Influence of *in situ*, sound-level calibration on distortion-product otoacoustic emission variability

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(Received 25 January 2008; revised 19 April 2008; accepted 22 April 2008)

Standing waves can cause errors during in-the-ear calibration of sound pressure level (SPL), affecting both stimulus magnitude and distortion-product otoacoustic emission (DPOAE) level. Sound intensity level (SIL) and forward pressure level (FPL) are two measurements theoretically unaffected by standing waves. SPL, SIL, and FPL *in situ* calibrations were compared by determining sensitivity of DPOAE level to probe-insertion depth (deep and "shallow") for a range of stimulus frequencies (1–8 kHz) and levels (20–60 dB). Probe-insertion depth was manipulated with the intent to shift the frequencies with standing-wave minima at the emission probe, introducing variability during SPL calibration. The absolute difference in DPOAE level between insertions was evaluated after correcting for an incidental change caused by the effect of ear-canal impedance on the emission traveling from the cochlea. A three-way analysis of variance found significant main effects for stimulus level, stimulus frequency, and calibration method, as well as significant interactions involving calibration method. All calibration methods exhibited changes in DPOAE level due to the insertion depth, especially above 4 kHz. However, SPL demonstrated the greatest changes across all stimulus levels for frequencies above 2 kHz, suggesting that SIL and FPL provide more consistent measurements of DPOAEs for frequencies susceptible to standing-wave calibration errors. [DOI: 10.1121/1.2931953]

PACS number(s): 43.58.Vb, 43.25.Gf, 43.64.Jb [BLM] Pages: 288–300

I. INTRODUCTION

Concern exists regarding measurement variability of distortion-product otoacoustic emissions (DPOAEs). Many of the sources of variability are extrinsic and potentially correctable (Mills *et al.*, 2007). One example is the method for calibrating stimulus level. Current DPOAE systems use the emission probe to calibrate sound pressure in the ear canal. *In situ* calibration is performed in an effort to equalize stimulus level across frequencies and subjects by compensating for individual differences in ear-canal acoustics. However, standing waves in the ear canal cause a partial cancellation of sound pressure near the emission probe around quarter-wave frequencies (e.g., Stinson, 1985; Gilman and Dirks, 1986; Dirks and Kincaid, 1987; Chan and Geisler, 1990; Siegel, 1994), resulting in inaccurate stimulus-level estimates, especially for frequencies above 2 kHz. These errors have the potential to impact both stimulus magnitude and DPOAE levels by as much as 20 dB in individual subjects (Siegel, 1994; Siegel and Hirohata, 1994; Dreisbach and Siegel, 2001). Proposed solutions are limited in terms of practicality of implementation and accuracy of estimate (Dirks and Kincaid, 1987; Siegel, 1994; Siegel and Hirohata, 1994; Whitehead *et al.*, 1995; Dreisbach and Siegel, 2001) and, consequently, none are being routinely used in the clinic.

The purpose of this study was to determine whether alternative measures of stimulus level in the ear canal provide practical solutions to calibration problems associated with standing waves and, as a consequence, decrease DPOAE variability. Sound intensity level (SIL) is one measure unaffected by standing waves and, thus, intensity measured at the emission probe is expected to be a good estimate of intensity at the eardrum at all frequencies (Neely and Gorga, 1998). In fact, Neely and Gorga demonstrated that behavioral thresholds were more consistent following *in situ* calibration using SIL compared to SPL, indicating that SIL was a more reliable measure of ear-canal stimulus level. SIL calibration, however, has not been extended to DPOAE measurements. A second alternative method for measuring level in the ear canal is forward pressure level (FPL). Ear-canal pressure can be separated into incident and reflected components (e.g., Farmer-Fedor and Rabbitt, 2002). Isolation of the incident pressure wave (i.e., FPL) eliminates the problem of standing waves and offers a theoretically stable *in situ* calibration that is equal to SPL when standing waves are not present.

Estimating the SIL or FPL of a stimulus with a microphone that directly measures only SPL is possible after performing a calibration procedure that estimates ear-canal load impedance. This calibration procedure requires known acoustic loads (i.e., a set of acoustic cavities) to determine the Thevenin-equivalent characteristics (impedance and pressure) of the sound source (Møeller, 1960; Rabinowitz, 1981; Allen, 1986; Keefe *et al.*, 1992). The specific procedure used in this study was based on the approach described by Neely and Gorga (1998).

In the present study, SPL, SIL, and FPL calibration methods were compared by focusing on the influence of calibration variability (errors) on measured DPOAEs using a within-subject design modeled after Neely and Gorga (1998). Repeated measurements of DPOAE levels were made for two ear-canal probe-insertion depths (deep and "shallow")

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 0001-4966/2008/124(1)/288/13/$23.00

for each subject, which changed the frequencies with standing-wave minima at the emission probe and, thus, intentionally introduced variability into the SPL calibration. Because middle ear and cochlear status is assumed to remain constant within a test session, changes in DPOAE level with changes in probe placement were taken as an indication of errors in the stimulus calibration.

Another concern with any *in situ* calibration is the consistency of observed errors. While all errors are undesirable, consistent errors are preferred to inconsistent errors because they can be predicted. Therefore, the effect of frequency and stimulus level was also of interest to further assess and compare calibration procedures. It is assumed that frequencies with standing-wave minima at the emission probe are most susceptible to calibration errors and, as a consequence, changes in DPOAE level following calibration methods affected by standing waves (i.e., SPL) are expected to be frequency dependent. There is evidence that the effect of calibration errors on DPOAE level is also dependent on stimulus level (Whitehead *et al.*, 1995; Dreisbach and Siegel, 2001). Errors in calibration are more likely to influence measured DPOAE levels on the steeply rising portion of the DPOAE input/output (I/O) function (where DPOAE level is dependent on stimulus level) and less likely to affect DPOAE levels on the asymptotic or saturating part of the I/O function (where DPOAE level is less dependent on stimulus level) (e.g., Lonsbury-Martin *et al.*, 1990; Nelson and Kimberley, 1992; Popelka *et al.*, 1993; Gorga *et al.*, 1994, 2000; Dorn *et al.*, 2001; Neely *et al.*, 2003). Therefore, changes in DPOAE level caused by calibration errors are expected to be larger at low stimulus levels.

The results of this study describe the influence of calibration procedure on the outcome measure of interest (change in DPOAE level). Depending on the outcome, the results may help determine whether SIL and/or FPL is preferable to SPL for *in situ* calibration both in experimental work and in the clinic.

II. METHODS

An ER-10C probe microphone (Etymōtic Research) was used to deliver stimuli generated with a 24 bit sound card (CardDeluxe, Digital Audio Labs) and to record responses. A locally developed software (EMAV Version 2.88; Neely and Liu, 1994) was used to perform (1) probe-source calibrations, (2) calculations of Thevenin equivalents, (3) SIL and FPL conversions, and (4) DPOAE measurements.

A. Calibration

The first step in estimating the Thevenin-equivalent source characteristics of the probe is to measure wideband pressure responses in known acoustic loads. For tubes of known lengths, an ideal expression for cavity impedance is

$$Z_c = -iZ_0 \cot(kL), \tag{1}$$

where Z_0 is the acoustic impedance of a plane wave propagating in the tube, L is the cavity length, and k is the wave number (Keefe *et al.*, 1992). The cavity set used for this study consisted of five brass tubes (11/32 in. o.d., 8 mm i.d.)

