# Influence of calibration methods and insertion depth on DPOAE level and behavioral threshold tests

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**Abstract** **2**

**Introduction** **3**

**Theory** **5**

Thévenin source calibration 5

Ear canal acoustic parameters 6

Forward pressure level 7

Sound intensity level 7

**Methods** **8**

Subjects 8

Procedure 8

**Results** **10**

**Discussion and conclusion** **14**

**Conclusion** **16**

**References** **17**

# Abstract

Two studies are reviewed that compared methods to calibrate stimuli for DPOAE level measurements and behavioral threshold measurements. The calibration methods were tested on the influence of insertion depth on the outcomes of the tests. Three different calibration methods were tested, being sound pressure level (SPL), forward pressure level (FPL) and sound intensity level (SIL) calibration. SPL calibration is highly affected by standing waves, where FPL and SIL are theoretically unaffected by standing waves. A Theoretical explanation is outlined on how Thévenin-source characteristics can be obtained which are needed to calculate FPL and SIL. The first study that is reviewed, did DPOAE level measurements with five different stimulus levels, ranging from 20 to 60 dB and over a range of 1 to 8 kHz. Both studies showed that using FPL is advantageous over using SPL to calibrate the stimulus. SIL showed similar differences in DPOAE levels as a FPL calibration stimulus, but further research on the SIL calibration methods must be done for both DPOAE level and behavioral threshold measurements.

# Introduction

The use of distortion product otoacoustic-emission (DPOAE) level measurements and behavioral threshold measurements are widespread used methods in diagnosis for hearing losses and for audiological research. Otoacoustic emissions (OAE) are faint sounds produced by the outer hair cells inside the cochlea (Probst, Lonsbury-Martin, and Martin 1991), that can occur spontaneously or can be evoked when a stimulus is applied to the ear.

DPOAEs are evoked combination tones that occur after applying two stimulus tones to the ear (Harris et al. 1989). In a good functioning human ear, the outer hair cells in the cochlea produce a sound when the stimulus tones are received by the cochlea. The produced sound is at least 60 dB lower than the primary tones. This sound is measured by a probe consisting of a sensitive microphone and speakers. These speakers can be used to deliver stimulus tones.Behavioral thresholds, also called hearing thresholds, are measured by applying pure tones to the subjects ear. The level of the first stimulus is such a level that a healthy human ear should hear the sound, if this sound is heard the level is lowered until the subject does not hear the sound anymore. The last heard stimulus level by the subject, is the threshold of the tested frequency. This same procedure is repeated for several frequencies.

Before measurements like these can be done, a calibration procedure need to be performed. An in situ sound calibration can provide a way to equalize stimulus levels in subjects and across frequencies by compensating for individual differences in acoustical properties of the ear canal. Normally, the stimulus calibration is based on the pressure measured at the probe. However, a problem occurs when stimuli above 2 kHz are used to calibrate or stimulate the ear. This is caused by standing waves which can cause cancellation of sound pressure measured at the emission probe (Stinson 1985; Siegel 1994; Neely and Gorga 1998). These errors can affect both the stimulus and threshold measure up to 20 dB in individual subjects (Siegel and Hirohata 1994; Siegel 1994; Dreisbach and Siegel 2001). These standing waves occur when the distance between the probe and the tympanic membrane (TM) is longer than the quarter wavelength of the stimulus tone.

Besides standing waves, movement of the measuring probe can cause problems too. When the probe moves slightly outwards of the ear canal, the volume of the cavity becomes larger which results in a lower pressure, according to Boyle's law. Movement of the probe also enlarges the distance between the measuring probe and the TM what results in standing waves having effects on lower frequencies.

In this literature study, two papers will be reviewed that compare calibration methods and their effect on measuring DPOAE levels and behavioral thresholds in subjects. The effect of insertion depth of the probe is also tested in these papers. Insertion depth can also influence the sound level of the stimulus tone, this occurs when the insertion depth is shallow, which results in a longer distance between the probe and the TM. Three different calibration methods will be compared in this literature study, sound pressure level (SPL) calibration, forward pressure level (FPL) calibration and sound intensity level (SIL) calibration.

