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Influence of Calibration Method on DPOAE Measurements: II. Threshold Prediction

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Abstract

Objective—Distortion-product otoacoustic emission (DPOAE) stimulus calibrations are typically performed in sound pressure level (SPL) prior to DPOAE measurements. These calibrations may yield unpredictable DPOAE response levels, presumably due to the presence of standing waves in the ear canal. Forward pressure level (FPL) has been proposed as an alternative method for stimulus calibration because it avoids complications due to standing waves. DPOAE thresholds following four FPL calibrations and one SPL calibration were compared to behavioral thresholds to determine which calibration results in data that yield the highest correlations between the two threshold estimates.

Design—Fifty-two subjects with normal hearing and 103 subjects with hearing loss participated, with ages ranging from 11 to 75 years. These were the same individuals whose data were used to address the influence of calibration method on test performance in an accompanying paper (Burke et al., 2010). DPOAE input/output (I/O) functions were obtained at f_2 frequencies of 2, 3, 4, 6, and 8 kHz with the primary frequency ratio fixed at $f_2/f_1 \approx 1.22$. L_1 was set according to the equation $L_1 = 0.4L_2 + 39$ (Kummer et al. 1998, 2000) with L_2 levels ranging from –20 to 70 dB SPL and FPL in 5-dB steps. I/O functions were obtained at each frequency for each of five stimulus calibrations: SPL, daily FPL at room temperature, daily FPL at body temperature, reference FPL at room temperature, and reference FPL at body temperature. DPOAE thresholds were estimated using two methods. In the first, DPOAE threshold was taken as the lowest L_2 for which DPOAE level is 3 dB or greater above the noise floor ($SNR \geq 3$ dB). In a second method, a linear regression method first described by Boege & Janssen (2002) and later adapted by Gorga et al. (2003), all DPOAE levels in each I/O function are converted to linear pressure and extrapolated to 0 μ Pa, where the L_2 is taken as threshold. Correlations of DPOAE thresholds with behavioral thresholds were obtained for each frequency, calibration method, and threshold-prediction method.

Results—Correlations were greatest for frequencies of 3–6 kHz and lowest for 8 kHz, consistent with the previous frequency effects reported by Gorga et al. (2003). Calibration method made little difference in correlations between DPOAE and behavioral thresholds at any frequency. A small difference was noted in correlations for the two threshold-prediction methods, with the linear regression method yielding slightly higher correlations at all frequencies.

Conclusions—Little difference in threshold correlations was observed among the five calibration methods used to calibrate the stimuli prior to DPOAE measurements. These results were not anticipated given the known effects of standing waves on ear-canal estimates of SPL at the plane of

the probe (Siegel, 1994; Siegel and Hirohata, 1994; Siegel, 2007; Driesbach and Siegel, 2001; Neely and Gorga, 1998; Scheperle et al., 2008). In addition, there was no effect of temperature (body vs. room) or timing (daily vs. reference) for FPL calibrations. It may be important to note that differences between SPL and FPL calibrations should not be seen if a standing wave does not occur at the plane of the probe at or near the frequency being tested. The frequencies 2–8 kHz were chosen because it was expected that effects from standing waves would occur between these frequencies due to the typical lengths of ear canals for the age group tested. Because measurements were taken at only five discrete frequencies in the interval, it is possible that standing waves were present but did not affect the specific test frequencies. In total, these results suggest that SPL calibrations may be adequate when attempting to predict pure-tone thresholds from DPOAEs, despite the fact that they are known to be susceptible to errors associated with standing waves.

I. Introduction

The measurement of distortion product otoacoustic emissions (DPOAEs) relies upon specific stimulus conditions, one of which is the absolute and relative levels of the two primary frequencies that elicit the response. One factor that can influence stimulus level is the variance in individual ear-canal acoustics. To ensure that intended stimulus levels are presented to the ear, *in situ* calibrations typically are performed in sound pressure level (SPL) prior to measurements. SPL is estimated at the plane of the probe, and it is assumed that this value represents the level at the plane of the tympanic membrane. SPL calibrations, however, are susceptible to influence from standing waves at specific frequencies depending on the dimensions of the ear canal (e.g., Siegel, 1994, 2007; Siegel and Hirohata, 1994). This situation can result in over- or underestimation of stimulus level at the eardrum, and thus a disparity between actual and intended stimulus levels. That is, the level measured at the plane of the probe would not accurately reflect the input level to the middle ear. Recently, Scheperle et al. (2008) showed that stimuli calibrated in forward pressure level (FPL) provide more consistent DPOAE measurements than stimuli calibrated in SPL when probe-insertion depth was varied. Their results were obtained on a group of normal-hearing subjects. The observation that calibration method can affect DPOAE level because of errors in stimulus-level calibrations suggests that these errors might also influence the clinical accuracy of DPOAE measurements. The purpose of the present study is to extend the work of Scheperle et al. by comparing SPL and FPL calibrations using correlations between predicted DPOAE thresholds and pure-tone behavioral thresholds for a group of normal-hearing and hearing-impaired subjects. In a companion paper, Burke et al. (2010) tested the extent to which calibration method impacts test performance, defined as the ability of DPOAEs to accurately classify ears as either normal-hearing or hearing-impaired.

