate of the noise level in the same frequency bin.

2. DPOAE I/O Functions—DPOAE I/O functions were recorded from each subject with $f_2 = 2$ and 4 kHz. At each f_2 , L_2 ranged from 0 to 80 dB SPL in 5-dB increments. The relationship between L_1 and L_2 and f_1 and f_2 was specified according to the following equations (Johnson et al., 2006a):

$$L_1 = 80 + 0.137 \cdot \log_2 (18 / f_2) \cdot (L_2 - 80) \quad (1)$$

$$f_2 / f_1 = 1.22 + \log_2 (9.6 / f_2) \cdot (L_2 / 415)^2 \quad (2)$$

We chose the stimulus conditions described by these equations (i.e., the L_1 for each L_2 and the f_2/f_1 for each f_2) because they result in the largest average L_{dp} for normal-hearing subjects (Johnson et al., 2006a).

For each f_2 , four different conditions were evaluated. In the control condition, the I/O function was recorded with no suppressor present. In the three experimental conditions, a suppressor (f_3), whose frequency was 16 Hz below the $2f_1$ - f_2 frequency, was presented at one of three levels. The three suppressor levels were chosen based on results described previously (Johnson et al., 2006b) so as to assure the likelihood that the response coming from the reflection source was suppressed. More specifically, the suppressor that was optimal at reducing fine structure in the Johnson et al. (2006b) average data was used as well as suppressors 10 dB above and 10 dB below this optimal level. This range of suppressor levels was used as a way of attempting to assure that at least one suppressor level was likely to be optimal in this new group of subjects.

When exploring the suppressor-level space (Johnson et al., 2006b), the suppressor level (L_3) was set according to the following equation:

$$L_3 = 0.75 \cdot L_2 + C \quad (3)$$

A broad range of C values were used for each L_2 . The optimal values of C for each f_2 and L_2 (as determined from Johnson et al., 2006b) are shown in Table 1. When determining the optimal value of C from the Johnson et al. (2006b) data, three rules were applied. Priority was given to suppressor levels (and corresponding C values) where there was a minimum in the magnitude of the fine-structure *and* a minimal reduction in the overall level of the DPOAE. In some cases,

consideration also was given to the suppressor level producing the smallest inter-subject variability. In addition to these rules, the C value was required to decrease monotonically or to remain constant as L_2 increased. The C values shown in Table 1 were those meeting all of the above conditions. The three suppressor levels used in the present study correspond to the L_3 values resulting from the C values in Table 1, which was the base condition (C0). Data also were collected with C set 10 dB above (Cp10) and 10 dB below (Cm10) this value, with the constraint that L_3 never exceeded 80 dB SPL. Thus, the suppressor levels were chosen as the previously determined optimal levels for each $L_2 \pm 10$ dB. Recording the I/O functions in the control condition and with the three different suppressor levels allowed us to evaluate the influence that the suppressors had on the accuracy of the dichotomous-decision task (i.e., normal or impaired hearing) as a function of L_2 . It also enabled us to evaluate the accuracy with which behavioral threshold was predicted from the DPOAE I/O function for each of the four conditions, using previously described procedures (e.g., Boege and Janssen, 2002; Gorga et al., 2003).

3. DPgrams—In addition to recording DPOAE I/O functions for each ear, DPgrams were recorded on a subset of ears recruited to return for additional data collection in efforts to understand why diagnostic errors occurred in some subjects. The 28 normal ears producing the smallest responses and the 23 impaired ears producing the largest responses participated in this additional data-collection effort. These ears were recruited based on the assumption that these would be ears for which diagnostic errors were most likely. DPgrams were recorded while f_2 was varied in 1/64-octave steps for the 1/3-octave interval centered at either 2 or 4 kHz. L_2 was fixed at 50 dB SPL for the interval surrounding 2 kHz and at 35 dB SPL for the 4-kHz interval. These level conditions were selected for more detailed exploration because they resulted in the best performance (defined as the largest area under the relative operating characteristic curve, AROC) in the control condition. The DPgrams were recorded in four different suppressor conditions: the control condition, where no suppressor was present, and suppressor conditions, in which the suppressor was simultaneously presented at each of the three suppressor levels described above (C0, Cp10, Cm10).

4. General Test Procedures—A sound-treated room was used for data collection. During data collection, subjects were seated in a reclining chair and slept, read quietly, or watched a silent, captioned movie. The DPOAE I/O-function data typically were collected during 2–3 two-hour sessions. The DPgram data collection required an additional session typically lasting no more than one or two hours. The amount of data-collection time per subject was variable because of our use of measurement-based stopping rules. Additionally, when recording DPgrams, some subjects had ears that met our inclusion criteria at both 2 and 4 kHz. This resulted in a longer test session than when testing a subject on whom data were collected at only one f_2 frequency. When recording both the DPOAE I/O functions and the DPgrams, the control (no suppressor) condition was always tested first. In-the-ear calibration of level was repeated before testing each condition. In this way, we were able to monitor the stability of the probe fit over the entire test session and to make adjustments if the fit changed.

5. Discrete Cosine Transform—As will be described below, the discrete cosine transform (DCT) (Rao and Yip, 1990) was computed on the DPgram data. The DCT was used to quantify the effectiveness of the suppressors with regard to how completely they reduced the fine structure in the DPgram, an approach we have used previously (Johnson et al., 2006b). The DCT is similar in concept to the FFT and is essentially an FFT for which the components with sine-function symmetry have been dropped. It provides a quantification of the overall level of the response (the DC component of the DCT) as well as the levels of the higher “frequency” (cycles/octave) components that ride on the DCT component. The elimination of sine-symmetry components reduces frequency-domain windowing artifacts. We interpret the

DC component of the DCT (or overall level of the response) as an estimate related to the level of the distortion-source component. Phase information is not used in the DCT analysis. The magnitude of the “high frequency” coefficients (coefficients between 1.5 and 22.5 cycles per octave) provides an estimate related to the amount of the fine structure that is present in each condition and, thus, can be used to evaluate the extent to which the suppressors have reduced the fine structure¹. The DCT analysis method was selected to quantify our visual assessment of fine structure based on plots of DPOAE level versus frequency.