SPL is the pressure level measured at the probe. This level can be affected by standing waves because it consists of the forward pressure waves and reversed pressure

waves combined. Both FPL and SIL are unaffected by standing waves. This will be further explained in the *theory* section.

To convert SPL into FPL and SIL, some acoustical properties of the ear need to be determined. This can be done by performing a Thévenin-source calibration of the probe prior to the experiment. Thévenin-source calibration determines the acoustical impedance (Zsrc) and pressure (Psrc) of the probe (Allen 1986). Using these two parameters, acoustical properties of the ear canal can be determined by applying a stimulus to the ear canal.

The first study determines the influence of in situ calibration methods on the threshold of DPOAE (Scheperle et al. 2008). The study compares the effect of insertion depth for SPL, FPL and SIL calibration. The second study compares nine methods to estimate the ear-canal stimulus levels, including insertion depth for SPL and FPL calibration (Souza et al. 2014). In this study, several other methods are compared too, but will not be included in this literature study.

The results of this literature study describe the influence of the used calibration methods and the effect of insertion depth on measuring DPOAE thresholds and behavioral thresholds.

# Theory

## Thévenin source calibration

For FPL and SIL calibration, the source characteristics of the probe need to be calculated, this can be done by a Thévenin-source calibration. The probe is fitted into several cavities with an impedance that can be calculated by theory. The setup can be seen as the following circuit.

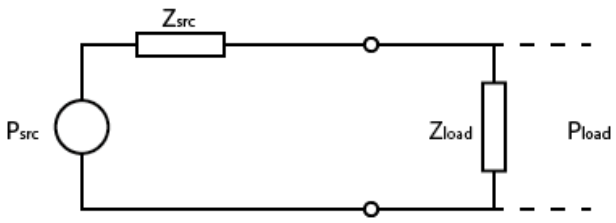


Figure 1. Acoustic Thévenin-source circuit, with the probe coupled to a dummy load.

The source pressure ($P_{src}$) and source impedance ($Z_{src}$) can be calculated by measuring the load pressure ($P_{load}$) response. The pressure response to a chirp stimulus, with frequencies up to the nyquist frequency, is measured using a insert probe. The probe is fitted into closed tubes with known impedances. The impedance of the tube ($Z_{tube}$) can be calculated from theory using *eq. 1.1*.

$$Z_{tube} = -j\frac{\rho_0 c}{A}cot(\frac{2\pi f}{c}l) \tag{1.1}$$

Where $\rho_0$ is the density of air, *c* the speed of sound, *A* the cross section area of the tube, *f* the frequency, and *l* the length of the tube (Stevens 2000). It is important that the closed tubes consists of a rigid wall from a smooth material what results in a lossless tube by approximation. The cross sectional area of the tubes is chosen to be the average of the human ear canal.

The volume velocity (*V*) of the sound wave is the ratio between the source impedance and the pressure difference following *eq. 1.2*.

$$V = \frac{P_{src} - P_{load}}{Z_{src}} \tag{1.2}$$

The source pressure can be calculated as follows.

$$P_{src} = P_{load}(\frac{Z_{src}}{Z_{load}} + 1) \tag{1.3}$$

Where $Z_{load}$ is the impedance of the tube calculated with *eq. 1.1.*

When the pressure is measured in two different loads ($Z_a$ and $Z_b$), the source parameters $P_{src}$ and $Z_{src}$ can be calculated (Rabinowitz 1981). $Z_{src}$ can be directly estimated from the measured pressure responses on the chirp stimulus mentioned before, at the entrance of the two different loads with the following equation.

$$Z_{src} = \frac{Z_a(\frac{P_a}{P_b} - 1)}{1 - \frac{Z_a P_b}{Z_b P_a}} \tag{1.4}$$

$P_{src}$ can now be calculated using *eq. 1.3* (Lynch, Peake, and Rosowski 1994).