Correlations between DPOAEs and audiometric thresholds have been reported previously (Martin et al, 1990; Gorga et al., 1997; Gorga et al, 1993). These correlations were limited to hearing losses no greater than 50 to 60 dB HL (Gorga et al, 1997), which was expected, given the relationship between outer hair cell damage (the presumed generators of OAEs) and sensitivity loss. Like estimates of test performance (Gorga et al., 1993, 1997 Gorga et al., 2000), correlations between DPOAE data and audiometric thresholds are highest for mid-to-high frequencies (Gorga et al., 2003). In some cases, DPOAE levels for fixed-level stimuli were correlated with behavioral thresholds, whereas in other cases, DPOAE threshold (defined as the stimulus level producing a DPOAE some criterion number of dB above the noise), was correlated with audiometric threshold (e.g., Martin et al., 1990; Gorga et al., 1997). As an alternative to these measurements, Boege and Janssen (2002) developed a method in which DPOAE levels obtained from an input/output (I/O) function were converted to pressure and fit with a linear equation. The L_2 (the level of the higher frequency in the primary-frequency pair) at which DPOAE pressure equals 0 μ Pa was defined as threshold in this linear regression method. Boege and Janssen (2002) demonstrated that, following the application of certain

inclusion criteria, their method provided DPOAE threshold estimates that correlated with behavioral thresholds. Using fits to the DPOAE I/O function to provide an estimate of DPOAE threshold has since been replicated and extended by Gorga et al. (2003) and Johnson et al. (2007). While both threshold estimation methods revealed correlations between DPOAE thresholds and behavioral thresholds, variability and prediction errors were evident. Notably, both approaches used *in situ* SPL calibrations at the plane of the probe to set the stimulus level during DPOAE measurements.

The impact of standing waves on the calibration of stimulus level could potentially affect behavioral-threshold estimations based on DPOAEs. The presence of incident and reflected waves in the ear canal creates pressure nulls at specific locations determined by an interaction between stimulus frequency and the dimensions of the canal. The level of sound in the ear canal will be underestimated when incident and reflected waves are out of phase at the point of measurement (the plane of the probe), resulting in a higher stimulus level than intended. This overcorrection could affect threshold prediction in that threshold could be (1) underestimated when incident and reflected waves are out of phase or (2) to a lesser extent, overestimated when incident and reflected waves are in phase at the probe. The influence of standing waves on DPOAE threshold estimates based on fits to the I/O function may be less, although this is unknown at the present time. Standing waves typically are not a problem for frequencies below approximately 2 kHz because these lower frequencies have wavelengths that are large relative to the length of the typical ear canal. However, information about auditory function above 2 kHz may be affected by standing waves, given the shorter wavelengths. This may be of particular clinical concern, especially for hearing loss caused by noise exposure and ototoxicity, where higher frequencies are first affected by the cochlear insult.

As alternatives to SPL, calibrations obtained in both sound intensity level (SIL) and forward pressure level (FPL) avoid the problem of standing waves (e.g., Neely and Gorga, 1998; Scheperle et al., 2008). SIL calibrations do not contain the reactive components of impedance, which are the cause of standing waves, and FPL calibrations quantify the forward pressure component of a sound wave only. Scheperle et al. noted effects of stimulus frequency and level on DPOAE level when comparing SPL, SIL, and FPL calibrations, with SPL demonstrating the greatest variability. However, it has been observed that stimuli calibrated in SIL may become uncomfortably loud, especially at high frequencies (Scheperle et al., 2008). It is mainly for this reason that FPL calibration was used in the present study. An additional advantage of FPL over SIL is that it is more easily comparable to SPL, as it shares the same reference. The measurement of an incident pressure wave independent of its reflected component requires information about the source and load characteristics of the transmission line. This requires measurements obtained in known acoustic loads in order to calculate the Thévenin-equivalent characteristics of the source. The source characteristics are then used to determine the ear-canal load impedance during *in-situ* calibration. Estimates of source characteristics, however, may be sensitive to temperature and (somewhat surprisingly) variable from day to day (Scheperle et al., 2008). It remains to be determined whether these measurements need to be performed daily or if an average or some other ideal calibration from a set of measurements is preferable in order to obtain the most reliable estimates of level, and, therefore, the most accurate estimates of cochlear function from DPOAE measurements.