III. RESULTS

A. Accuracy of the dichotomous decision

The influence of controlling the DPOAE source contribution on test performance was quantified using clinical decision theory (CDT) (Swets and Pickett, 1982; Swets, 1988). This approach, which is well suited to assessing the accuracy with which diagnostic tests provide dichotomous classifications (i.e., normal or impaired hearing in the present case), has been used previously to evaluate DPOAE test performance (e.g., Gorga et al., 1993, 1997, 1999, 2000, 2005; Kim et al., 1996; Stover et al., 1996a; Dorn et al., 1999). In these applications of CDT, audiometric threshold served as the gold standard to which the results from the experimental measurement (typically DPOAE level) were compared. As in previous applications of CDT to assess DPOAE test performance, behavioral thresholds were used in the present study to classify an ear as either normal (thresholds ≤ 20 dB HL) or impaired (thresholds > 20 dB HL). This classification was made on a frequency-specific basis. In other words, if an ear had a behavioral threshold ≤ 20 dB HL at 2 kHz but > 20 dB HL at 4 kHz, it would be considered normal at 2 kHz and impaired at 4 kHz. By computing hit rates (i.e., correct identification of hearing loss or sensitivity) and corresponding false-alarm rates for all possible DPOAE levels, a complete description of test performance was obtained. The results from the DPOAE I/O function measurements were summarized in the form of relative operating characteristic (ROC) curves, which are plots of hit rate as a function of false-alarm rate. The area under the ROC curve (A_{ROC}) provided a single estimate of test accuracy. Possible A_{ROC} values range from 0.5, which indicates chance performance, to 1.0, which indicates perfect test performance, where the hit rate is 100% for all false-alarm rates. In the present study, ROC curves were constructed for each of the four test conditions (control, C0, Cp10, and Cm10) at each f_2 and L_2 , and A_{ROC} was computed for every condition.

Figure 1 plots A_{ROC} as a function of L_2 based on data collected from the entire sample of subjects. Results for $f_2 = 2$ and 4 kHz are plotted in the left and right panels, respectively. The parameter in each panel is test condition. The thick, solid line represents results for the control condition. The dashed lines represent results for the 3 suppressor conditions, with increasing line thickness indicating increasing suppressor level, from a minimum for Cm10 (thinnest dashed line) to a maximum for Cp10 (thickest dashed line). For virtually every condition (the exception being the highest suppressor level, Cp10, when $f_2 = 2$ kHz), A_{ROC} increases with L_2 , reaches a maximum over a range of moderate stimulus levels and then decreases with further increases in L_2 . This pattern of results was observed for both $f_2 = 2$ and 4 kHz; this dependence on L_2 has been observed previously (e.g., Stover et al., 1996a). When $f_2 = 2$ kHz, the largest A_{ROC} was observed for the control condition when $L_2 = 50$ dB SPL. The largest A_{ROC} when $f_2 = 4$ kHz occurred when $L_2 = 35$ dB SPL in the control condition, although, at both f_2 frequencies, there was a range of L_2 's for which similar A_{ROC} 's were observed. Regardless of

¹A reduction in the contribution of the reflection source to the DPOAE does not necessarily result in a reduction in the depth of the fine structure. In cases where the reflection source dominates the DPOAE response, reducing the reflection-source contribution to the point where it is equal in level to the distortion-source component will produce more complete cancellation between the two sources. In this case, the depth of the fine structure may increase with reductions in reflection-source contribution (Talmadge et al., 1999; Dhar and Shaffer, 2004).

L_2 , A_{ROC} for the suppression conditions (dashed lines), in which the contribution from the reflection source presumably has been reduced, is less than or equal to the A_{ROC} for the control condition (solid line). This result was observed for both $f_2 = 2$ kHz and $f_2 = 4$ kHz and demonstrates that test performance was either unchanged or decreased when suppressors were presented simultaneously with the eliciting stimuli.

B. Generalizability of predetermined suppressors

If A_{ROC} had increased when suppressors were presented, then this would have been consistent with the view that uncontrolled source contribution increased the variability (and decreased the accuracy) of DPOAE measurements as a diagnostic tool. If the A_{ROC} was the same with or without the presentation of the suppressors, then this would have indicated that contributions from the reflection source have no influence on DPOAE test performance or the suppressors used to control source contribution were not effective. However, the results shown in Fig. 1 indicate that suppressors, which were used to reduce or eliminate contributions from the reflection source, most frequently had a deleterious effect on test performance, as shown by the reduction in A_{ROC} for essentially all suppressor conditions.

The data plotted in Figs. 2, 3, 4 represent an effort to better understand the results that were described in Fig. 1. These additional data were collected for the subset of subjects who participated in the main experiment for whom it was most likely that diagnostic errors would have occurred based on the original set of measurements. Specifically, the normal-hearing ears producing the smallest DPOAE levels and the hearing-impaired ears producing the largest DPOAE levels for the control (no suppressor) condition with the largest A_{ROC} ($L_2 = 50$ dB SPL for $f_2 = 2$ kHz; $L_2 = 35$ dB SPL for $f_2 = 4$ kHz) were recruited to return for additional data collection. Sixteen normal ears and 10 impaired ears for the 2-kHz conditions and 12 normal ears and 13 impaired ears for the 4-kHz conditions participated in this additional study. The decision to recruit in this manner was based on the idea that the normal-hearing ears with the smallest DPOAE levels were most likely to be misidentified as impaired, whereas the hearing-impaired ears with the largest DPOAE levels were most likely to be erroneously labeled as normal.

