Critical Review:
The (Sound) Wave of the Future: Is Forward Pressure Level More Accurate than Sound Pressure Level in Defining *In Situ* Sound Levels for Hearing Aid Fitting?

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This critical review examined the use of forward pressure level (FPL) as an alternative to sound pressure level (SPL) for defining sound levels *in situ.* A total of six studies were reviewed; four within-group and two mixed (between- and within-group) analyses. Three studies examined calibration and measurement of distortion product otoacoustic emissions (DPOAEs) and found that FPL was less susceptible to changes in probe depth placement and was potentially a more accurate measure of DPOAEs at 8000 Hz. Three studies examined the use of FPL to define behavioural thresholds and found that FPL does not show the same notches in frequency response as SPL, suggesting it is less susceptible to standing waves and thus a more accurate representation of sound delivered to the tympanic membrane than SPL. FPL appears to be a theoretically preferable measure of *in situ* sound level, however, there are practical constraints that limit its clinical utility. Calibration of FPL is temperature-dependent and the theoretical assumptions underlying the calibration procedure appear to be appropriate only up to 6000 Hz. Further research on the use of FPL to measure *in situ* hearing aid output levels is required.

Introduction

Ear canal sound levels are typically measured in decibels of sound pressure level (dB SPL) for the purpose of hearing threshold definition and hearing aid output measurement. The use of a probe microphone apparatus positioned to within 5 mm of the tympanic membrane typically results in accurate SPL measurement up to approximately 6000 Hz (Moodie, Seewald & Sinclair, 1994). This type of *in situ* measure of sound level takes into account individual ear canal acoustic properties to provide an estimate of sound reaching the tympanic membrane. However, SPL measurement can be affected by standing waves in the ear canal which create pressure minima at the measurement microphone as the forward and reverse traveling sound waves interact deconstructively (McCreery, Pittman, Lewis, Neely, & Stelmachowicz, 2010). Beyond 6000 Hz, *in situ* SPL measurement is susceptible to standing wave minima and is thus a potentially unreliable measure (McCreery et al., 2010). Standing wave minima may also occur at frequencies within the bandwidth of "traditional" hearing aids (i.e., below 6000 Hz; e.g., see McCreery et al., 2010). Standing wave minima can result in an underestimation of the true level of sound reaching the tympanic membrane. For hearing aid fitting, this underestimation of sound level could result in potential over-amplification, which could cause discomfort and/or damage.

Forward pressure level (FPL) is an alternative measure of sound level that is a mathematical derivation of the incident (i.e., forward going) sound wave. It is theoretically immune to the effects of standing wave minima because it includes only the incident sound wave (Scheperle, Neely, Kopun, & Gorga, 2008). FPL is referenced on the same scale as dB SPL (i.e., re: 20 uPa). The determination of the incident sound pressure in an individual ear requires careful calibration of the sound source. The first step is to determine the Thevenin-equivalent source characteristics, which involves measuring a wideband pressure response in a known acoustic load (i.e., in a hard-walled cavity). By using cavities of known length and diameter, the ideal impedance is known and cavities can be chosen such that they result in resonant peaks at key frequencies (typically 5 brass tubes of various lengths which result in resonant frequencies at 2, 3, 4, 6 and 8 kHz) (Scheperle et al., 2008). Knowing the source load impedance characteristics provides the information necessary to convert load pressure (in SPL) into FPL. When the known source is placed in an unknown cavity (e.g., the ear canal), the resulting measurements can be converted from SPL to FPL.

There is evidence that perception of high frequency speech cues is not possible with current hearing aid technology (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004) and that providing these high frequency speech cues (e.g. up to 9 kHz) can improve speech perception abilities of hearing impaired children and adults (Pittman, 2008; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). There is a trend in the hearing aid industry (e.g. Widex, Oticon) for providing aids with extended bandwidth, with useable gain reportedly up to 10,000 Hz. In order to assess the high frequency amplification (i.e., above 6000 Hz) of these aids, it is necessary to be able to quantify sound levels *in situ*. FPL offers the potential to be able to assess this high frequency amplification *in situ*.