The current study examines the effects of calibration method on estimates of DPOAE thresholds, defined either as the lowest L_2 at which the SNR is ≥ 3 dB or by the linear regression method first described by Boege and Janssen (2002). The outcome measure in this study was the accuracy with which DPOAE thresholds, estimated from both techniques, predicted behavioral thresholds in subjects with normal hearing and subjects with hearing loss. Four different FPL calibration conditions were used to examine the effects of temperature (body vs. room) and the timing of the calibration (daily vs. a reference taken from repeated measurements

prior to all data collection). For comparison purposes, data were collected using an SPL calibration as well. DPOAE I/O functions were measured at 2, 3, 4, 6, and 8 kHz using each of the five calibration procedures. Effects of stimulus frequency, calibration method, and method of threshold estimation were examined in order to determine which calibration method and which DPOAE threshold estimate results in the highest correlation with behavioral threshold. If one calibration method is shown to be superior, it would be reasonable to implement it in clinical applications of DPOAE measurements. If there is no difference in correlations, then the simpler SPL calibration that is in current use may be preferred.

II. METHODS

A. Subjects

Fifty-two subjects with normal hearing and 103 subjects with hearing loss participated in this study, with ages ranging from 11 to 75 years. These subjects were the same individuals whose data were used to address the influence of calibration method on test performance in an accompanying paper (Burke et al., 2010). Table I shows the number of ears at each frequency for each behavioral threshold, expressed in dB HL. Note that the largest cell is the one that includes thresholds exceeding 65 dB HL. Because we were interested in evaluating the relation between behavioral and DPOAE thresholds for a wide range of hearing losses, no restrictions were made regarding degree and configuration of hearing loss during subject recruitment. However, extra effort was made to include subjects whose behavioral thresholds ranged from 0 to 65 dB HL. Our interest in focusing on this range relates to the need to have measurable DPOAEs from which predictions of behavioral thresholds can be made. Individuals with hearing losses outside this range were included, but they represented a minority of the subjects. Ideally, analyses would be simplified if the number of observations were equal in all cells in Table I. Given the source of subjects for this study, it was not possible to achieve this goal. However, every cell between 0 and 60 dB HL had at least 4 subjects at all frequencies, which should be sufficient for the correlation analyses that will be described subsequently. Notably, only 5 of 70 cells between 0 and 65 dB HL had only 4 subjects, and all of these occurred at 8 kHz. All other cells include data from a larger number of subjects.

For the purposes of global characterizations, an individual was considered to have normal hearing if thresholds at all five test frequencies (in addition to other typical audiometric frequencies) were ≤ 20 dB HL. Hearing impairment for any subject was defined as behavioral thresholds exceeding 20 dB HL at any octave or inter-octave frequency from 2 to 8 kHz. For the purpose of data analysis, thresholds were considered at each individual frequency for each subject. Hearing losses were generally determined to be of cochlear origin based upon clinical history and other common clinical tests. However, the specific etiology of hearing loss was not considered during subject recruitment.

B. Equipment

Data collection, source calibrations, calculations of Thévenin-equivalents, and FPL conversions were performed using custom-designed software (EMAV version 3.1; Neely & Liu, 1994). DPOAE stimuli were produced and responses were recorded using a 24-bit soundcard (CardDeluxe, Digital Audio Labs) housed in a PC. The two primary tones (f_1 and f_2) were produced by separate channels of the soundcard and sent to two loudspeakers in a probe-microphone system (Etymotic Research, ER-10C), which was coupled to the ear using a foam tip. Pure-tone air- and bone-conduction behavioral thresholds were measured using a Grason-Stadler GSI-61 audiometer with EAR-Tone ER-3A earphones.