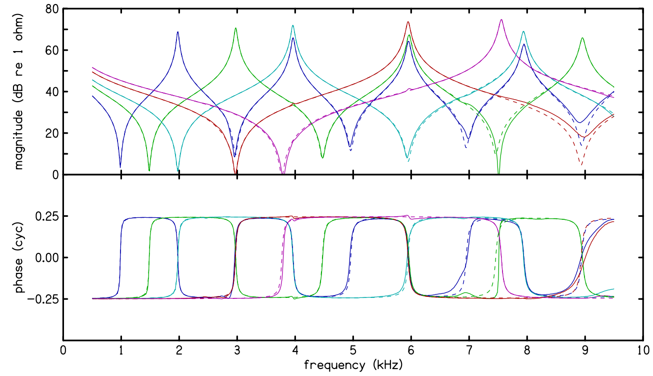

FIG. 1. (Color online) Ideal and empirical impedance of a calibration cavity set with error values of <1.0. The top panel displays the magnitude and the bottom panel displays phase, both as a function of frequency. Each tube (with lengths L_1–L_5) is represented by a pair of lines. Dotted lines represent ideal values based on equations from Keefe (1984) and solid lines represent the empirical values for one sound-source channel. The lines are nearly superimposed, indicating close agreement between ideal and empirical values. Tube length can be identified by the corresponding resonant frequency (e.g., the solid and dotted lines with the first maximum at ~2 kHz correspond with the longest tube in the set). The phase of the bottom panel does not exceed $\frac{1}{4}$ cycle in either the positive or negative direction, signifying that the real part of the impedance value is positive, which is a physical requirement for a passive system.

that were 83, 54.3, 40, 25.6, and 18.5 mm in length. Tube lengths were selected so that, with the coupler and probe in place, resonant peaks would occur at approximately 2, 3, 4, 6, and 8 kHz. A wideband chirp stimulus with a sampling rate of 32 kHz was presented to each tube of the cavity set, and the pressure response was measured with the probe microphone. Total averaging time was approximately 4 s per source channel per cavity, resulting in a total of 160 averaged chirps. Ideal cavity impedance (Z_c) and measured cavity pressure (P_c) are related to source pressure (P_s) and source impedance (Z_s) by the following equation:

$$\frac{P_s}{Z_s + Z_c} = \frac{P_c}{Z_c}. \tag{2}$$

An improved set of cavity lengths and corresponding Thevenin-equivalent source characteristics (P_s and Z_s) was obtained by iterative solution of a set of five linear equations that minimized deviation between measured and expected pressure responses based on Eq. (2) (Allen, 1986). Cavity calibration to determine P_s and Z_s was performed daily. Figure 1 shows the agreement typically observed between empirical and ideal cavity impedances. The separation between empirical and ideal data sets (error) increases with frequency and is the greatest at the pressure nulls, where the measured pressure is higher than what would have been ideal. These trends are consistent with the effects of cross-talk described by Siegel (1995) for the ER-10C probe; however, the implications on the calculation of P_s and Z_s are small. The error calculation weights the peaks and, consequently, estimated Thevenin-equivalent characteristics should have little dependence on whether the nulls are inaccurate.

Prior to initiating DPOAE measurements, a preliminary investigation demonstrated that air temperature within the calibration cavities significantly affects the estimated source characteristics (see Appendix A). In light of this result and the absence of a procedure to adjust for temperature, the cavities were warmed to approximate body temperature (95–105 °F) during each daily probe calibration.

In situ calibration was performed on each subject with the same DPOAE probe and chirp stimulus that was used for the source calibration. Load pressure (P_ℓ) was measured by the probe microphone and ear-canal load impedance (Z_ℓ) was calculated,

$$Z_\ell = \frac{Z_s P_\ell}{P_s - P_\ell}. \tag{3}$$

Load impedance provides the information necessary to convert load pressure, which is measured as SPL, into the corresponding SIL and FPL.

B. SIL and FPL conversion

When Z_ℓ is known, sound intensity (I_ℓ) is determined by

$$\mathcal{I}_\ell = \tfrac{1}{2}|P_\ell|^2 \cdot G_\ell, \tag{4}$$

where $G_\ell = \Re(1/Z_\ell)$ is the load conductance, which is defined as the real part ($\Re$) of the load admittance. SIL does not include the reactive/imaginary components of impedance, which store (but do not consume) energy. Consequently, SIL is unaffected by reflected waves.

Forward pressure (P_+) is determined by

$$P_+ = \frac{1}{2} P_\ell \left(1 + \frac{Z_0}{Z_\ell}\right), \tag{5}$$

where Z_0 is the characteristic impedance of the calibration cavities. FPL calibration is based on the forward-traveling component of the sound wave, thereby avoiding interactions with reflected waves and eliminating the potential for standing-wave calibration errors. A derivation of FPL is provided in Appendix B.

C. Subjects

Data collection was completed on 21 subjects, ranging in age from 14 to 49 years. Inclusion criteria included (1) normal audiometric thresholds (≤15 dB HL re: ANSI, 1996, for octave and interoctave audiometric frequencies from 0.25 to 8 kHz) and (2) normal 226 Hz immittance test results (peak compensated, static acoustic admittance of 0.3–1.8 mmho and tympanometric peak pressure (TPP) of −50 to 25 daPa) just prior to DPOAE measurements. In addition, otoscopic examinations revealed no contraindications to making DPOAE measurements (i.e., excessive cerumen or scarring of the eardrum). If both ears met the inclusion criteria, then the ear with better behavioral thresholds, TPP closest to 0 daPa, and/or easiest probe insertion was chosen. If there were no differences between ears, then the test ear was chosen randomly. Subjects were seated in a comfortable reclining chair situated in a sound-attenuating booth during data collection, which lasted approximately 2–3 h. Subjects were paid an hourly rate for participation.

D. Procedures

Measurements were obtained with the probe at two different insertion depths in the selected ear canal. For the first probe position, effort was made to insert the probe as deeply as possible so that calibration of the wideband chirp stimulus would show an ear-canal pressure spectrum with a "notch" at the highest possible frequency (i.e., between 4 and 8 kHz), indicating a standing-wave minimum. After measurements were obtained for all three calibration methods (SPL, SIL, and FPL) with the probe placed deeply, the probe was removed, the ear tip was replaced, the probe was reinserted approximately 2–3 mm less deep than the first insertion (i.e., shallow), and the measurements were repeated. While the deep insertion was always performed first, the order of calibration methods was counterbalanced. Adhesive tape secured the probe to prevent movement during measurements. Subjects were not excluded based on the absence of a notch or lack of downward shift in the notch frequency during the shallow insertion.

DPOAEs were elicited by pairs of primary tones (f_1 and f_2) with a fixed frequency ratio ($f_2/f_1 = 1.22$) and with levels set according to $L_1 = 0.4L_2 + 39$ (Kummer *et al.*, 1998). For each probe-insertion depth and for each calibration method, DPOAE levels were elicited across $f_2 = 1–8$ kHz (four points per octave) at $L_2 = 20$, 30, 40, 50, and 60 dB. *In situ* calibrations were repeated prior to each L_2.

Ear-canal wave forms were placed in alternate buffers during DPOAE measurements. After performing Fourier transforms on each buffer, DPOAE level was determined at $2f_1 - f_2$ by summing the bins (width=4 Hz) containing this frequency. Noise level was estimated by combining the four adjacent frequency bins on each side of $2f_1 - f_2$ in addition to the bin containing $2f_1 - f_2$. For each stimulus condition, averaging continued until one of three stopping criteria was met: (1) noise was ≤−25 dB SPL, (2) artifact-free averaging time reached 32 s, or (3) signal-to-noise ratio (SNR) was ≥60 dB. The SNR criterion was selected so that it was never invoked, resulting in a situation in which the measurements stopped mainly on the noise criterion and seldom on test time.