Figure 2 plots examples of DPOAE level as a function of f_2 for closely spaced frequencies in the 1/3-octave band surrounding 2 kHz for two subjects with normal hearing. This f_2 was selected because it is more likely that fine structure will be observed at this frequency, compared to when $f_2 = 4$ kHz (Dhar and Shaffer, 2004; Johnson et al. 2006b). Each column in Fig. 2 plots results for a different subject and each row represents data for a different test condition, as indicated in each panel. Results for the control condition are plotted in the top row, with the results for conditions in which suppressor level increased presented in subsequent rows. Within each panel, DPOAE level is plotted (thick solid or dashed line) along with the associated noise levels (thin, solid line). For the subject whose data are shown in the left column, the Cm10 suppressor was effective at reducing the fine structure, without reducing the overall DPOAE level. The C0 and Cp10 suppressor levels produced differing amounts of over-suppression in which the overall level of the DPOAE was reduced. The data shown in the right column suggest that the predetermined suppressor levels were less effective for this subject. Fine structure is reduced in the Cm10 condition, particularly for $f_2 > 2$ kHz, but not as completely as for the subject whose data are shown in the left column. The C0 and Cp10 suppressors reduced overall DPOAE level, but were no more effective at smoothing the fine structure. Additionally, the Cp10 condition would be expected to result in a false-positive error because the overall level of the response has been suppressed to the noise floor. These data suggest that there is between-subject variability in the effectiveness of the predetermined suppressors, making it difficult to select conditions for general use, as would be needed for clinical measurements.

The mean data (± 1 SD) shown in Fig. 3 describe the effectiveness of the suppressors for the entire group of subjects who returned for additional data collection. These data were obtained by computing a DCT on the DPOAE fine-structure measures (see Fig. 2). The left column of Fig. 3 plots data for the 2-kHz conditions, with data for the 4-kHz conditions plotted in the right column. The top row plots the overall DPOAE level (the DC component) in dB re: the control condition as a function of suppressor level (i.e., the three suppressor conditions used in the present study). The data in the bottom row describe the change in fine-structure depth for the three suppressor conditions relative to the control condition. These data were obtained by computing the rms level of the “high frequency” DCT coefficients, which provides a single value corresponding to fine-structure depth for each condition. These values for the suppressor conditions were then subtracted from the control condition value. The data plotted in the bottom row of Fig. 3, therefore, represent the difference in rms level in the suppressor conditions relative to the control condition. The parameter in each panel is group (open circle = normal, filled circle = impaired) with the symbols indicating the mean value (± 1 standard deviation). The dashed horizontal line indicates the point at which the responses for control and suppressor conditions are equivalent.

In the top row, points below the dashed line indicate conditions where suppressors reduced the overall level. In the bottom row, points below the dashed line indicate conditions where suppressors reduced the fine-structure depth. As shown in Fig. 3, the lowest suppressor level (Cm10) was most effective at reducing the fine-structure depth without reducing the overall level for this sub-group of normal ears in the frequency interval surrounding 2 kHz, although there was variability across subjects, as represented by the error bars. The higher-level suppressors (C0 and Cp10) produced reductions in the overall level for both the normal and impaired sub-groups. A different pattern emerged for frequencies surrounding 4 kHz. In the 4-kHz interval, the suppressors had little influence on either fine-structure depth or overall level in both subject groups. The lack of a suppression effect at 4 kHz may be due to the lower prevalence of fine structure observed at 4 kHz as compared to 2 kHz (i.e., 1 of 12 normal ears had fine structure at 4 kHz as compared to 7 of 16 normal ears at 2 kHz), a frequency-dependent pattern that has been previously reported (Dhar and Shaffer, 2004; Johnson et al., 2006b).

Figure 4 shows cumulative distributions of DPOAE level (dB SPL) for the subset of subjects who returned for additional data collection. Recall that these are the ears most at risk for diagnostic errors during the primary analysis based on the measurements of unsuppressed DPOAE level (Fig. 1). Results for $f_2 = 2$ kHz and 4 kHz are plotted in the left and right columns, respectively. These data were collected for the primary levels at which the A_{ROC} was largest in the control condition in the larger sample of subjects ($L_2 = 50$ and 35 dB SPL at 2 and 4 kHz, respectively). From top to bottom, the rows represent results for the control condition, the three suppressor conditions, and a frequency-smoothing condition (the DCT condition). In the frequency-smoothing condition, the fine structure was eliminated through the use of the DCT as described in Johnson et al. (2006b). When using the DCT to eliminate DPOAE fine structure, the coefficients of the high-frequency components are set to zero so that only the DC and slowly varying components remain. This preserves the overall level of the response but eliminates the fine structure.

Within each panel of Fig. 4, arrows indicate the DPOAE levels associated with the 50th percentile of the distribution of responses from both the normal (solid line) and impaired (dashed line) subgroups of subjects. The A_{ROC} values associated with each test condition for these subsets of subjects are shown as insets in each panel. These A_{ROC} values are lower than the best values shown in Fig. 1 because they represent results for the small group of ears on which diagnostic errors were most likely to occur. Stated another way, these ears were specifically selected because they represented cases in which there was the greatest overlap between normal and impaired responses, which, in turn, must result in a lower A_{ROC} .