C. Stimuli

DPOAE I/O functions were obtained at 2, 3, 4, 6, and 8 kHz. These frequencies were chosen because they are clinical test frequencies whose levels may be affected by standing waves in the ear canal. The $2f_1$ - f_2 DPOAE was measured, with the primary-frequency ratio (f_2/f_1) $\approx$ 1.22. These stimulus-frequency parameters are in common clinical use and similar to those used in previous efforts to predict behavioral thresholds from DPOAEs (Martin et al., 1990; Gorga et al., 2003; Boege & Janssen, 2002). The L_2 starting level was set to 70 dB SPL or FPL, and decreased in 5-dB steps. L_1 was set according to the equation $L_1 = 0.4L_2 + 39$, a commonly used primary-level paradigm described by Kummer et al. (1998, 2000). This relationship between primary levels was also used in the two studies that correlated behavioral thresholds from DPOAE thresholds that were predicted from fits to the DPOAE I/O function (Boege & Janssen, 2002; Gorga et al., 2003). There is evidence that other relationships between L_1 and L_2 might result in larger DPOAEs, at least among subjects with normal hearing (Neely et al., 2005; Johnson et al., 2007). However, the present study was designed to determine the influence of calibration procedure on threshold predictions from DPOAE data, not the algorithm used to select stimulus levels. Given this goal, it seemed appropriate to select stimulus levels the same way they were selected in previous studies in which threshold predictions were made.

D. Calibration methods

Calibration procedures for this study have been described in detail previously (Burke et al., 2010), and will only be briefly summarized here. FPL calibration procedures were performed using a set of five brass cavities with known load impedances to determine the Thévenin-equivalent characteristics of the stimulus source. The foam ear tip of the ER-10C probe-microphone system was coupled to each cavity, and a wide-band chirp stimulus (sampling rate of 32 kHz) was presented. The pressure response of each loudspeaker was measured with the probe microphone, and the software used this measurement along with the known load impedance to estimate the source impedance and pressure. A comparison between the estimated source pressure and measured pressure were expressed as an error value. An *in situ* calibration was performed prior to the measurement of each I/O function in order to measure the pressure response in the ear, and the source impedance and pressure were used along with load pressure to determine the ear-canal load impedance. A transform was then derived to convert SPL to FPL for each of four calibration conditions.

FPL calibration conditions included (1) a daily calibration at room temperature, (2) a daily calibration at body temperature, (3) a reference calibration at room temperature, and (4) a reference calibration at body temperature. For comparison purposes, SPL calibration, which is the approach to calibration that is currently in widespread use, was obtained *in situ* prior to DPOAE measurement. Body-temperature calibrations were obtained by heating the cavity set with a heating pad and measuring the temperature inside each cavity with a digital thermometer. Temperatures varied from 96–102 degrees. Calibrations were performed at both room and body temperatures in view of the results described by Scheperle et al. (2008), which showed effects of temperature on FPL calibrations. In the present study, another goal (in addition to the one in which the effects of calibration method were assessed) was to determine whether these temperature effects were significant in the relationship between behavioral and DPOAE thresholds.

Reference calibrations at both room and body temperatures were obtained prior to the initiation of any data collection. Twenty-five calibrations were obtained for both temperatures, and the calibrations with the smallest errors associated with source estimates were taken as the reference calibrations for each temperature. For each day of data collection, a daily calibration was also obtained for both temperatures. As in Scheperle et al. (2008), calibrations were

variable in terms of the error values obtained. It appears that the variability in error values may be due to differences in the insertion or compression of the foam tip in the coupler (Burke et al., 2010).

E. Procedures

A routine hearing evaluation was completed to provide pure-tone thresholds and to determine whether subjects met inclusion criteria. Just prior to DPOAE measurement, an otoscopic examination was performed, and a 226-Hz tympanogram was obtained to evaluate middle-ear status. Pure-tone thresholds were measured at octave frequencies of 0.25–8 kHz and inter-octave frequencies of 3 and 6 kHz using clinical procedures (ASHA, 2005). DPOAE I/O functions (DPOAE level as a function of L_2) were measured at f_2 frequencies of 2, 3, 4, 6, and 8 kHz for each of the four FPL calibration conditions as well as for the SPL calibration, for a total of 25 I/O functions per subject. The orders of the conditions were counterbalanced across subjects. In order to increase data-collection efficiency, I/O function measurements started with an $L_2 = 70$ dB SPL or FPL, decreased in level in 5-dB steps, and were terminated manually once the DPOAE level was less than 3 dB greater than the noise (i.e., an $SNR < 3$ dB) floor for each individual subject.