E. Estimation of expected, incidental changes in emission level

The study was designed to produce DPOAE level changes when the calibration method was unreliable in controlling *stimulus level* in the ear canal (i.e., when standing-wave minima were present at the emission probe). Unfortunately, DPOAEs are doubly affected by insertion depth. Even if the input level is controlled at the eardrum and the response from the cochlea is the same, the *measured* response in the ear canal will depend on the insertion depth because DPOAE level measured with the ER-10C probe some distance from the eardrum depends on the impedance of the volume of air in the ear canal, which acts as an acoustic load for the emitted sound. Increasing the volume by moving the probe to a more shallow insertion decreases ear-canal impedance. Assuming that the volume velocity of the eardrum (due to the DPOAE traveling out of the cochlea) remains constant for an ideally calibrated stimulus, a shallower insertion will cause pressure of the DPOAE to decrease at the emission probe. Consequently, a cochlear response (DPOAE level) measured with a deep probe placement will be larger than a response of the same size measured with a shallow probe placement. This level difference (i.e., incidental change) will occur in conjunction with any changes in emission level caused by calibration errors. Since the study design introduced the additional, incidental change in DPOAE level unrelated to stimulus level, it was important to try to eliminate this variable prior to analysis. Isolating the effects of calibration errors on DPOAE level allows a more accurate comparison among calibration methods. It is acknowledged that predicting the incidental effect of ear-canal impedance on measured emission level is more complicated than addressed in our estimate (described below), which reflects the gross effects on emission level and is more accurate for low frequencies.[1]

Because ear-canal impedance is similar to the impedance of a tube, the incidental change in DPOAE level can be estimated using the relationship between length and impedance in Eq. (1). When kL is small, $\cot(kL) \approx 1/kL$. The wave number (k) is small at low frequencies because $k \approx \omega / c$ (Beranek, 1954). Accordingly, low-frequency impedance approximates inverse proportionality to length of the ear canal between the probe and the eardrum,

$$Z_c \approx \frac{-iZ_0}{kL}. \tag{6}$$

Impedance of the ear canal was calculated from 4 to 15 996 Hz (in 4 Hz increments) during each of the *in situ* SIL and FPL calibrations. For each subject, four of the calibrations were used to assess changes in probe-insertion depth during data collection: two representing deep probe placement and two representing shallow placement. Each of the four representative load estimates was reduced to a single value by averaging impedance magnitude across 250 to 500 Hz.[2] This frequency range is both high enough to have a good SNR and low enough to have the expected proportional relationship between impedance and length. The resulting mean impedance values for the two deep-insertion and the two shallow-insertion calibrations were averaged. The incidental change in DPOAE level due to changes in the probe-insertion depth was assumed to be equal to the decibel difference in impedance magnitude between the two depths over the selected low-frequency range.

Figure 2 shows low-frequency impedance magnitudes used to estimate the incidental change in DPOAE level for three subjects. The top panel represents a favorable case in which the estimate appeared ideal. Note the consistency in the decibel difference (the estimated, incidental change due to changes in volume) for both sets of measurements. The middle panel illustrates a less favorable case in which the two deep-insertion impedance levels are separated, indicating an *unintentional* change in insertion depth over time within the same probe placement. Furthermore, the decibel differences between insertion depths for the lowest frequencies are larger than the decibel differences at the highest frequencies, indicating a change in estimated impedance difference between insertions over the frequency range for which the impedance difference was assumed to be constant. The bottom panel shows the worst case from the subject in which the largest volume change with (supposedly) the same probe placement occurred. Results from this subject were atypical but were not excluded from the analysis.

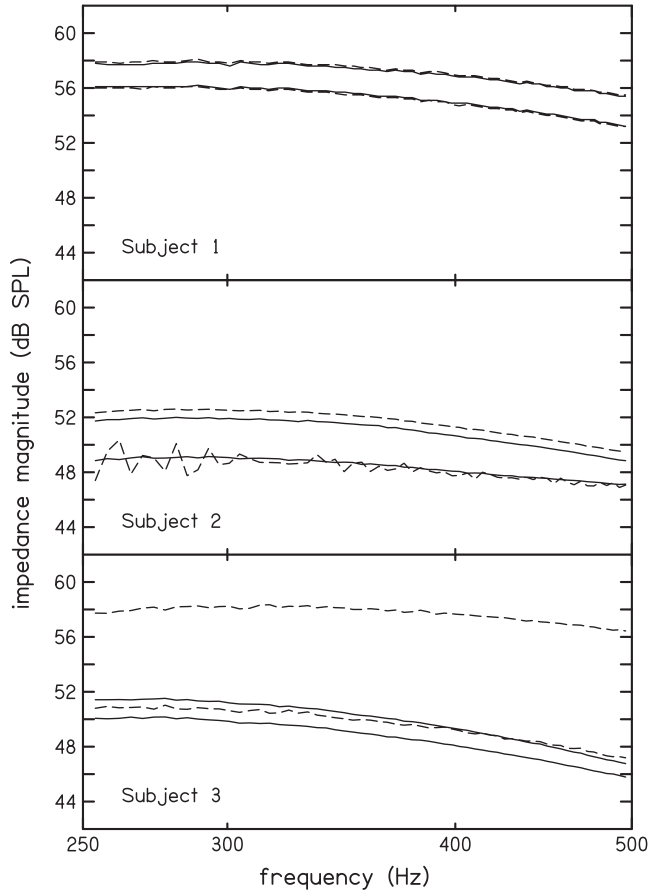

FIG. 2. Four sets of ear-canal impedance magnitudes from 250 to 500 Hz for three subjects. In each panel, the solid and dotted lines closer to the top are impedance values obtained with the deep probe insertion, and the solid and dotted lines lower in the panel are impedance values obtained with the probe inserted less deeply (shallow). The differences between the two solid lines and the two dotted lines were averaged to provide the estimate of intentional probe movement (the incidental change in DPOAE level introduced by the study design) for each subject. The differences between the top-solid and top-dotted lines and the lower-solid and lower-dotted lines provided estimates of unintentional probe movement for each insertion. The top two panels are representative of the types of impedance values obtained for the majority of subjects. The bottom panel is from the subject with the greatest estimated volume change for a single insertion (notice the difference between the top-dotted and top-solid lines).

F. Estimation of unintentional changes in emission level

Differences in impedance estimates for the *same* insertion raised concern about unintentional changes in ear-canal volume within a given probe placement, for which impedance magnitude was expected to be stable. While efforts were made to secure the probe in the ear canal, and *in situ* calibrations were examined for spectral changes that would indicate probe movement, empirical data reveal differences in impedance magnitude for a single insertion depth, suggesting that it was not always possible to maintain constant