In this group of subjects, the separation between the 50th percentiles for the suppressor and DCT conditions tended to be larger than or equivalent to the separation observed in the control condition, but only when $f_2 = 2$ kHz. At this frequency, 2 of 3 suppression conditions and the DCT condition resulted in larger A_{ROC} (by 12–15%), compared to the control condition. No differences in A_{ROC} were observed when $f_2 = 4$ kHz, regardless of test condition. Here, the lack of a difference between the control and any of the conditions in which the reflection source was removed is expected, given the previous observations that fine structure (which presumably results from source interactions) is infrequently observed at 4 kHz (Dhar and Shaffer, 2004; Johnson et al., 2006b). Furthermore, even the results from this small subset of ears at 2 kHz ($N = 26$) should be viewed cautiously because they differ from the trends observed in the large sample ($N = 205$). For the small group of ears on which diagnostic errors were most likely to occur, the data suggest that controlling source contribution, through either the use of a suppressor or using a frequency-smoothing approach (the DCT), resulted in fewer errors. The contrasting result in the large group, where no difference or poorer performance was observed, suggests that the use of suppressors to control cochlear source in a more general population of subjects introduced errors for cases where errors were not made in the control condition (i.e., the condition where source contributions were uncontrolled).

C. Threshold prediction

Data describing the relationship between behavioral thresholds and DPOAE thresholds are plotted in Figs. 5 and 6. Figure 5 plots these data for the $f_2 = 2$ kHz conditions, with comparable data for the $f_2 = 4$ kHz conditions plotted in Fig. 6. In both figures, behavioral threshold (dB HL) is plotted as a function of DPOAE threshold (dB SPL) for two different approaches to obtaining a DPOAE threshold (right and left columns). In both figures, the top row provides data for the control conditions and each subsequent row represents a different suppression condition, with suppressor level increasing as one moves down each column. Solid lines within each panel represent linear fits to the data. Insets in each panel describe the test condition and the equations associated with the linear fits.

Two definitions of DPOAE thresholds were used and subsequently correlated with behavioral thresholds. The DPOAE thresholds plotted in the left columns of Figs. 5 and 6 were obtained by fitting the DPOAE I/O function with a linear equation as was described in Gorga et al. (2003), which represents a modification of the technique originally proposed by Boege and Janssen (2002). Here, we will refer to this technique as the I/O-function approach for estimating DPOAE threshold. Briefly, these DPOAE thresholds were estimated for I/O functions meeting several inclusion criteria. First, DPOAE I/O functions were required to have a minimum of three points with $SNR \geq 10$ dB (the SNR inclusion criterion). For those I/O functions meeting this requirement, the DPOAE level was converted to pressure (μPa) and then plotted as a function of L_2 (in dB SPL). A linear equation was fit to the resulting semi-log (μPa vs. dB SPL) I/O functions. To be included in the next stage of analysis, the semi-log I/O functions had to meet the following additional regression-based inclusion criteria: slope ≥ 0.1 $\mu\text{Pa}/\text{dB}$, correlation coefficient (r) ≥ 0.7 , and standard error ≤ 9 dB. For those I/O functions in which these regression-based inclusion criteria were met, DPOAE threshold was computed by solving the linear equation for the L_2 producing a DPOAE of 0 μPa . The relation between these DPOAE thresholds and behavioral threshold is shown in the left column of Figs. 5 and 6.

The DPOAE thresholds plotted in the right column of Figs. 5 and 6 were obtained by taking a simpler approach in which the lowest L_2 for which the SNR was ≥ 3 dB was defined as DPOAE threshold. This alternate approach was evaluated because correlations between behavioral threshold and simple estimates of DPOAE thresholds (such as those based on SNR) have been reported previously (e.g., Dorn et al., 2001; Gorga et al., 1996; Martin et al., 1990; Nelson and

Kimberly, 1992). Here, we will refer to this approach to estimating DPOAE threshold as the SNR approach.

Table 2 describes the number of ears meeting inclusion criteria, the correlation between behavioral and DPOAE thresholds, and the associated standard errors for the two approaches to threshold prediction when $f_2 = 2$ and 4 kHz. As can be seen in Figs. 5 and 6 and Table 2, when predicting behavioral thresholds using the I/O-function approach, the lowest suppressor level (Cm10) resulted in the highest correlation between behavioral and DPOAE thresholds, although the differences were small (improvements of 0.02 to 0.03). When using the simpler SNR approach, the correlation was always poorer for the suppression conditions than for the control condition. Visual comparison of the data plotted in the left and right columns suggests more variability between behavioral and DPOAE thresholds when using the approach in which the L_2 at which $\text{SNR} \geq 3$ dB was defined as DPOAE threshold (the SNR approach). However, correlations and associated standard errors were similar for the two methods for obtaining DPOAE thresholds (see Table 2), and actually favored the SNR approach in the control condition. The appearance of an increase in variability is most likely a consequence of the observation that the SNR approach could be applied to nearly every ear ($N = 204$ or 205), regardless of test condition. In contrast, a number of ears did not meet the inclusion criteria when using the I/O function approach. These data suggest that the simpler SNR approach may be more useful under clinical conditions and can be expected to produce results similar to those for the I/O-function approach but for a larger number of ears.