Measurements for each test condition were terminated automatically when one of the following measurement-based stopping rules was met: the noise floor was ≤ -25 dB SPL or FPL, 32 seconds of artifact-free averaging time had elapsed, or the signal-to-noise ratio (SNR) was > 60 dB. These rules were selected so that measurement would ideally end when the noise-floor criterion was met and would never stop on the SNR criterion. In order to obtain reliable estimates of DPOAE thresholds, it was important to ensure that the noise floor was reduced as much as possible so that DPOAE responses were measured at low levels and over a wide dynamic range. The noise-floor criterion was selected in relation to a conservative estimate of the level at which system distortion occurs. If averaging were continued with a noise floor at or below -25 dB SPL (FPL), it would be unknown whether responses measured were biological in nature. For several subjects, however, the noise-floor criterion could not be met before 32 seconds of artifact-free averaging had elapsed. For these subjects, the DPOAE and noise levels were taken as the average across the 32 seconds, which may have resulted in higher threshold estimates. However, care was taken to ensure that noise levels were kept relatively low (i.e., data collection was paused or restarted) even if they did not meet the -25 dB SPL (FPL) criterion. A longer averaging time was not used because of the need to collect data on a large sample of normal-hearing and hearing-impaired subjects for this study. The calculation of noise levels in the EMAN software was the same for both parts I and II of this study and is described in detail in Burke et al. (2010). Briefly, data was stored in 11 frequency bins, one at $2f_1$ – f_2 and five bins on each side of $2f_1$ – f_2 , in two-second alternating sub-averages. The contents of the sub-averages were summed to estimate signal level and the level in the $2f_1$ – f_2 frequency bin and subtracted to estimate the noise level in all 11 bins.

F. Threshold prediction

Two methods were used estimate DPOAE thresholds. Figure 1 illustrates these methods as well as the estimated DPOAE thresholds for each calibration method at 4 kHz for a single normal-hearing subject, whose audiometric threshold was 5 dB HL at this frequency. In the simplest method, which is shown in the upper panel, threshold was estimated at the lowest L_2 for which DPOAE level was ≥ 3 dB above the noise floor (i.e., $SNR \geq 3$ dB). This threshold definition depends upon the level of the noise floor, which is why the primary measurement-stopping rule was a noise level of ≤ -25 dB SPL (FPL). In those conditions in which measurement did not stop based on the noise level, it is likely that threshold was overestimated. However, as stated above, care was taken to ensure that noise levels were kept relatively low. Thresholds estimated in this fashion are provided as insets in the top panel of Figure 1 for each

of five calibration methods. Note that the DPOAE threshold for SPL in this case is 10 dB lower than for any of the FPL calibrations. A possible explanation for this finding would be that, during SPL calibration, a standing wave occurred, resulting in destructive interaction between incident and reflected waves. As a consequence, the level at the plane of the probe was less than the level at the eardrum, producing greater stimulus levels than specified, which resulted in larger DPOAEs than expected, leading to an underestimation of threshold.

The second method, shown in the lower panel of Fig. 1, followed procedures that were described by Boege & Janssen (2002) and later adapted by Gorga et al. (2003). For each DPOAE I/O function, DPOAE levels were converted to pressure and fit with a linear equation. Linear-regression analysis was performed to extrapolate DPOAE amplitude to 0 μPa . The L_2 at which this DPOAE pressure occurred was taken as DPOAE threshold, which subsequently was compared to the behavioral threshold. In order to fit the I/O function with a linear equation, several different criteria had to be met. At least three data points on the I/O function had to have SNRs of ≥ 6 dB. In addition, there were inclusion criteria associated with the linear regressions: (1) the slope of the individual linear regressions had to be $\geq 0.2 \mu\text{Pa/dB}$, (2) the variance accounted for (r^2) had to be ≥ 0.8 , and (3) the standard error had to be ≤ 10 dB. These criteria were similar to those specified by Boege & Janssen (2002), who demonstrated that their use tended to reduce the difference between DPOAE and behavioral thresholds. Estimated DPOAE thresholds from linear regressions were included in comparisons with behavioral thresholds only if they met the ≥ 6 dB SNR inclusion criteria and all three inclusion criteria associated with the linear regressions. Referring to Fig. 1, while the differences between SPL and FPL calibrations are less using the linear-regression method of threshold estimation as opposed to the simpler SNR-based method, it is still the case that the DPOAE threshold based on SPL calibration was lower than any of the thresholds based on FPL calibration. The standing-wave interpretation that was used to explain the SNR-based threshold discrepancies could explain these findings as well.