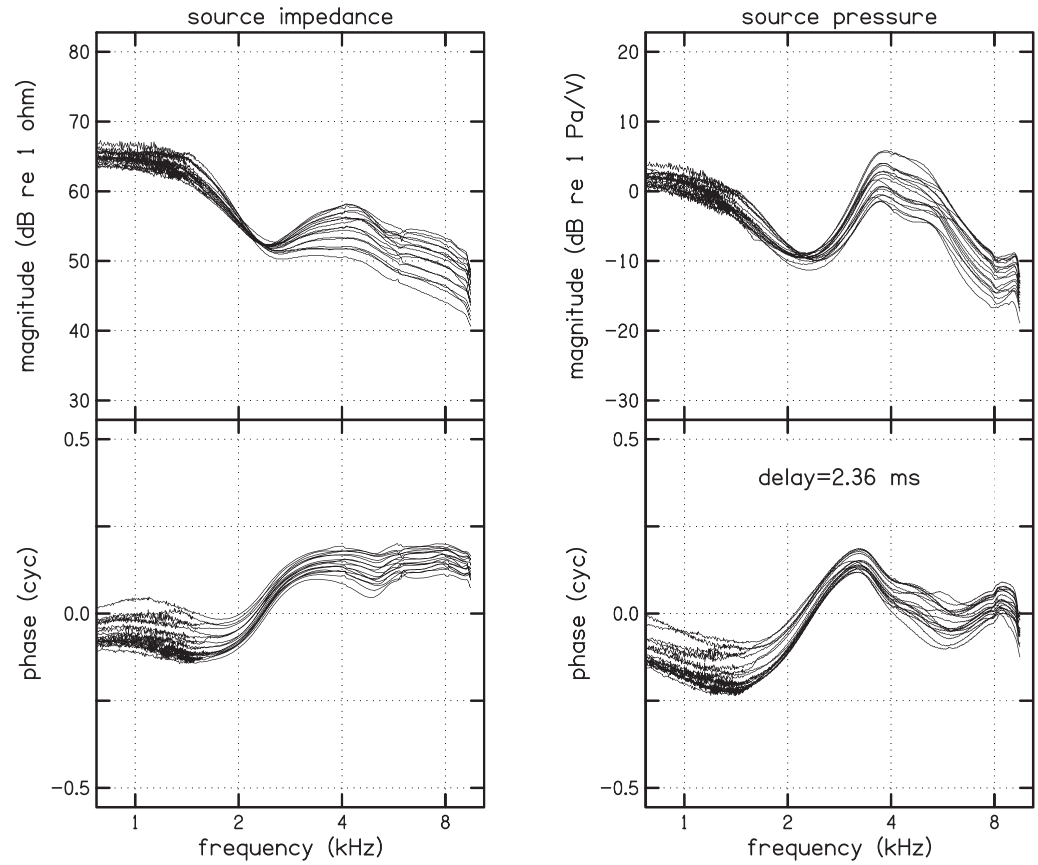

FIG. 3. Eighteen calculations of Thevenin-source (ER10-C probe) characteristics from the daily acceptable (error of <1.0) cavity calibrations. The characteristics for only one sound-source channel are plotted. The delay value in the fourth panel refers to the measurement-system delay between stimulus generation and response recording by the sound card, a small portion of which is due to the internal travel time of the acoustic signal through the ER-10C probe. The number of cycles that occur during this time was subtracted from the phase value on a frequency basis, resulting in the values plotted in panel four.

probe position during the entire set of measurements for a given placement. These differences may be viewed as estimates of within-subject measurement error. The effect of unintentional probe movement on DPOAE level was estimated using the same impedance values described above and taking the difference between values for a single insertion depth. Ideally, these differences would be zero, but as shown in Fig. 2, this was not always the case.

III. RESULTS

A. Daily cavity calibrations

The consistency of the Thevenin-equivalent source characteristics calculated during daily probe calibrations was examined by plotting the magnitude and phase of source impedance and pressure (see Fig. 3). The range of values (variability) suggests that the calibration procedure is a potential source of error when converting to SIL and FPL. While cross-talk is recognized as an error that may have influenced the Thevenin-equivalent source characteristics, it is expected that the effects would be the same upon repeated measurements and therefore would not be a source of variability. Additionally, while variability indicates error in the calibration procedure used to determine SIL and FPL, observed variability in probe characteristics does not necessarily indicate the same variability in load-impedance estimates because the relationship between probe characteristics and load impedance is not simply proportional.

B. Estimation of incidental changes in DPOAE level

Incidental DPOAE level changes unrelated to calibration errors were anticipated as a result of the study design, for which probe movement was intentional. Unintentional movement of the probe, however, was unavoidable. Figure 4 describes the distributions of the estimated impact of intentional and unintentional probe movement on DPOAE responses. The distributions are displayed in the form of box-and-whisker plots, in which average absolute changes in decibel are plotted. Absolute changes were preferred in case unintentional movement of the probe was in the direction opposite of what would be expected.

Intentionally moving the probe from a deep to a shallow insertion resulted in a larger decibel change than unintentional probe movement during either the deep or shallow insertions. The distribution when intentionally moving the probe is large, indicating that the estimated, incidental change observed across subjects varied widely. In two subjects, the decibel difference is <1.0 dB, which might imply that the insertion depth was not altered in these cases. For the majority of subjects (19 of 21), the estimated, incidental

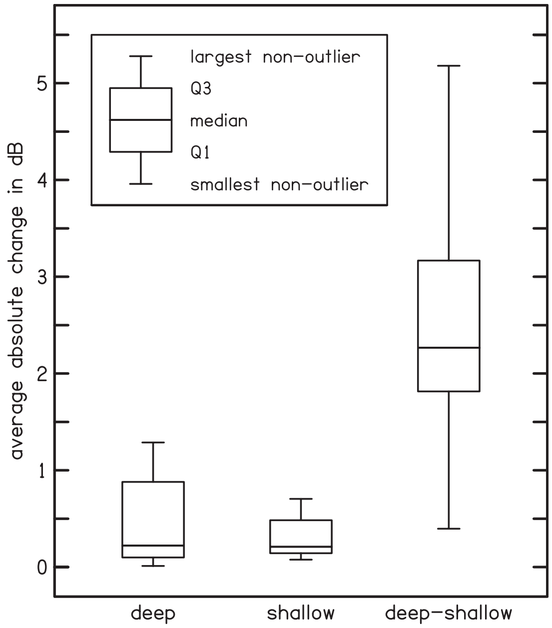

FIG. 4. Distributions of estimated, incidental changes in DPOAE level in response to changes in the ear-canal volume. The first two plots (deep and shallow) are estimates of unintentional volume changes due to slipping of the probe during a single insertion depth. The third plot (deep-shallow) represents estimates of the incidental change in DPOAE level that can be expected based on intentionally changing ear-canal volume by moving the probe. Outliers are not plotted in this figure. The largest unintentional change was 8 dB for one subject, which could not be explained based on review of the *in situ* calibration spectra. While excluded from the figure, this subject's data were included in the analyses.

change in emission level was >1.0 dB, indicating that manipulating probe placement had the intended effect.

Prior to data collection, there was greater concern about unintentional probe movement during the shallow insertion, on the assumption that less deep insertions would be less stable; however, Fig. 4 shows a larger decibel change for the deep insertion. For the deep insertion, a smaller shift in probe position has a greater impact on the decibel value due to a greater proportional change in volume. In other words, the larger decibel change during the deep insertion does not necessarily indicate greater probe movement. Rather, the same absolute movement for deep and shallow insertions produces a larger relative change for the deep insertions. More importantly, the unintentional changes for both deep and shallow insertions are small compared to the decibel change produced by intentionally moving the probe.

C. DPOAE level

The mean DPOAE and noise levels across subjects for deep and shallow insertions are plotted for all three calibration methods as a function of frequency (DPgrams) in Fig. 5 and as a function of level (I/O functions) in Fig. 6. Positive SNRs, even at 20 dB, indicate that reliable DPOAE measurements were possible (except, perhaps, at the lowest stimulus levels when $f_2 = 8$ kHz). Averaging across subjects could reduce or eliminate some of the changes in emission level that exist for individual subjects, especially for the SPL calibration, where standing waves introduce greater errors in estimates of stimulus level on an individual basis. However, while the specific effects of standing-wave minima are idiosyncratic and likely to be underestimated when averaging across subjects, they are not random and should be evident to some degree.