Figure 7 and Table 3 provide additional information regarding the ears not meeting the inclusion criteria for the I/O-function approach (either the SNR or the regression-based inclusion criteria). When compared to similar data reported by Gorga et al. (2003), a larger proportion of ears met all inclusion criteria in the control condition for the present study. In the control condition, 57% and 76% of ears for $f_2 = 2$ and 4 kHz, respectively, met all inclusion criteria as compared to 40% and 55% of ears for $f_2 = 2$ and 4 kHz, respectively, in the Gorga et al. dataset. This overall higher success rate may be due, in part, to the fact that the present study restricted hearing-loss severity to no greater than 60 dB HL at 2 and 4 kHz, whereas ears with more severe hearing losses were included in Gorga et al. It also may relate to differences in the stimulus conditions used in the present study as compared to those used in Gorga et al. The present study used stimulus conditions that previously have been shown to produce larger DPOAEs in normal-hearing ears than those used by Gorga et al. (Neely et al., 2005; Johnson et al., 2006a). These conditions might be expected to result in more ears meeting the inclusion criteria for the I/O-function approach.

As shown in Fig. 7 and Table 3, when using the I/O-function approach in the present study, only a small number of the 205 ears did not meet the SNR inclusion criterion in the control condition [10/205 (5%) when $f_2 = 2$ kHz and 4/205 (2%) when $f_2 = 4$ kHz]. This represents a smaller proportion of subjects not meeting the SNR inclusion criterion than those reported by Gorga et al. for the same f_2 frequencies (45% and 38% for $f_2 = 2$ and 4 kHz, respectively), which again was probably a consequence of differences in hearing-loss severity among the subjects included in that study and in the present one, but also may relate to the stimulus differences. Of those ears not meeting the SNR inclusion criterion (I/O-function approach), the ear was most likely to have a hearing loss that exceeded 30 dB HL, which is consistent with previous observations (Gorga et al., 2003). With the exception of the highest suppressor level (Cp10) when $f_2 = 2$ kHz, the suppressors produced little change in the number of cases meeting the SNR inclusion criterion. The highest suppressor level when $f_2 = 2$ kHz resulted in more cases in which the 10-dB SNR inclusion criterion was not met, especially among ears with less hearing loss, an observation that is consistent with the idea that this suppression condition reduced the overall level of the DPOAE. In the control condition in the present study, more ears were excluded for not meeting the regression inclusion criteria than was reported by

Gorga et al. For $f_2 = 2$ kHz, 38% did not meet the regression criteria as compared to 14% in the Gorga et al. dataset. When $f_2 = 4$ kHz, 22% and 7% of cases did not meet inclusion criteria for the present study and for Gorga et al. study, respectively. While it is not clear why there were differences in the number of ears meeting the regression inclusion criteria for the present study as compared to Gorga et al., the different suppressor levels had little influence on the extent to which regression-based criteria were met.

The data plotted in Figs. 8 ($f_2 = 2$ kHz) and 9 ($f_2 = 4$ kHz) represent the average I/O functions recorded for ears with behavioral thresholds ranging from -5 to 50 dB HL. Each panel represents data for ears having different behavioral thresholds, as indicated within each panel; thus, each cell plots the average DPOAE level as a function of L_2 for all ears with the same behavioral threshold. Test condition is represented by line thickness and type (solid versus dashed), with the control condition plotted as a thick, solid line and the suppressor conditions plotted as dashed lines with increasing thickness indicating increasing suppressor level. Although the present study included ears with behavioral thresholds of -10 , 55 , and 60 dB HL, the average I/O functions for these threshold categories are not plotted because fewer than 5 ears were represented at both 2 and 4 kHz. For each of the cells shown in Figs. 8 and 9, the average I/O function was based on data from at least 5 subjects, with the number of ears contributing data in the control condition identified in each panel. The number of ears for the suppressor conditions in each panel may be less than the control condition due to over suppression that is observed in some ears and particularly for the highest suppressor level (Cp10).

The data plotted in Fig. 8 indicated that the lowest suppressor level (Cm10) had little influence on the shape of the average I/O function regardless of threshold category. The higher suppressor levels (C0 and Cp10) tended to reduce the DPOAE level, particularly for low L_2 levels. The reduction in DPOAE level was most pronounced for the highest suppressor level and ears with better behavioral thresholds. Inspection of the data plotted in Fig. 9 for $f_2 = 4$ kHz suggests that the suppressors had little effect on the DPOAE I/O functions. All of these observations are consistent with previous results showing that (1) high level suppressors have the largest effect on DPOAE level (e.g., Heitmann et al., 1998; Konrad-Martin et al., 2001; Johnson et al., 2006b), (2) source interactions appear to be more apparent for low-level stimuli, compared to higher primary levels (e.g., Stover et al., 1996b; Konrad-Martin et al., 2001; Mauermann and Kollmeier, 2004), and (3) source interactions (as reflected in fine structure) are less evident at 4 kHz, compared to 2 kHz (e.g., Dhar and Shaffer, 2004; Johnson et al., 2006b).

It is possible that the presence of the suppressor had little influence on the shape of the I/O function, but had an influence on the variability in DPOAE levels among ears with the same behavioral thresholds. If mixing of contributions from the distortion and reflection sources contributes to variability across ears, reducing the contribution from the reflection source might be expected to reduce the variability in DPOAE levels recorded from ears with the same behavioral threshold. Data exploring the influence of the suppressors on between-ear variability are plotted in Figs. 10 ($f_2 = 2$ kHz) and 11 ($f_2 = 4$ kHz), where average standard deviations are plotted as a function of stimulus condition for each of 12 behavioral-threshold categories. The standard deviation in DPOAE level for each of the threshold categories was computed for each L_2 . These standard deviations were then averaged for all L_2 levels within a given threshold category to provide the average SD for each threshold category and each test condition.

There were individual threshold categories where one or more suppressor levels produced a reduction in the average standard deviation (see, for example, BT -5 when $f_2 = 2$ kHz and BT = 30 when $f_2 = 4$ kHz). However, in general, the effect of the suppressors on the average standard deviation was small and included both reductions and increases in variability across

behavioral-threshold category. It, therefore, appears that the suppressors had little influence on between-ear variability in DPOAE level.