III. RESULTS

A. Individual examples of DPOAE I/O functions

For examples of individual I/O functions, see Figure 3 of Burke et al. (2010). These I/O functions are representative of the functions measured in other subjects and are consistent with expectations for both normal-hearing and hearing-impaired subjects.

B. Effects of calibration method

Figure 2 displays behavioral thresholds (dB HL) as a function of DPOAE thresholds (dB SPL and FPL) for each calibration method collapsed across frequency. In the left column, the SNR-based method is used to estimate DPOAE thresholds. In the right column, the linear-regression method is used to estimate DPOAE thresholds. The solid line in each panel represents the best-fit line to the data. Also shown as insets in the upper left corner of each panel are correlation coefficients, the number of threshold comparisons, and standard errors.

In an effort to improve the accuracy with which the data from DPOAE I/O functions predicted behavioral thresholds, all behavioral thresholds less than 0 dB HL were set to 0 dB HL and all estimated DPOAE thresholds less than 0 dB SPL (FPL) were set to 0 dB SPL (FPL). This truncation was based on the assumptions that (1) any DPOAE threshold below 0 dB would be particularly affected by the noise floor and (2) common clinical procedures may not warrant presentation levels less than 0 dB HL for the purpose of behavioral-threshold measurements, as maximum permissible noise levels in audiometric test rooms are based upon ambient noise masking at 0 dB HL (Frank et al., 1993). Another truncation occurred at the upper limits of behavioral and estimated DPOAE thresholds in that any threshold greater than 60 dB SPL

(FPL) was set to 60 dB SPL (FPL), which was based on the assumption that a complete loss of outer hair cells (the presumed generators of OAEs) would produce a hearing loss no greater than 60 dB in the absence of inner hair-cell damage. The differences between correlation coefficients for both threshold-prediction methods are less than 0.05 for each of the five calibration methods when data are collapsed across frequency. The largest correlation coefficient was for the daily body-temperature calibrations (0.82 and 0.84 for SNR-based and linear-regression methods, respectively) and the smallest correlation was observed for the reference room-temperature calibrations (0.78 and 0.80 for SNR-based and linear-regression methods, respectively). As before, these differences were minimal. In an upcoming section, we introduce Figure 5, which shows these data expanded across frequency.

C. Effects of threshold prediction method

Referring again to Fig. 2, the differences between correlation coefficients across calibration methods are less than 0.03 between the two threshold prediction methods, although the linear-regression method consistently yielded slightly higher correlations. This may have been partially due to the inclusion criteria for this method. Specifically, by eliminating cases in which less than three points on the I/O function had an $\text{SNR} \geq 6$ dB, we increase the chance that thresholds will not be predicted for subjects whose hearing thresholds exceed 60 dB HL.

Figure 3 displays the cumulative proportion of subjects as a function of behavioral threshold for each calibration method that failed to meet the inclusion criteria associated with the *linear-regression method of estimating DPOAE threshold*. Failed-SNR refers to the proportion of subjects who failed to meet the criterion stating that the I/O function must have three points at which SNR is ≥ 6 dB in order for the linear regression to be applied. Failed-LR refers to the proportion of subjects failing to meet the additional criteria associated with regression analysis: (1) the slope of the individual linear regressions had to be ≥ 0.2 $\mu\text{Pa}/\text{dB}$, (2) the variance accounted for (r^2) had to be ≥ 0.8 , and (3) the standard error had to be ≤ 10 dB. The upper cluster of functions represent the proportion of subjects failing to meet the criteria associated with the regression analysis, while the lower cluster of functions describe the proportions failing to meet the SNR criterion. Approximately 95 percent of the DPOAE I/O functions excluded based on the SNR criterion had behavioral thresholds greater than 30 dB HL. Thus, it is highly probable that a subject whose I/O function could not be used during the linear regression analysis because they did not produce responses with positive SNRs had hearing loss. Approximately 70 percent of the I/O functions that were excluded based on the criteria associated with the linear fit had behavioral thresholds of 40 dB HL or less. Thus, it is likely that subjects who failed the LR criteria have normal to near-normal hearing. This has implications regarding the extent to which the linear-regression method and its associated criteria were applicable. Since the SNR criterion was applied first, every subject failing to meet the criteria associated with the linear fits produced at least three responses with SNRs ≥ 6 dB. Amongst all five of the calibration methods, I/O functions obtained using SPL calibrations had the highest cumulative percentage of those failing both sets of inclusion criteria.