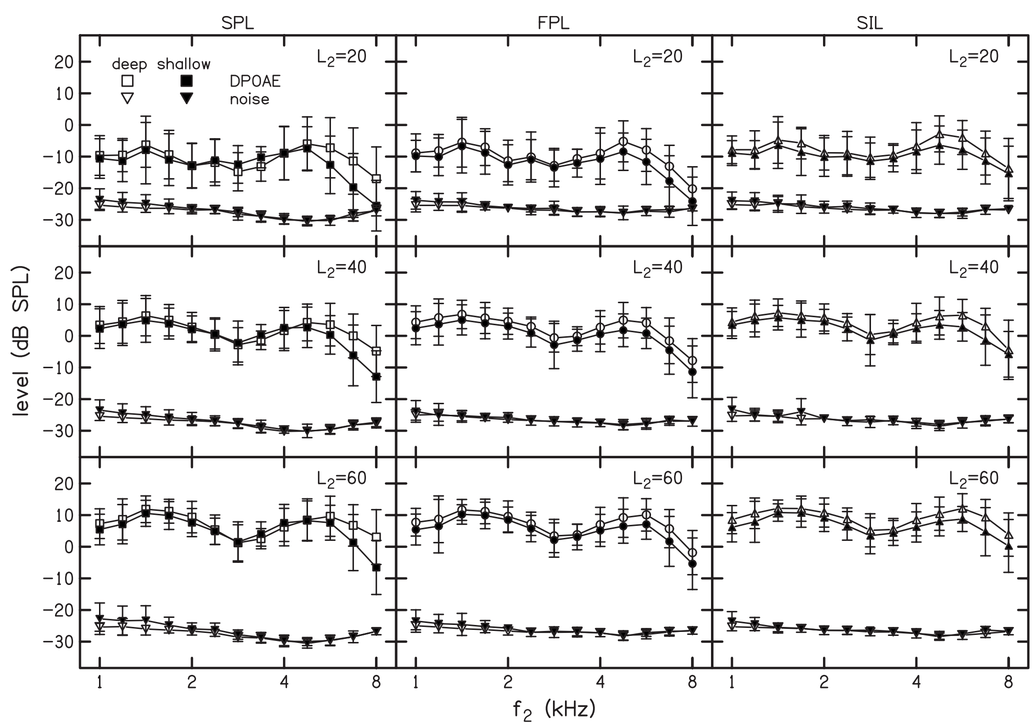

FIG. 5. DPgrams of subject means and standard deviations of noise and DPOAE levels for three calibration methods (SPL, FPL, and SIL) and three stimulus levels (20, 40, and 60 dB). Open symbols represent values obtained during deep insertion and closed symbols represent values obtained during shallow insertion.

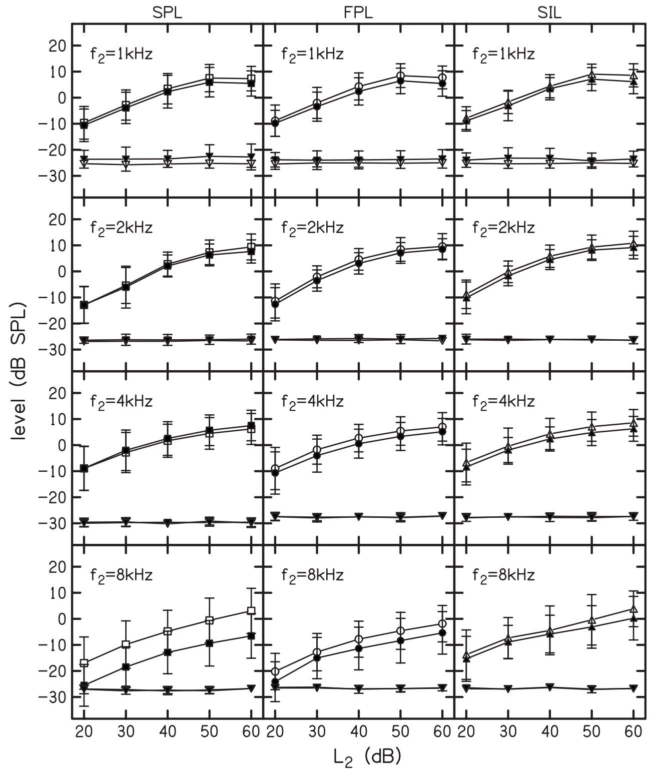

FIG. 6. Input/output functions of subject means and standard deviations of noise and DPOAE levels for the three calibration methods (SPL, FPL, and SIL) and four frequencies (1, 2, 4, and 8 kHz). Open symbols represent values obtained during the deep insertion and closed symbols represent values obtained during the shallow insertion.

The difference in DPOAE levels between insertion depths is the measurement of interest. Although difference values are not plotted in Figs. 5 and 6, the relationship between DPOAE levels obtained with the deep and shallow insertions can be observed. The summaries provided in Figs. 5 and 6 indicate that probe placement had a greater effect on DPOAE level for the SPL calibration compared to either FPL or SIL. Because the data have not been corrected, a uniform decrease in DPOAE level for the shallow insertion is expected based on the inverse relationship between pressure and volume (i.e., the incidental change introduced by the study design). For SIL and FPL calibrations, the deep insertion always resulted in higher DPOAE levels than the shallow insertion. Additionally, the change in DPOAE level is relatively uniform across frequency and intensity for SIL and FPL, especially for the 40 and 60 dB stimulus-level conditions (Fig. 5). A similar uniformity is noted for SPL at frequencies below 2 kHz (where standing-wave errors are less of a concern); however, at higher frequencies, more variability is evident, with DPOAEs measured for the deep insertion lower than, equal to, or higher than the emissions measured during the shallow insertion, with the greatest difference at 8 kHz. The presence of smaller DPOAEs for the deep insertion is opposite of what would be predicted if the effect of ear-canal impedance on the *measured* response was the sole determinant of changes in emission level. The greater variability with the SPL calibration in how DPOAE levels for the two insertion depths are related across frequency suggests calibration errors. Figure 5 shows systematic decreases in DPOAE level for the deep insertion, for frequencies between 2 and 4 kHz, and increases at higher frequencies (relative to DPOAE level during the shallow insertion), which is what would be predicted as a result of the effects of ear-canal length on frequencies affected by standing-wave calibration errors.

For SPL calibration, variability of DPOAE level changes across stimulus level is also noted. In Fig. 6, SPL calibrations for 2 and 4 kHz reveal increasing differences between the two insertions as the stimulus level increases. Not only is the relationship nonuniform across level, but it is also opposite of the prediction based on the growth rate of DPOAEs, which is linear at low levels, and becomes increasingly compressive (e.g., Dorn *et al.*, 2001; Neely *et al.*, 2003). It was expected that at high-stimulus levels, where the I/O function exhibits the most compression, a calibration error would result in little or no change in measured DPOAE level. Larger changes were predicted for responses on the steeper portion of the DPOAE I/O function (lower stimulus levels). The possibility that standing waves affected the calibration of the two primary levels (L_1 and L_2) differently (Whitehead *et al.*, 1995) may account for the unexpected outcome. DPOAE level is not only dependent on the absolute stimulus level but also on the difference between L_1 and L_2. Standing-wave errors have the greatest impact on a narrow frequency range, so when a calibration error affects the level of one primary, the level difference between primaries will also be affected. This may result in either a more or less optimal stimulus for eliciting a DPOAE, making the change in DPOAE level less predictable. A second explanation is that zero difference in uncorrected data does not necessarily mean that DPOAE level was not affected, as an incidental change was introduced by the study design. This same reasoning may also explain the apparent difference at higher intensities. This finding demonstrates a situation where it is more appropriate to base interpretations on corrected values, which allows for changes caused by calibration procedure to be isolated.

Figure 7 displays the mean absolute differences between deep and shallow insertions after applying the individual corrections that remove the incidental effect of volume change on DPOAE level, while leaving intact the differences due to calibration procedure. *Absolute* changes in DPOAE level for each subject were used to avoid averaging out differences in sign that may have occurred if the direction of the difference was not removed. The rationale for evaluating absolute values is that all changes, whether in the positive or negative direction between insertion depths, were considered to reflect calibration errors. Note that the y axis covers a 10 dB range in Fig. 7 compared to the 50 dB ranges used in Figs. 5 and 6, making the differences among calibration procedures more apparent. The smallest corrected differences in DPOAE level between deep and shallow insertions were observed mainly for frequencies below 2 kHz for all three calibration methods. The largest differences in DPOAE level were observed at the highest frequencies regardless of the calibration procedure. This effect indicates that controlling stimulus level with *in situ* calibrations is more difficult at higher frequencies for all three methods. While the change in DPOAE level varies as a function of stimulus frequency for all calibration

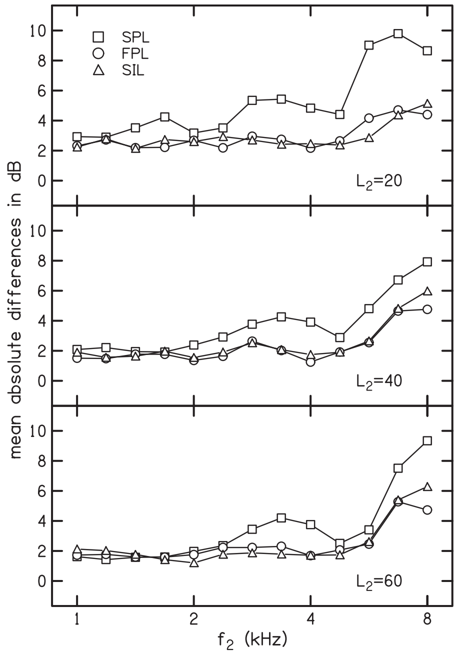

FIG. 7. DPgrams of the mean absolute changes in DPOAE levels due to changes in insertion depth after individually correcting for the expected change in emission level introduced by the study design. The three calibration methods (SPL, FPL, and SIL) are compared for three stimulus levels (20, 40, and 60 dB). The y axis differs in this figure from Figs. 5 and 6 by a factor of 5, making the differences between calibration methods more apparent.

methods, SPL, as expected, produced more variable measurements.