This critical review examines whether FPL is less affected by standing wave minima than SPL and if FPL can be used to define *in situ* sound levels for frequencies greater than 6000 Hz for the purpose of hearing aid fitting.

Objectives

The primary objective of this paper is to analyze and critically evaluate selected studies that have compared the use of forward pressure level and sound pressure level to define ear canal sound levels. A secondary objective is to comment on the potential clinical utility of FPL for hearing aid output measurement/verification.

Methods

Search Strategy

Computerized databases including CINAHL, PubMED, SCOPUS, and Medline were searched using the strategy (Forward Pressure Level) OR (FPL). No limitations were applied to this strategy.

Selection Criteria

Studies selected for review were required to examine FPL for the purpose of defining *in situ* sound level in an audiometric context. No limitations on the specific context of FPL use were imposed.

Data Collection

Results of the literature search yielded six articles consistent with the selection criteria: four within-group and two mixed (within- and between-group) design studies. Three articles focused on calibration and measurement of distortion product otoacoustic emissions and three focused on the definition of hearing thresholds. There were no articles specifically dealing with measurement/verification of hearing aid levels using FPL. The intention was to examine all peer-reviewed articles focusing on forward pressure level.

Results

Calibration/Measurement of DPOAEs

Standing waves can result in lower SPL measured at an otoacoustic emission probe than is actually arriving at the tympanic membrane (Scheperle et al., 2008). Thus, the level at the tympanic membrane can exceed the desired levels for distortion product otoacoustic emission (DPOAE) testing. A calibration error such as this may introduce diagnostic errors (Burke, Rogers, Neely, Kopun, Tan, & Gorga, 2010). Scheperle et al. (2008) undertook a within-group comparison of three DPOAE calibration and measurement methods: SPL, FPL and sound intensity level (SIL; a power measurement). The authors were interested to see if use of FPL or SIL could reduce the variability observed in DPOAE measurement either due to improvements in DPOAE calibration or actual measurement. DPOAEs were measured on 21 normal hearing subjects at two probe-tube insertion depths (deep and shallow). The authors stated that the deep probe insertion was as deep as possible, though no specific distance from the tympanic membrane was noted. The shallow placement was approximately 2-3 mm less than the deep placement and was devised to intentionally introduce variability in the SPL measurement. DPOAEs were measured at each insertion depth following calibration using SPL, FPL and SIL. Thus, there were a total of six measurement conditions (2 depths x 3 calibration methods). DPOAEs were measured at octave and inter-octave frequencies between 1000 and 8000 Hz and at L2 levels ranging from 20 to 60 dB.

Initial FPL calibration results demonstrated a temperature effect. FPL calibration was more accurate when completed at body temperature (i.e., when the brass tubes were heated with a heating pad to approximately body temperature) versus room temperature. As such, FPL calibration was completed daily at room temperature. However, daily calibration values showed variability, despite being completed at the same temperature. Thus, daily source calibration for FPL may be a source of error.

Deeper insertion of the probe tube resulted in higher average DPOAE levels for all calibration methods, as was expected. The increase in SPL with deep insertion was fairly uniform up to 2000 Hz, but was more variable at higher frequencies with deep insertion resulting in lower, equivalent or higher DPOAEs than the shallow insertion. The increase in level for the deep insertion for SPL calibration was greatest at 8000 Hz. The increase in level for deep insertion was relatively consistent across frequencies for FPL and SIL calibration. The authors corrected the deep and shallow insertion DPOAE values to remove the effect of volume change on DPOAE level, leaving only differences in calibration method. The smallest differences between calibration methods were seen below 2000 Hz, with the largest differences observed above 4000 Hz for all calibration methods. The most variability was observed for SPL calibration, however some variability was observed for FPL and SIL calibration, suggesting that controlling stimulus level *in situ* is difficult at high frequencies. A three-way ANOVA was performed on the absolute differences in DPOAE level with calibration method (3) x DPOAE L2 level (5) x DPOAE f2 level (13) as factors. The analysis was performed on both uncorrected and corrected values with the same results. Findings suggested that the effects of stimulus level, frequency and calibration method were significant as were their interactions. Results showed that DPOAE level differences between deep and shallow placement for SIL and FPL were similar while SPL calibrations were more variable than both SIL and FPL across frequency and intensity. The authors did not use post hoc tests to statistically test these results. At each stimulus level, probe depth had the greatest impact on SPL calibrated results (as observed in mean and standard deviations of absolute differences between deep and shallow insertion), however no statistical tests were completed.