D. Effects of degree of hearing loss

For each calibration method, the difference between DPOAE and behavioral thresholds as a function of behavioral thresholds is shown in Fig. 4, collapsed across frequency. This figure is used to illustrate differences between calibration methods and DPOAE threshold-estimation methods in relation to degree of hearing loss. The open symbols represent the differences when DPOAE thresholds were estimated using the SNR-based method, and the closed symbols represent the differences when DPOAE thresholds were estimated using the linear-regression method.

E. Frequency effects

In Fig. 5, behavioral thresholds (dB HL) as a function of DPOAE thresholds (dB SPL and FPL) are shown for each frequency (shown separately in each row) and for each calibration method (shown separately in each column) when the linear-regression threshold-estimation method is used. Frequency effects for the SNR-based threshold-estimation method are essentially the same and thus not shown. Correlations were greatest at 3, 4, and 6 kHz and lowest at 8 kHz, with intermediate correlations at 2 kHz. More importantly, there does not appear to be an effect of calibration method at any frequency. There are conditions in which one of the FPL calibration methods resulted in the highest correlation, but there are also conditions in which the correlations between behavioral and DPOAE thresholds were highest following SPL calibration. In any case, the differences in correlations among calibration methods were small.

IV. DISCUSSION/CONCLUSIONS

The purpose of the present study was to determine the extent to which stimulus-level calibration method affects the prediction of behavioral thresholds from DPOAE thresholds. Although differences were observed among calibration procedures, the differences were always small and there were no consistent trends among calibration method relative to threshold predictions. Recall that the calibrations were taken at both room and body temperatures. A lack of difference among calibration methods indicates a lack of temperature effects. Results also indicate no effect of the time the calibration was taken (daily vs. a reference taken on a single day prior to any data collection). Effects of frequency were similar to those noted by Gorga et al. (2003). Regardless of the way stimulus levels were calibrated, correlations between DPOAE and behavioral thresholds were largest for frequencies between 3 and 6 kHz and lowest at 8 kHz. Correlations were slightly higher when DPOAE thresholds were estimated using the linear-regression technique, compared to the SNR-based technique, but again these differences were small and inconsistent.

Referring to Figure 4, the differences between the two threshold-estimation methods as a function of behavioral thresholds are small. However, almost without exception, there is better agreement between behavioral thresholds and those estimated using the linear-regression method, compared to the SNR-based method. Note that differences between DPOAE and behavioral thresholds are relatively constant for behavioral thresholds up to about 45 dB HL, with DPOAE threshold 5–15 dB higher than behavioral thresholds. At and above behavioral thresholds of 45 dB HL, there is a trend towards decreasing differences as behavioral threshold increases, with some differences below zero. This may be due to a smaller number of conditions where thresholds could be estimated from DPOAEs, the truncation of thresholds as described in relation to Fig. 2, or more accurate predictions of behavioral thresholds at these levels. Importantly, there is no apparent effect of calibration method. While it appears that DPOAE thresholds for both threshold estimation methods overestimate behavioral thresholds, the size of this effect appears to be independent of calibration procedure, further demonstrating that there was little or no effect of calibration method on the extent to which DPOAEs accurately predict behavioral threshold. In total, these results suggest that SPL calibrations may be adequate when attempting to predict pure-tone thresholds from DPOAEs, at least for the five frequencies studied in the present experiment.

These findings are in agreement with those reported by Burke et al. (2010) in a companion paper in which the effects of stimulus calibration on DPOAE test performance were assessed. Burke et al. found a calibration effect only at 8 kHz with essentially no differences in performance related to calibration method at other frequencies. The results from the present study and from Burke et al. were not anticipated, given the known effects of standing waves on estimates of ear-canal SPL at the plane of the probe (Siegel, 1994; Siegel and Hirohata, 1994; Siegel, 2007; Dreisbach and Siegel, 2001). The results are particularly surprising because

frequencies were studied at which standing-wave effects are expected to occur. However, it is important to note that differences between calibrations will only occur at or near frequencies where standing waves are present. In this study and in its current clinical form, the measurement of DPOAEs is performed at discrete frequency intervals. This approach samples frequency broadly, and it is possible that the dimensions of the ear canals of the present sample of subjects had few occurrences of standing waves at specific test frequencies, even though we evaluated DPOAE threshold estimations for octave and inter-octave frequencies in a range in which standing-wave problems are expected.