IV. DISCUSSION

In summary, the data reported here suggest that using a suppressor to control the cochlear sources contributing to the DPOAE did not improve the accuracy of the dichotomous decision in which auditory status is determined from DPOAE measurements. There was variability in the effectiveness of the suppressors across ears, although (on average) the lowest suppressor level reduced the depth of DPOAE fine structure in a small group of subjects in whom diagnostic errors were most likely to occur. For these subjects, the use of the suppressors also improved the accuracy of the dichotomous decision. Although the analyses for this group showed an improvement in DPOAE test performance when cochlear-source contribution was controlled, the lack of improvement (or, in some cases, the reduction) in the larger, unselected group suggests that the use of a suppressor will not improve test performance during more general clinical applications. Additionally, there was no improvement in the accuracy with which DPOAE measures predict behavioral threshold when using suppressors to control source contribution as compared to the control condition.

A. Dichotomous decision

In contrast to our hypotheses at the outset, the use of a suppressor did not improve test performance at any L_2 for either f_2 in the large group of subjects ($N = 205$). If anything, the use of a suppressor resulted in poorer test performance (smaller A_{ROC}) for virtually every stimulus condition. As described above, there are several possible reasons for these observations. It may be that uncontrolled cochlear-source interaction and the resulting DPOAE fine structure does not play a role in limiting DPOAE test performance. It is also possible that the use of predetermined suppressor levels to control cochlear-source contribution is not an effective approach. And, finally, it appears to be the case that suppressors have the unintended effect of reducing DPOAE level in some subjects with normal hearing, with a concomitant negative impact on test performance.

Regardless of the factors that underlie the reasons for the results observed in the present study, the fact remains that the use of suppressors to control source contribution under clinical conditions would be expected to reduce test performance, not improve it. The data collected in the small group of subjects for whom diagnostic errors were most likely were examined in order to further understand the results that were observed in the large group. The data presented in Figs. 2 and 3 suggest that, while there was variability in the effectiveness of the predetermined suppressors, the lowest suppressor level (Cm10) frequently reduced fine structure without affecting overall DPOAE level at the frequency for which fine structure was most evident in the control condition ($f_2 = 2$ kHz). Additionally, as shown in Fig. 3, the suppressors had little influence on fine-structure depth in the ears with hearing loss when $f_2 = 2$ kHz or in either group when $f_2 = 4$ kHz. Although some ears with hearing loss may produce DPOAE fine structure, previous reports indicate that it is only observed when auditory function at the cochlear location from which the reflection source arises is normal or nearly normal (Mauermann et al., 1999a; Stover et al., 1999; Konrad-Martin et al., 2002). Additionally, as observed in the present study, and in previously reported data (e.g., Dhar and Shaffer, 2004; Johnson et al., 2006b; Reuter and Hammershoi, 2006), fine structure is less prevalent in ears with normal hearing for frequencies surrounding 4 kHz. Given these observations, it was unlikely that we would see an effect of suppression in the ears with hearing loss or in ears with normal hearing at 4 kHz. Extending these observations to predictions of results from the small group, for the conditions where fine structure was not likely to be present, no effect of the suppressors was observed. In contrast, for the condition where fine structure was likely (normal

ears for frequencies surrounding 2 kHz), the lowest suppressor level was effective at reducing fine-structure depth.

Our rationale for recruiting the normal ears with the smallest DPOAEs and the impaired ears with the largest DPOAEs for additional data collection was based on the idea that these ears were most likely to be misclassified when DPOAE level is used to make dichotomous decisions regarding auditory status. Furthermore, we hypothesized that, if interactions between distortion and reflection sources produce errors in the interpretation of clinical DPOAE measures, these errors would occur because the two sources added together in a destructive manner in normal ears, making them look more like impaired ears, or added in a constructive manner in impaired ears, making them look more like normal ears. The observation of larger A_{ROC} values for the lowest suppression levels and for the DCT condition as compared to the control condition when $f_2 = 2$ kHz suggests that the interaction of the distortion and reflection sources played a role in producing errors in this restricted subject population. Furthermore, these data suggest that the use of both the lowest suppressor level and the DCT improved the accuracy of the dichotomous decision. It is important to remember, however, that these results are in conflict with the results observed in the larger, unselected group of subjects.

The most likely explanation for the differences in results between the larger group and the small, selected sample is that the suppressors introduced more errors in the larger, unselected group, than they reduced in the smaller group. To be effective clinically, suppressors must not only reduce fine-structure depth but also must cause little or no change to the overall DPOAE level, which presumably is generated near the f_2 place (i.e., the distortion source). It is for this reason that three suppressor levels were included in the present measurements. In this way, we hoped to include at least one suppressor level for each condition and each subject that was effective without directly determining the effectiveness of each suppressor in every subject, a procedure that cannot be used during clinical assessments. The effect of the suppressors on fine-structure depth and overall level in the larger group of subjects is unknown, but appears to differ from what was observed in the small group, in whom these effects were evaluated in more detail. In the large group, the most likely explanation for the reduction in A_{ROC} for the highest suppressor level is that this suppressor level reduced the overall DPOAE level in ears with normal hearing. The lack of improvement in A_{ROC} for the lower suppressor levels suggests that any normal ears for which the suppressors improved the accuracy of the dichotomous decision (i.e., those normal ears included in the small group) were more than offset by additional normal ears for which the suppressors introduced errors (presumably by suppressing the overall level). The poorer test performance in the larger sample cannot be attributed to influences on DPOAE level in ears with hearing loss because a reduction in DPOAE level in those subjects could only improve test performance (by increasing the hit rate).