DPOAE levels showed the greatest variability across stimulus level and frequency after SPL calibration when probe tube depth was varied. However, FPL and SIL calibration methods were affected by probe depth above 4000 Hz. The authors were unsure of why this was observed. Overall, this study suggested that DPOAE results obtained after FPL and SIL calibration are more reliable than SPL calibration. Because SIL is a measure of power, it is on a different scale than either FPL or SPL and is thus more difficult to interpret loudness levels and the relationship to behavioural thresholds. As such, FPL is likely a more clinically useful measure than SIL. The authors caution that further research is needed to determine if FPL calibration would result in clinically different diagnoses than SPL and if temperature effects make FPL use impractical.

Burke et al. (2010) completed a mixed design (between- and within-group) study of DPOAE calibration methods. Fifty-two normal hearing and 103 hearing impaired subjects participated in a study examining the differences between standard SPL calibration and four FPL calibrations: daily and a reference calibration (performed once at the start of the study) at room and body temperature. DPOAEs were measured at half-octave steps from 2000 to 8000 Hz with L2 levels ranging from -20 to 70 dB SPL in 5 dB steps. Receiver operator characteristic (ROC) curves were developed for each frequency, calibration method and L2. Based on these curves, areas under the curve (AROC) were computed. Any AROC differing from another by more than 2 standard deviations was said to be significantly different. Cohen's d was computed to determine the effect size of any differences.

DPOAE i/o functions were similar across all calibration methods. Stimulus level had a larger effect than calibration method or frequency, with the best performance observed for moderate stimulus levels. At 8000 Hz, the SPL AROC was lower than all of the FPL calibration AROCs. Cohen's d suggested a large effect size for the difference at 8000 Hz, however no statistically significant differences between AROCs based on calibration methods were observed at any frequency. At 8000 Hz, the daily body temperature calibration had the highest sensitivity while SPL calibration had the lowest sensitivity. The authors speculated that the lack of statistical difference between the calibration methods may have been due to a ceiling effect (i.e., SPL calibration performed well). If SPL standing waves resulted in lower levels being measured at the probe than were actually at the tympanic membrane, then the SPL calibrated response would be higher than intended and thus would be more likely to result in a response. At higher levels, this unintended increase in level would likely cause some hearing impaired ears to respond, thus reducing the SPL calibration sensitivity. The authors concluded that daily calibration resulted in best test performance at 8000 Hz, but it was also the least clinically feasible. However, all of the FPL calibrations were superior (though not statistically so) to the SPL calibration at 8000 Hz.

Rogers, Burke, Kopun, Tan, Neely, and Gorga (2010) completed a companion study to the Burke et al. (2010) study. Rogers et al. examined the accuracy of DPOAE predicted thresholds based on SPL and the four FPL calibration methods noted above. The authors measured DPOAE i/o functions for each normal hearing and hearing impaired participant starting with an L2 of 70 dB and decreasing in 5 dB steps. Threshold was determined using two methods: one was the L2 at which the DPOAE was $\geq$ 3 dB above the noise floor (i.e., SNR $\geq$ 3 dB). The second method converted DPOAE levels into pressure and a linear regression was completed. The level at which the linear regression line crossed 0 uPa was taken as threshold. The i/o function was measured at 2, 3, 4, 6, and 8 kHz.