Although the results of this study do not suggest a need to change the current calibration methods for DPOAEs, it is possible that future changes in DPOAE test protocol (i.e., the inclusion of more test frequencies or swept frequencies) may warrant further investigation of calibration effects. Despite our inability to detect a calibration-method effect, it remains the case that SPL is susceptible to standing-wave problems and FPL is not. Furthermore, Scheperle et al. (2008) reported that FPL calibrations provide more consistent DPOAE measurements when probe insertion depth is varied, suggesting that FPL calibrations may yield less variable test results if the probe is removed and re-inserted during testing, a fairly common clinical scenario, or if DPOAEs are being monitored over time. Thus, the increase in calibration time required for FPL calibrations may still be warranted in order to provide a consistently reliable estimate of level in the ear canal.

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Figure 1.

An example of both DPOAE threshold-estimation methods for all five calibration methods based on data from one normal-hearing subject with a behavioral threshold of 5 dB HL at 4 kHz. In the top panel, DPOAE I/O functions are shown with DPOAE level (dB SPL & FPL) as a function of L_2 (dB SPL & FPL). Thresholds were defined as the lowest L_2 for which the $\text{SNR} \geq 3 \text{ dB}$. For the linear-regression method, demonstrated in the bottom panel, DPOAE I/O functions are shown following transformation of the data into pressure (μPa). Linear functions were fit to the data and solved for the L_2 's resulting in pressures of 0 μPa , which were defined as threshold.

Figure 2.

Behavioral thresholds (dB HL) as a function of DPOAE thresholds (dB SPL & FPL) for each calibration method collapsed across frequency. In the left column, the SNR-based method is used to estimate DPOAE thresholds. In the right column, the linear-regression method is used to estimate DPOAE thresholds. The solid line in each panel represents the best-fit line to the data. Also shown as insets in the upper left corner of each panel are correlation coefficients, the number of threshold comparisons, and standard errors. In an effort to improve the accuracy with which the data from DPOAE I/O functions predicted behavioral thresholds, all behavioral thresholds less than 0 dB HL were set to 0 dB HL and all estimated DPOAE thresholds less

than 0 dB SPL & FPL were set to 0 dB SPL & FPL. Additionally, any threshold greater than 60 dB was set to 60 dB as explained in the text.

Figure 3.

Cumulative proportions of subjects who failed the inclusion criteria for the linear regressions in the linear-regression threshold-estimation method as a function of behavioral threshold (in dB HL). DR=daily room, DB=daily body, RR=reference room, and RB=reference body. Failed-SNR refers to proportion of subjects who failed the SNR criterion, in which the I/O function must have at least 3 points with an SNR of 6 dB or greater. This criterion is applied first. Failed-LR refers to those subjects who then failed the LR criteria, which are used to determine how well a linear equation fits the transformed DPOAE I/O functions. These criteria included: (1) the slope of the individual linear regressions, which had to be $\geq 0.2 \mu\text{Pa/dB}$, (2) the variance accounted for (r^2), which needed to be ≥ 0.8 , and (3) the standard error, which had to be $\leq 10 \text{ dB}$). The SNR criterion associated with this figure should not be confused with the SNR-based threshold prediction method described throughout this paper. This figure applies to the linear-regression method of threshold estimation only.

Figure 4.

For each calibration method the difference between DPOAE and behavioral thresholds as a function of behavioral thresholds is collapsed across frequency. Open symbols represent the differences when the SNR-based method was used to estimate DPOAE thresholds, while closed symbols represent the case when DPOAE thresholds were estimated by the linear-regression method.

Figure 5. Behavioral thresholds (dB HL) as a function of DPOAE thresholds (dB SPL & FPL) at each frequency (shown separately in each row) and for each calibration method (shown separately in each column) when the linear-regression threshold-estimation method is used. Insets in each panel provide correlations, number of subjects, and standard errors.

Table 1

Number of ears at each test frequency per threshold.

Threshold (dB HL)	Frequency (Hz)					
	2000	3000	4000	6000	8000	
-10	1	1	0	0	0	0
-5	3	4	2	6	6	6
0	10	14	17	9	14	14
5	15	14	17	19	20	20
10	22	15	12	12	10	10
15	17	10	6	9	13	13
20	11	11	9	5	5	5
25	8	11	6	5	4	4
30	8	8	7	6	4	4
35	7	5	9	7	4	4
40	5	5	6	7	4	4
45	7	11	5	7	4	4
50	7	5	10	5	5	5
55	7	10	10	9	6	6
60	6	5	8	10	8	8
65	5	6	10	7	9	9
>65	16	20	21	32	39	39