A three-way analysis of variance (ANOVA) was performed on the absolute differences in DPOAE levels with the following factors: calibration method (3 levels), L_2 (5 levels), and f_2 (13 levels). Because incidental changes were estimated and not always ideal (see footnote 1 and Fig. 2), adding a correction to the measured values introduces another potential source of error into the calculation. Therefore, both uncorrected and corrected data were analyzed. The significance observed in both sets of data is similar, indicating that correcting for the incidental changes in DPOAE level did not confound the results. Moreover, the F ratio was almost four times larger for the measurement effect when the correction was applied, which is evidence that removing the estimated, incidental change in DPOAE level positively influenced the analysis and subsequent interpretation. Due to these findings, only the results of the ANOVA on the corrected values are described (Table I).

The effects of stimulus level, stimulus frequency, calibration method, and interactions involving calibration method on changes in DPOAE level were significant ($p < 0.05$). While the ANOVA does not specify which calibration method had the greatest impact on the significance, Figs. 5–7 demonstrate that DPOAE level differences for SIL and FPL are similar and that data based on SPL calibrations are more variable across frequency and intensity. These findings suggest that SPL calibration is responsible for both the significant main effects and the interactions. None of the calibration methods resulted in zero change in DPOAE level after correcting for the expected, incidental change (Fig. 7), which indicates that none of them are completely insensitive to probe-insertion depth.

The observations thus far demonstrate that both SIL and FPL calibrations result in smaller changes in DPOAE level when the insertion depth is varied compared to SPL calibration. However, the least variable calibration method may depend on stimulus frequency or stimulus level. It is not practical to customize calibration depending on the frequency and/or level of a specific stimulus. Therefore, to provide a more general assessment of the calibration methods, the changes in DPOAE level were averaged across stimulus frequency and eventually level for each calibration method (Table II).

At each stimulus level, probe-insertion depth had a greater impact for measurements based on SPL calibrations, as expected, with the mean differences in DPOAE level about 1–2 dB greater than the differences obtained with SIL and FPL calibrations. In contrast, the greatest difference in mean emission levels between SIL and FPL calibrations is about 0.2 dB. SPL calibration also resulted in the largest standard deviations at each stimulus level due to individual variability of the frequencies at which standing-wave errors occur. Another noteworthy observation is that mean differences in DPOAE level decrease as the intensity increases for SPL calibration, which was the expected trend and is oppo-

TABLE I. The main effects for and interactions between calibration method, stimulus level, and frequency on the absolute change in DPOAE level between deep and shallow insertions after correcting for the incidental difference due to a change in ear-canal volume. The asterisk (*) denotes statistical significance for $p < 0.05$.

Source	Sum Sq.	df	Mean Sq.	F ratio	p value
		Main effects			
*Stimulus level (L_2)	525.9	4	131.48	15.40	<0.0001
*Calibration method	2 195.1	2	1 097.55	128.58	<0.0001
*Frequency (F_2)	8099.8	12	674.98	79.08	<0.0001
		Interactions			
*L_2 and method	213.4	8	26.68	3.13	0.0016
L_2 and F_2	291.8	48	6.08	0.71	0.9329
*Method and F_2	1 168.6	24	48.69	5.70	<0.0001
Error	34 108.6	3 996	8.54		
Total	46 603.3	4094			

TABLE II. Means and standard deviations of the absolute change in DPOAE level between insertions after correcting for the expected, incidental change. The first five rows are averaged across frequency for each calibration method and the sixth row is also averaged across level..

	Calibration method					
	SPL		SIL		FPL	
L_2	Mean	SD	Mean	SD	Mean	SD
20	5.21	2.41	2.91	0.87	2.93	0.90
30	4.41	2.21	2.49	1.20	2.50	1.02
40	3.67	1.88	2.48	1.36	2.26	1.16
50	3.56	2.12	2.40	1.49	2.26	1.16
60	3.44	2.42	2.44	1.56	2.42	1.19
Average	4.06	0.75	2.54	0.21	2.47	0.28

site of the trend observed in Fig. 6. The most probable reason for the apparent disagreement between Fig. 6 and Table II is that the summary provided in Table II removes the estimated, incidental change in DPOAE level and is based on absolute values, whereas Fig. 6 plots the uncorrected raw data. When averaged across levels, SPL calibration differs from SIL and FPL by approximately 1.5 dB, whereas SIL and FPL differ from each other by about 0.07 dB, which is less than half the standard deviation for either calibration method. All of the changes in DPOAE level are small in the aggregate; yet, the effects of calibration method and interactions of calibration method with stimulus frequency and level are statistically significant (Table I).

IV. DISCUSSION

The results from this study are summarized by the following observations.

(1) DPOAEs measured after SPL calibration demonstrated greater changes and greater variability of changes across frequency and stimulus level than DPOAEs following SIL or FPL calibrations when the probe-insertion depth was manipulated.
(2) All calibration methods were sensitive to probe placement, especially above 4 kHz.
(3) Temperature significantly affected estimates of source impedance and, therefore, SIL and FPL calibration procedures.

A. Temperature effects

A significant effect of temperature on the calculation of ear-canal impedance was observed, similar to results reported by Neely and Gorga (1998). A summary of the temperature effect is provided in Appendix A. Since estimates of ear-canal impedance are essential for conversion of SPL into SIL and FPL, the cavities were warmed to approximate body temperature during daily calibrations. However, cavity temperatures across the daily calibrations varied over a 10° range due to imprecision in the method used to warm the cavities, and this could have affected the accuracy of SIL and FPL calibrations. Additionally, it may be clinically impractical to warm test cavities to approximate body temperature as part of daily calibrations. A frequency-specific correction factor might reduce the influence of temperature on SIL and FPL calibrations; however, current methods do not offer a simple correction factor. Furthermore, the differences between the mean Thevenin-equivalent source characteristics calculated at room and body temperatures (Fig. 8) were similar to the differences between repeated measurements at a single temperature (Fig. 3), which complicates understanding the temperature effect. Until the effect of temperature is better understood and/or a method of temperature compensation becomes available, it is recommended, based on observations from Neely and Gorga (1998) and the present study, that consideration be given to cavity temperature for sound-source calibrations.

B. Incidental changes in DPOAE level

If the ear-canal volume had no effect on stimulus level but only affected DPOAE level measured at the emission probe, then applying the individualized correction would have eliminated any gross changes in DPOAE level, but this was not seen for any of the calibration methods. Mills *et al.* (2007) made repeated measurements of DPOAE level with the probe in a constant position and found variations of 1–2 dB, which were attributed to intrinsic variability. While intrinsic variability could account for most of the changes that were observed with SIL and FPL calibrations (and SPL at frequencies below 2 kHz), changes in DPOAE level greater than 2 dB were observed at frequencies above 4 kHz (Fig. 7). Although this is the frequency range where standing-wave problems are expected, SIL and FPL calibrations are, in principle, unaffected by standing waves, and the source of additional variability in DPOAE level remains unknown at this time.