Correlations between the DPOAE estimated threshold and measured behavioural (dB HL) thresholds were calculated. The largest correlation coefficient was for daily body temperature FPL calibration (r=.82 SNR method, r=.84 regression method) and the lowest was for reference room temperature FPL calibration (r=.78 SNR method, r=.8 regression method). The authors did not test for significant differences between correlation coefficients for the various calibration methods. The SPL calibration resulted in the greatest number of normal hearing individuals failing to meet the normal hearing criteria, however no statistical tests were completed to determine if this was significantly different from FPL calibration methods. There was no effect of calibration method on estimated threshold by frequency. Regardless of the calibration method, the highest correlation between DPOAE estimated and measured behavioural threshold was at 6 kHz and the lowest at 8 kHz. Estimates of behavioural thresholds were said to not differ between the calibration methods, however, no statistical tests were completed.

The authors concluded that for DPOAE measurement, use of SPL calibration may be sufficient. Standing waves may occur, but if they do not affect the frequencies being tested, then they are of little consequence. However, as discussed by Scheperle et al. (2008), FPL is less susceptible to changes in probe insertion, and thus may be more appropriate for monitoring DPOAEs over time.

Definition of Hearing Thresholds

Lewis, McCreery, Neely, and Stelmachowicz (2009) completed a within-group analysis comparing three methods of measuring the amount of sound delivered to the middle ear for the purpose of threshold definition: SPL, FPL and incident pressure level (IPL; an estimate of sound across the tympanic membrane). Custom earmolds were made for each of the twenty-two normal hearing participants and ear canal sound level was recorded using a probe-tube microphone placed 4mm past the medial end of the earmold. One set of behavioural thresholds were obtained for each participant at octave and inter-octave frequencies from 500 to 10,000 Hz. As part of the *in situ* measurement of threshold in SPL, each participant's notch frequency (i.e., the frequency at which a standing wave null was located) was identified. Behavioural thresholds at each participant's notch frequency, plus one octave below to ½ octave above the notch frequency at ¼ octave increments were obtained. Thresholds were calculated in dB SPL, FPL and IPL. Notch depth was calculated as the average threshold of ½ octave above ½ octave below the notch frequency minus the threshold at the notch frequency. The authors also explored the dependence of FPL and IPL on middle ear status.

Results showed that SPL measurements resulted in notches in threshold response that were less evident with FPL or IPL. The lowest observed notch was at 4000 Hz and the highest was at 7660 Hz. A one-way ANOVA revealed significant differences in notch depth between the three measurement methods. Post hoc testing with a Bonferonni correction for multiple comparisons showed that SPL notch depth was larger ($p<0.05$) than FPL and IPL but the later two were not significantly different. IPL was found to be more affected by middle ear status than FPL, which suggests that FPL may be a more reliable estimate of sound being delivered to the middle ear. These results suggest that underestimation of sound at the tympanic membrane could occur with SPL measures at frequencies as low as 4000 Hz when using a clinically acceptable probe placement. Underestimations of up to 16 dB were observed. Below 4000 Hz, SPL (and FPL) is an accurate estimate of sound delivered to the tympanic membrane. FPL is not affected by standing wave minima and is thus a better predictor of sound delivered to the tympanic membrane at frequencies above 4000 Hz.

Withnell, Jeng, Waldvogel, Morgenstein, and Allen (2009) completed a within-group study that examined different methods of quantifying hearing threshold *in situ* for thirteen normal hearing participants. The authors determined the standing wave frequency for each participant's ear canal and also measured behavioural thresholds at octave and inter-octave frequencies between 250 and 6000 Hz. The authors commented that they did not explore any frequencies above 6000 Hz because calibration of a source using a straight rigid tube (as is done with FPL) is only valid up to 6000 Hz (see Stinson, 1985). Sound level was measured in the ear canal via a probe tip assembly. Insertion depth was not specifically stated.

Four participants showed a standing wave response at a frequency below 6000 Hz. Four participants did not have a standing wave response. The authors speculated that these participants had standing waves above 6000 Hz, but unfortunately there is no evidence to confirm. The authors did not address why they included only eight of the thirteen participants' data in the paper. The SPL behavioural thresholds for the four participants who showed standing wave notches below 6000 Hz were lower than the FPL thresholds at the frequency affected by the standing wave (4000 Hz for three participants, 6000 Hz for one participant). For the participants who did not show a standing wave below 6000 Hz, FPL thresholds were also higher at 6000 Hz in three of the four cases. The authors do not perform any statistical analysis on the data, potentially due to the relatively small number of participants in each group. The authors concluded that FPL is less susceptible to standing wave minima and is thus a preferable method to SPL for measuring behavioural thresholds.