The improvement in test performance (i.e., larger A_{ROC} values) observed in the small, selected group of ears for the lowest suppressor levels relative to the no-suppressor conditions suggests that interaction between the distortion and reflection sources may play a role in producing errors in identification of auditory status. However, observations in the large, unselected group of subjects, demonstrate that the suppression approach to controlling source contribution will not improve test performance, most likely because it introduces errors by over-suppressing the distortion source in ears with normal hearing. The DCT (and other frequency-smoothing approaches, e.g., Kalluri and Shera, 2001), can eliminate the reflection-source contribution without affecting the contribution from the distortion source, thereby leaving the overall level of the DPOAE unchanged, and might produce improvements in DPOAE test performance in an unselected group of subjects. However, the time involved in collecting the data with sufficient frequency resolution to compute the DCT is prohibitive in clinical contexts. As an alternative to the time-consuming approach associated with the DCT procedure, Long et al. (2004) have suggested that a frequency-sweep paradigm may be used to eliminate fine structure

in DPOAE responses. It remains to be seen if this technique produces improvements in DPOAE test performance for a general unselected group of subjects in a clinically feasible manner.

B. Threshold prediction

In general, the correlations between behavioral thresholds and DPOAE thresholds (control condition) are consistent with other reports in the literature (e.g., Martin et al., 1990; Dorn et al., 2001; Boege and Janssen, 2002; Gorga et al., 2003). As noted above, suppressors did not improve the correlation and, in some cases, reduced the correlation. Of interest is the observation that nearly identical correlations were observed when either the simple SNR approach or the more complicated I/O-function approach were used to predict behavioral thresholds for both the control and suppression conditions (compare correlations for SNR Approach and I/O Approach in Table 2). The SNR-based approach is conceptually simpler and has the added advantage of being applicable to a larger proportion of ears because threshold is defined as the L_2 for which the SNR = 3 dB rather than the more restricted I/O function approach that requires at least 3 points with 10-dB SNR. When $f_2 = 2$ kHz, the SNR-based approach could be used to estimate DPOAE thresholds in 100% (205/205) of ears. In contrast, the I/O-function approach could be used to predict DPOAE thresholds in only 57% (117/205) of ears at the same frequency. When $f_2 = 4$ kHz, the SNR and I/O function approaches resulted in predictions of DPOAE thresholds in 99.5% (204/205) and 76% (156/205) of ears, respectively. While the number of cases in which the SNR-based approach could be used to predict DPOAE thresholds decreases when hearing losses exceed 60 dB HL, a similar decrease would be expected in the number of cases for which the I/O-function approach could be used to provide an estimate of DPOAE threshold.

The observation that the highest suppressor level excluded more ears for failing to meet the SNR inclusion criterion (I/O-function approach) is consistent with the idea that over-suppression occurred for this suppressor level. In other words, the highest suppressor level reduced both the reflection- and the distortion-source contributions to the DPOAE. Changes observed in the shape of the mean I/O functions plotted in Figs. 8 and 9 are also consistent with this idea. These data also demonstrated that over-suppression was a more frequent occurrence when $f_2 = 2$ kHz as compared to 4 kHz.

V. CONCLUSIONS

In summary, the present data suggest that there would be little or no value in adding a suppressor during routine clinical DPOAE measurements, either to predict auditory status or to predict behavioral threshold from DPOAE threshold. In fact, the use of suppressors sometimes decreased test performance. While it was possible to improve diagnostic accuracy in a subset of pre-selected subjects for whom errors were most likely to occur, the improvement in test performance for these subjects was only achieved at the expense of a decrease in test performance in the larger, unselected sample of subjects. Furthermore, it is not possible to identify, a priori, those clinical subjects for whom the simultaneous presentation of a suppressor will improve diagnostic accuracy. Given that the unselected sample is representative of the patients one might encounter in the clinic, the present data would argue in favor of clinical measurements of DPOAEs without regard to concerns related to controlling source contribution with a suppressor.

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Figure 1.

ROC curve area as a function of L_2 (dB SPL). Results for $f_2 = 2$ kHz and 4 kHz are shown in the left and right panels, respectively. The parameter in each panel is test condition, with the control condition represented by the thick, solid line and the suppression conditions indicated by the dashed lines. Increasing dash thickness indicates increasing suppressor level.

Figure 2.

DPOAE level (dB SPL) as a function of f_2 (kHz) for the 1/3-octave interval surrounding 2 kHz with $L_2 = 50$ dB SPL. Each column represents data for a different normal-hearing subject with each row representing a different test condition. Data for the control condition are plotted in the top row, with suppressor level increasing from top to bottom, as indicated by the inset in each panel. Within each panel the thick solid lines and dashed lines represent the DPOAE level and the thin solid lines near the bottom of each panel represent the associated noise.

Figure 3.

The average overall DPOAE level (top row) and average fine-structure depth (bottom row) for the three suppression conditions relative to the control condition for the small group of subjects in whom diagnostic errors were most likely. Standard error bars represent ± 1 standard deviation. Results for $f_2 = 2$ kHz are plotted in the left column with corresponding data for $f_2 = 4$ kHz in the right column. The results for the normal and impaired ears are represented by the open and filled circles, respectively. The horizontal dashed line represents the point at which the control and suppression conditions are equivalent. These data were obtained from the DCT analyses as described in the text.

Figure 4.

Cumulative percentages of DPOAE level (dB SPL) for the 2 kHz (left column) and 4 kHz (right column) conditions for the small group of subjects (see text for details). The rows represent, from top to bottom, results for the control condition, the 3 suppression conditions, and the frequency-smoothing (DCT) condition. The parameter in each panel is subject group (normal or impaired), as indicated in the figure legend. The arrows in each panel indicate the 50th percentile of DPOAE level for the normal and impaired ears. Also shown as an inset in each panel is the A_{ROC} for each test condition for this group of subjects.