C. Unintentional change in DPOAE level

The impedance values used to determine unintentional probe movement represent repeated measurements for the same condition (deep or shallow insertion), for which the measured responses were not expected to vary. While the impedance change from unintentional probe movement was estimated to be <0.2 dB for more than half of the subjects, it was $\geqslant 1$ dB for four subjects. This was unexpected because calibrations (performed prior to each DPgram for a single insertion) were monitored for probe stability. If pressure-

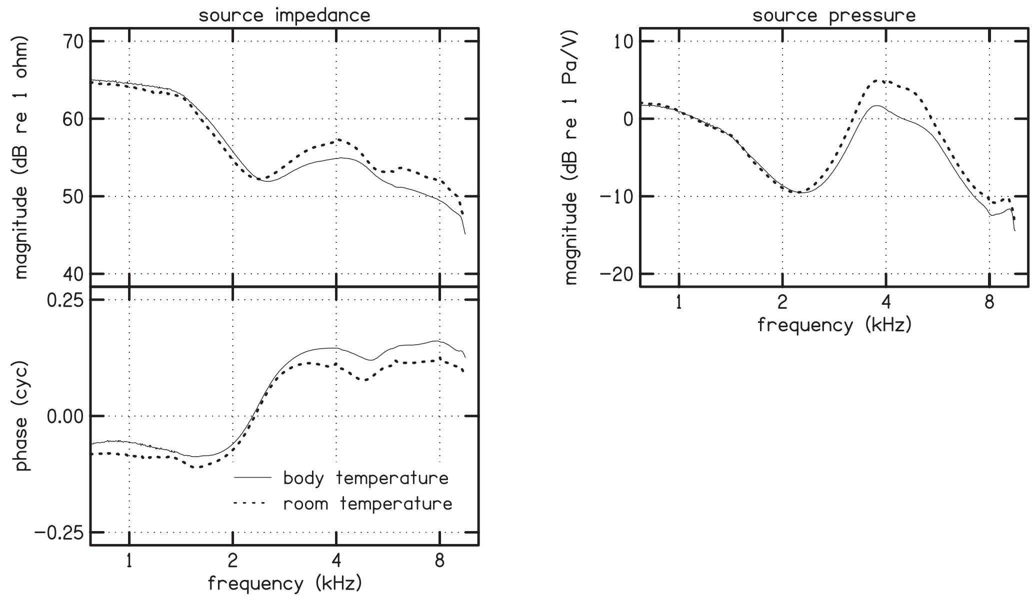

FIG. 8. Means for 18 repeated cavity calibrations at both room and body temperatures as a function of frequency. Phase of source pressure was not plotted as subtracting the delay complicated averaging. The delay values were within 0.01 ms of each other.

spectrum changes were detected from one calibration to the next (i.e., the notch became shallower or shifted to a lower frequency), then the affected conditions were repeated. However, Mills *et al.* (2007) reported an informal observation that even slight probe movement could affect DPOAE level by several decibels. More formal assessment by Kalluri and Shera (2007) suggested that apparent calibration stability might still allow slight changes in stimulus pressure, which can significantly affect DPOAE level.

For this investigation, unintentional movement compromised the study design; however, as shown in Fig. 4, the effects of intentional probe movement were larger than those due to unintentional movement. As a result, while errors (unintentional effects) are evident in the present data, the effects are small relative to the effects resulting from intentional changes in probe placement, which were the main focus of this study. While unintentional movement does not invalidate our findings, it may have reduced the observed differences among the calibration methods, even though counterbalancing the order of the calibration methods reduced possible bias due to probe shift over time. Aside from the potential effects on the present study, the findings indicate that it may be important to consider the impact of unintentional probe movement in all DPOAE studies.

D. Clinical implications

The present study suggests that both FPL and SIL are more reliable calibration methods compared to SPL, even with our conservative study design, which (1) did not attempt to maximize the emission changes caused by standing-wave errors by comparing DPOAE level when calibrating the stimulus at the tympanic membrane and at the emission probe, (2) did not exclude subjects even if a null was not observed in the pressure spectrum of the *in situ* calibration, and (3) averaged across subjects and eventually frequencies and stimulus levels, even though the frequencies at which standing-wave errors occur are idiosyncratic. Our method of manipulating the probe-insertion depth within the ear canal was expected to result in SPL calibration differences of 5–6 dB for individual subjects, depending on frequency (Dirks and Kincaid, 1987). Thus, the potential changes in DPOAE level were also expected to be smaller than the 10–20 dB changes noted in other studies (Dreisbach and Siegel, 2001; Siegel and Hirohata, 1994), which more accurately quantify the errors that are currently occurring when controlling the SPL of the stimulus. While it may have been beneficial to create an experimental design to maximize calibration errors and, consequently, to maximize differences among the calibration methods, the design is reflective of clinical measurement reliability. Our method underestimates the magnitude of calibration errors but is similar to potential test/retest situations that are encountered clinically, where a calibration microphone near the eardrum is not used. Additionally, probe-insertion depth during clinical measurements is not exact but dependent on many factors including probe design, physical properties of the ear canal, skill/experience of the clinician (especially if there are multiple testers for the same patient), and patient comfort. Given these factors, it is likely that probe placement will be different from trial to trial. In this study, the probe was intentionally moved approximately 2–3 mm, which is within a range that could feasibly occur during clinical test/retest DPOAE measurements.

Restricting the analysis to data at frequencies relative to pressure minima during SPL calibrations may also have been beneficial in order to make the differences between calibration methods more evident; however, nulls were not present in all subjects. A criterion requiring evidence of a standing-wave minimum at the emission probe during *in situ* SPL calibration was not included, in part, based on the knowledge that test-performance data are best around the same frequencies most susceptible to standing-wave errors (e.g., Gorga *et al.*, 1993, 1997, 2005; Kim *et al.*, 1996), which implies that standing-wave errors may not cause diagnostic errors when DPOAEs are used clinically. While this study does not assess test performance, the results are meant to relate to clinical issues.

Even though the differences between calibration methods were underestimated, the fact that effects were present and statistically significant indicates that the differences among calibration methods were substantial enough to withstand the conservative study design. The present results demonstrate that measurement reliability was the worst following SPL calibration, which further supports the need for an alternative calibration method.

E. Comparison of SIL and FPL

SIL and FPL *in situ* calibrations are both unaffected by standing waves and resulted in similar changes in DPOAE level between insertions. One concern with a power measurement (such as SIL) is the relationship between power and hearing thresholds (Hudde *et al.*, 1999). While Rosowski *et al.* (1986) demonstrated similarity between the SPL required to maintain a constant power at the cochlea and the SPL-referenced behavioral thresholds across frequency, Puria *et al.* (1997) subsequently demonstrated, across a broader frequency range, that pressure in the cochlea related more closely to behavioral thresholds than power. Although DPOAEs are not directly proportional to behavioral thresholds, the two measurements are often compared during clinical evaluations. A potential advantage to using FPL (instead of SIL) is that this method uses the same sound reference as SPL (i.e., 20 μPa rms). The relationship between hearing thresholds and SPL is well known across frequency (e.g., Sivian and White, 1933; Dadson and King, 1952; Robinson and Dadson, 1957; Killion, 1978), while the relationship between hearing thresholds and SIL is not well known. Therefore, using FPL to measure stimulus level may facilitate comparisons between hearing thresholds and DPOAE levels.

A more practical reason for selecting FPL over SIL stems from experience with implementing these two calibration methods. Initially, the protocol included a 70 dB stimulus-level condition; however, the relationship between SIL and SPL is frequency dependent. Subject discomfort due to excessively loud stimuli became a concern, especially at high frequencies, resulting in the decision to eliminate the 70 dB condition. FPL calibration did not raise concerns about subject comfort because the relationship between FPL and SPL is closer.