McCreery, Pittman, Lewis, Neely, and Stelmachowicz, (2009) conducted two consecutive within-group experiments comparing *in situ* measures of sound pressure level and forward pressure level. In Experiment 1, ear canal SPL measurements were made at four probe tube depths in ten normal hearing adults: at the tympanic membrane (TM), TM-2mm, 2mm past the medial sound bore of an earmold (EM) and EM+4mm. A 5 second 70 dB SPL broadband noise was delivered to the ear canal and the ear canal SPL was measured via the probe tube. Individual frequency response notches were visually identified and the notch depth was calculated as the difference between the maximum SPL below the notch and the SPL at the notch frequency.

Pressure minima (i.e. notches) from 12 to 26 dB were observed at all probe placements, even at the TM placement. An ANOVA was used to analyze the differences between probe placements with notch depth and notch frequency as within-subject factors. Notch frequency significantly increased with depth ($p<0.05$) (i.e., the closer to the TM the higher the notch frequency). Post hoc comparisons with Bonferonni corrections for multiple comparisons revealed that only the TM and EM+2 differed significantly. Notch depth did not differ significantly between probe placements. Test-retest values were within 2 dB below 4000 Hz and less than 5 dB on average above 4000 Hz for all probe positions. However, individual variations of up to 8 dB were observed at all positions. The greatest variations were observed at notch frequencies, suggesting a complex interaction of the forward and reverse travelling waves. These results suggest that SPL standing waves were present at all insertion depths, even at the TM and often within the bandwidth of hearing aids (i.e. 6000 Hz or less). Notches were observed at frequencies other than what would be predicted based on ¼ wavelength resonances in the ear canal, likely due to the complex reflectance and impedance of the TM (McCreery et al, 2009).

McCreery et al. (2009) conducted a second experiment comparing behavioural thresholds in dB SPL, FPL and voltage (dB re 1 uV). A reference to dB voltage was used because the behavioural threshold obtained would be unaffected by ear canal resonances. Sixteen normal hearing children were recruited, however four showed high frequency (4-10 kHz) hearing thresholds that were outside of the normal range for this study (>15 dB HL), thus a total of 12 children participated. Each child had a custom earmold created for the purpose of threshold measurement. Thresholds were measured at octave and inter-octave frequencies between 500 and 10,000 Hz and also from ½ octave below the measured notch threshold to ½ octave above, at ¼ octave intervals. A probe-tube placed at 4mm past the medial end of the earmold was used to measure sound levels. One set of behavioural thresholds were obtained and then expressed in dB SPL, dB FPL and dB uV.

Ten of the twelve participants had SPL notch depths that were deeper than the FPL depth, while two showed no difference. A repeated measures ANOVA comparing SPL and FPL thresholds below 2000 Hz was significant; post hoc testing with Bonferonni corrections suggested that SPL and voltage did not differ, but both were significantly higher than FPL (by approximately 6 dB). Thus, dB voltage appears to be an appropriate standard against which SPL and FPL can be relatively compared. The authors commented that the 6 dB difference between FPL and SPL is likely from the constructive addition of forward and reverse traveling waves found in SPL (but not FPL, which is only the incident wave) and that this difference would simply have to be accounted for in hearing aid measurement. Above 2000 Hz, SPL thresholds showed pressure minima (i.e., notches) that were not present in FPL. A repeated measures ANOVA comparing threshold values at each participant's notch frequency was significant. Post hoc testing with Bonferonni corrections suggested significant differences between all three measures. SPL provided the lowest estimate of sound level, while FPL provided a higher estimate. FPL was on average 12.2 dB higher than SPL at the notch frequency suggesting that FPL is much less susceptible to standing waves than SPL. The variation observed in FPL was similar to that of dB uV (which is not affected by ear canal resonance).