Figure 5.

Behavioral threshold (dB HL) as a function of DPOAE threshold (dB SPL) for two approaches to estimating DPOAE thresholds when $f_2 = 2$ kHz. The left column represents DPOAE thresholds obtained from the DPOAE I/O functions using the Gorga et al. (2003) modification of the Boege and Janssen (2002) technique (the I/O-function approach). The right column represents comparable data when the 3-dB SNR point is taken as the DPOAE threshold (the SNR approach). Each row represents data for a different suppression condition with suppressor level increasing from the top to the bottom of the figure. Solid lines in each panel represent linear fits to the data. The associated linear equations are shown as insets in each panel.

Figure 6.

Behavioral threshold (dB HL) as a function of DPOAE threshold (dB SPL) for the two approaches to estimating DPOAE thresholds when $f_2 = 4\text{ kHz}$. The plotting convention is the same as for Fig. 5.

Figure 7.

Cumulative percentage of the behavioral thresholds (dB HL) for those I/O functions not meeting the Gorga et al. (2003) SNR inclusion criterion (top row) or the regression inclusion criteria (bottom row) when using the I/O-function approach to estimating DPOAE threshold. Data for the 2 and 4 kHz conditions are plotted in the left and right columns, respectively. The parameter within each panel is test condition. The control condition is represented by the thick, solid line, with increasing suppressor level represented by dashed lines of increasing thickness.

Figure 8.

Average DPOAE level (dB SPL) as a function of L_2 (dB SPL) when $f_2 = 2$ kHz. Each panel plots the average DPOAE level as a function of L_2 for all ears with the same behavioral threshold, the inset in each panel indicate the number of ears contributing in the control condition. Test condition is indicated by line type and thickness. Data for the control condition are plotted as thick solid lines with increasing suppressor level indicated by dashed lines with increasing thickness.

Figure 9.

Average DPOAE level (dB SPL) as a function of L_2 (dB SPL) when $f_2 = 4$ kHz. The plotting convention is the same as for Fig. 8.

Figure 10.

Average standard deviation (dB) of DPOAE level across the entire I/O function as a function of test condition for each of 12 behavioral-threshold categories when $f_2 = 2\text{ kHz}$. These data represent the standard deviations associated with the I/O functions shown in Fig. 8.

Figure 11.

Average standard deviation (dB) of DPOAE level across the entire I/O function as a function of test condition for each of 12 behavioral-threshold categories when $f_2 = 4\text{ kHz}$. These data represent the standard deviations associated with the I/O functions shown in Fig. 9.

Table 1

Optimal suppressor levels for reducing DPOAE fine structure.

L_2 (dB SPL)	$f_2 = 2$ kHz C	$f_2 = 4$ kHz C
20	40	45
30	35	30
40	30	30
50	30	20
60	20	15
70	15	15
80	10	15

Table 2
Summary of the threshold prediction results for $f_2 = 2$ and 4 kHz. Number of ears meeting the inclusion criteria for two approaches to threshold prediction along with correlations and associated standard errors for the 4 test conditions.

Condition	$f_2 = 2$ kHz					
	No. of ears meeting inclusion criteria I/O Approach	SNR Approach	I/O Approach	Correlation SNR Approach	I/O Approach	Standard error (dB) SNR Approach
Control	117	205				
Cm10	117	205	0.81	0.82	10.60	10.52
C0	131	204	0.84	0.77	9.87	11.55
Cp10	75	204	0.74	0.75	12.09	11.96
			0.38	0.50	16.29	15.79

Condition	$f_2 = 4$ kHz					
	No. of ears meeting inclusion criteria I/O Approach	SNR Approach	I/O Approach	Correlation SNR Approach	I/O Approach	Standard error (dB) SNR Approach
Control	156	204				
Cm10	164	204	0.86	0.90	10.87	9.61
C0	147	205	0.88	0.86	10.30	11.39
Cp10	145	204	0.86	0.78	10.97	13.76
			0.80	0.76	12.81	14.31

Table 3

These data refer to the I/O-function approach to estimating DPOAE threshold. Shown here are the number of ears that did not meet the SNR and regression-based inclusion criteria, the percentage of these ears that have behavioral thresholds ≤ 30 dB HL, and the mean thresholds and standard deviations for these ears when $f_2 = 2$ and 4 kHz.

Condition	No. not meeting SNR criterion	% with thresholds ≤ 30 dB HL	$f_2 = 2$ kHz	
			Mean threshold	Standard deviation
Control	10	10	49.5	9.6
Cm10	10	30	47	13.8
C0	10	10	46	13.3
Cp10	56	46	31.6	17.8

Condition	No. not meeting Regression criteria	% with thresholds ≤ 30 dB HL	$f_2 = 2$ kHz	
			Mean threshold	Standard deviation
Control	78	88	13.8	14.5
Cm10	78	86	14.4	14.8
C0	64	88	14.5	16.3
Cp10	74	91	11.3	14.1

Condition	No. not meeting SNR criterion	% with thresholds ≤ 30 dB HL	$f_2 = 4$ kHz	
			Mean threshold	Standard deviation
Control	4	25	52.5	15
Cm10	5	40	39	27.5
C0	10	20	46	20.8
Cp10	9	11	47.8	10.9

Condition	No. not meeting Regression criteria	% with thresholds ≤ 30 dB HL	$f_2 = 4$ kHz	
			Mean threshold	Standard deviation
Control	45	53	26.3	23.7
Cm10	36	42	33.6	21.8
C0	48	58	25.4	22.1
Cp10	51	61	24.3	22.9