V. CONCLUSIONS

Our results indicate that both SIL and FPL calibrations are less susceptible than SPL to standing waves; however, further research is needed to determine whether these calibration methods improve test performance clinically. Although implementation of either of these two methods may be easier than the alternative procedure of placing a microphone close to the eardrum, the possible need to control the temperature of the calibration cavities may reduce the clinical practicability of both SIL and FPL. Further study of the impact temperature has on test performance is needed to determine whether heating the cavities is warranted in clinical implementation. The present results indicate that SIL and FPL calibrations lead to measured DPOAE responses that are less variable than those obtained with SPL calibration. FPL may be of particular interest because it simplifies comparisons with behavioral thresholds based on SPL calibration and reduces concerns about subject comfort when presenting high stimulus levels at high frequencies. Errors due to standing waves that are known to occur during *in situ* SPL calibration may be avoided by switching to either SIL or FPL calibration.

ACKNOWLEDGMENTS

This study was supported by the NIH (R01 DC2251, R01 DC8318, and P30 DC4662). The work was performed while the first author was supported by a training grant (T35 DC8757-01). The authors thank Hongyang Tan for valuable assistance during data analyses and Sarah Michael, Wafaa Kaf, Jonathan Siegel, and an anonymous reviewer for their suggestions.

APPENDIX A: TEMPERATURE EFFECTS

Neely and Gorga (1998) noted that calibrating the probe at body temperature resulted in fewer negative conductance values (a physically unrealistic occurrence) than when calibrating at room temperature. Because of this observation, the impact of cavity temperature on Thevenin-equivalent source and load characteristics was evaluated prior to initiating DPOAE measurements. Due to unknown measurement errors, repeated cavity calibrations are typically variable even when temperature is constant. Therefore, a preliminary study was undertaken with the objective of determining whether there are significant differences in source and load values between cavities at room temperature and body temperature (beyond typical repeated-measurement variability).

Five cavity calibrations were performed at both room and body temperatures. Body temperature was produced with an inexpensive heating pad that raised the internal temperature of the cavities to the range from 94.5 to 100.1 °F, as measured by a digital, oral thermometer placed inside each tube. Although these temperatures are closer to body temperature than they are to room temperature, which was about 70 °F, ear-canal temperatures in humans are more stable and closer to 98 °F. The implications of differences between body and cavity temperatures will be discussed below. Ten load-impedance estimates were obtained for one subject by repeated in-the-ear calibrations, which, by definition, were made at body temperature. Five of these estimates used the Thevenin-equivalent source characteristics calculated at room temperature and five used the source characteristics at body temperature.

Magnitude and phase values based on the cavity and *in situ* calibrations of one sound source were analyzed for 4, 4.758, 5.656, 6.727, and 8 kHz. ANOVAs were performed with the following factors: temperature (two levels), frequency (five levels), and repetitions (five levels). Both impedance and pressure measurements were analyzed for the cavity calibrations, but for the *in situ* calibrations, only impedance measurements were analyzed as load pressure is not dependent on the calculation of source characteristics.

For the purposes of these analyses, a p value <0.05 was considered significant. Source pressure magnitude was significantly affected both by temperature and an interaction between temperature and frequency ($p<0.0498$ and $p<0.0411$, respectively). For calibrations in the ear canal, main effects of temperature and frequency, along with temperature and frequency interactions, were found on both impedance magnitude and phase ($p<0.0001$).

Based on these results, the decision was made to warm the cavities to approximate body temperature for the daily calibrations required for this study. However, while the effect of temperature was significant, it remains unknown how temperature affects the calculation of source-pressure magnitude and, subsequently, load-impedance magnitude and phase. The procedure used in this study to heat the cavities was imprecise, resulting in temperatures ranging from 95 to 105 °F for the calibrations used during DPOAE data collection. Additionally, while controlling temperature may be feasible in the research setting, heating the cavities is time consuming and may be impractical for clinics. Therefore, additional effort was made to further describe the effects of temperature.

The magnitudes and phases of source impedance and the magnitudes of source pressure from the 18 daily cavity calibrations at body temperature were averaged for frequencies from 4 to 15 996 Hz (in 4 Hz increments). The same averages were obtained for 18 repeated cavity calibrations at room temperature. Both sets of averages are plotted in Fig. 8. Recall that pressure magnitude was the only Thevenin-equivalent source characteristic significantly affected by temperature, most probably due to the differences observed around 4 kHz. However, it should also be noted that, for all panels, the mean data sets for both temperatures fall within the range of daily variability (Fig. 3), which may have a greater effect on the accuracy of SIL and FPL calibration methods than temperature. Since we do not have a way to determine the accuracy of the Thevenin-equivalent source calculations at this point, effort should be placed on reducing variability. A calibration procedure that compensates for differences in temperature between the calibration cavities and ear canals and reduces variability could improve the estimation of load impedance for SIL and FPL calibrations.

APPENDIX B: FORWARD PRESSURE LEVEL

A solution of the wave equation for a one-dimensional wave with harmonic time dependence is

$$P(x,t) = A_+ e^{i(\omega t - kx)} + A_- e^{i(\omega t + kx)}, \tag{B1}$$

where $\omega=2\pi f$ is the frequency in radians per unit time and k is the wave number in radians per unit distance. One-dimensional wave propagation is often analyzed in terms of a wave traveling along a transmission line. In a uniform transmission line, Z_t (series impedance per unit length) and Y_t (shunt admittance per unit length) do not vary with x, and the relation between $P(x)$ (pressure) and $V(x)$ (volume velocity) is described by the following differential equations:

$$\frac{\partial}{\partial x} P(x) = - Z_t V(x), \tag{B2}$$

$$\frac{\partial}{\partial x} V(x) = - Y_t P(x). \tag{B3}$$

When $k^2=-Z_t Y_t$, the expression for $P(x,t)$ in Eq. (B1) satisfies Eqs. (B2) and (B3) and may be interpreted as the sum of forward and reverse propagating waves, $P_+=A_+ e^{i(\omega t-kx)}$ and $P_-=A_- e^{i(\omega t+kx)}$, respectively.

The impedance of an acoustic load is defined as $Z_\ell = P/V$ and can be expressed in terms of P_+ and P_-,

$$Z_\ell = Z_0 \frac{P_+ + P_-}{P_+ - P_-}, \tag{B4}$$

where $Z_0=\sqrt{Z_t/Y_t}$ is the characteristic impedance of the transmission line. For acoustic plane waves in a cylindrical cavity, $Z_0=\rho c/A$, where ρ is the air density, c is the sound speed in air, and A is the cross-sectional area of the cavity. Rearranging Eq. (B4) allows for the expression of forward pressure P_+ in terms of Z_0 and Z_ℓ,

$$P_+ = \frac{1}{2} P_\ell \left(1 + \frac{Z_0}{Z_\ell}\right). \tag{B5}$$

In this equation, $P=P_\ell$ represents the cavity load pressure. Note that $|P_+|$ can be much larger than $|P_\ell|$ when $|Z_\ell|$ is small and that $|P_+|$ approaches $\frac{1}{2}|P_\ell|$ when $|Z_\ell|$ is large. Note also that there is no reverse wave when $Z_\ell=Z_0$.

[1]Ideally, surge impedance would have been used for frequencies above 1 kHz, where the ear canal is more accurately represented as a transmission line instead of a lumped volume. However, doing so would have had a small impact on the estimated correction. A more complicated issue with the correction is that, at high frequencies, standing waves can create problems when measuring emission level the same as when measuring stimulus level. At this time, it is complicated, and perhaps impossible, to account for all of the factors influencing measured emission level, which is why the estimate was general. The fact that the statistical analysis was stronger (see Sec. III) when the corrections were applied is evidence of a positive influence and convinced us to incorporate the corrections in our analyses and subsequent interpretations.

[2]In one subject, the frequency range was relocated to 750–1500 Hz to avoid a poor impedance magnitude estimate at lower frequencies, which was probably due to an air leak caused by an improper probe fit.

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