The authors concluded that substantial (i.e. greater than 10 dB) SPL minima could be observed at all probe placements, including at the TM. Forty-five percent of probe placements had pressure minima within the bandwidth of hearing aids (i.e., below 6000 Hz). For all participants, use of FPL could result in smaller errors in estimating *in situ* sound levels. For the two participants in Experiment 2 whom did not have SPL notches, use of FPL would result in the same thresholds as SPL above 2000 Hz.

Discussion

The articles reviewed above suggest that FPL may be a more reliable method for calibration of DPOAE stimulus levels, especially when probe depth is varied (e.g., for repeated visits of the same patient). Varying probe insertion depth had an impact on SPL thresholds, whereas there was less (but still some) variability in FPL thresholds (Scheperle et al., 2008). Scheperle et al. (2008) used a conservative approach in their study – the change in probe depth was small and did not maximize standing wave effects for SPL; they did not exclude participants without a measured null; and they averaged across frequencies even though standing wave minima are individualized. Despite this conservative approach, use of FPL still appeared to be warranted. When DPOAE test performance was examined, results suggested that FPL could potentially provide more accurate DPOAE i/o results at 8000 Hz (Burke et al., 2010). However, results from Rogers et al. (2010) suggested that use of SPL calibration may be sufficient for estimation of behavioural thresholds with DPOAEs. While the Rogers et al. (2010) and Burke et al. (2010) studies have good statistical strength due to the large number of participants studied, they unfortunately don't allow for comparison of individuals, which would be of clinical relevance and importance.

The use of FPL appears to be a more accurate measure of *in situ* sound level than SPL, at least for the purpose of behavioural threshold definition. The studies reviewed demonstrated that FPL is less susceptible to the influence of standing waves in the ear canal and is thus a more accurate representation of sound being delivered to the middle ear than SPL. Pressure response minima that resulted in an altered definition of hearing threshold were observed with SPL measurements that were not observed with FPL (Lewis et al, 2010;

McCreery et al., 2010). Frequency response notches in SPL were observed within the bandwidth of current hearing aids (i.e., less than 6000 Hz) (Lewis et al, 2010; McCreery et al., 2010) which suggests that FPL may be an appropriate measure for all hearing aid verification, including "traditional" aids and those with extended bandwidth. The fact that FPL is referenced on the same scale as SPL would likely facilitate its use and interpretation. Implementation would likely require little change clinically, aside from the calibration procedure, as the difference between SPL and FPL is essentially mathematical. Modifications could be implemented in the software of current hearing aid and real-ear measurement devices to allow for use of FPL. While no study directly measured the output of a hearing aid using FPL, these results suggest that FPL would be less susceptible to standing wave minima and would thus be a more accurate measure of hearing aid output than SPL.

Conclusion

Despite the potential advantages of FPL, there are practical constraints that limit its current use in a clinical setting. There is an effect of air temperature on FPL calibration (Scheperle et al., 2008) which must be addressed prior to clinical adoption. The extent that this temperature effect affects definition of behavioural thresholds or measurement of hearing aid output needs to be studied. The development of a simple and accurate calibration method is likely required before FPL can be adopted clinically. To date, no studies have explored the use of FPL to measure both hearing thresholds and hearing aid output, specifically high frequency hearing aid output. While FPL is theoretically a preferable measure to SPL for measuring output, research is needed to determine if clinically relevant differences between SPL and FPL exist. Further research on ear canal modeling is required as the current model of the ear canal as a hard-walled cylinder appears to be appropriate only up to 6 kHz (Stinson, 1985). There would be little incentive to change to FPL unless it was an accurate measure of sound level beyond 6000 Hz.

Clinical Implications

At this time, ensuring proper and consistent probe tube placement is essential to obtaining the most accurate assessment of *in situ* sound levels possible. While use of FPL would likely result in more accurate measurement of *in situ* sound levels, it is currently not clinically practical. Caution in fitting extended bandwidth hearing aids should be taken until an appropriate measurement protocol is developed.

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