$P_{src}$ and $Z_{src}$ are often calculated using 4 or 5 test loads, which results in an overdetermined system. To solve an overdetermined system, the least-squared method can be used. With the number of test loads as *n,* there are *n* measurements of the load pressure. When *eq. 1.3* is written in a matrix form, the equation for the *n* measurements is as follows.

$$\begin{bmatrix} P_{load,1} Z_{load,1} \\ P_{load,2} Z_{load,2} \\ \dots \\ P_{load,n} Z_{load,n} \end{bmatrix} = \begin{bmatrix} P_{load,1} & -Z_{load,1} \\ P_{load,2} & -Z_{load,2} \\ \dots & \dots \\ P_{load,n} & -Z_{load,n} \end{bmatrix} \begin{bmatrix} P_{src} \\ Z_{src} \end{bmatrix} \tag{1.5}$$

By solving *eq. 1.5* the source characteristics of the probe can be obtained.

# Ear canal acoustic parameters

With $Z_{src}$ and $P_{src}$ calculated, there are only two unknowns when the probe is fit inside the subjects ear, being impedance of the ear canal ($Z_{ec}$) and the pressure response of the ear canal ($P_{ec}$) in the Thévenin circuit (Figure 2).

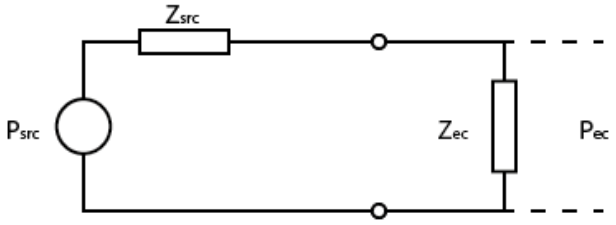


Figure 2. Acoustic Thévenin circuit, with the probe fit in to an ear canal.

By measuring $P_{ec}$, on the same wideband chirp stimulus used for calculating the source characteristics, the $Z_{ec}$ can be calculated with the following equation.

$$Z_{ec} = \frac{Z_{src} P_{ec}}{P_{src} - P_{ec}} \tag{2.1}$$

## Forward pressure level

When a stimulus is applied to the ear canal, the sound wave is reflected multiple times between the TM and the probe. The forward pressure ($P_{for}$) is the sum of all the forward going waves (from the probe) and reverse pressure ($P_{rev}$) is the sum of all the reverse going waves (towards the probe). When these two waves interact with each other, it can result in standing waves. This means that the amplitude of the total pressure measured by the probe can be amplified or canceled out. The forward pressure is not affected by the reverse pressure and can be calculated with the following equation(Souza et al. 2014).

$$P_{for} = \frac{1}{2} P_{ec}(1 + \frac{Z_0}{Z_{ec}}) \tag{3.1}$$

The pressure reflectance can be calculated from the $Z_{ec}$ *(Lynch, Peake, and Rosowski 1994; Voss and Allen 1994)* with the following equation.

$$R = \frac{Z_{ec} - Z_0}{Z_{ec} + Z_0} \tag{3.2}$$

Where $Z_0$ is the surge impedance of the ear canal and can be estimated from $Z_{ec}$ as described in (Rasetshwane and Neely 2011). $Z_{ec}$ and $R$ are both complex. This simplifies equation 3.1 to

$$P_{for} = \frac{P_{ec}}{1 + R} \tag{3.3}$$

The calculated $P_{for}$ is converted to forward pressure level in dB SPL (dB re 20 $\mu$Pa rms), as function of frequency.

## Sound intensity level

The sound intensity of the ear canal ($I_{ec}$) only includes the real part of the impedance of the ear canal, and thus does not include the reactive/imaginary part of the impedance, which stores energy. For this reason the SIL is not affected by the waves reflected by the TM. The $I_{ec}$ can be calculated as follows (Scheperle et al. 2008).

$$I_{ec} = \frac{1}{2} |P_{ec}|^2 G_{ec} \tag{4.1}$$

Where $G_{ec}$ is the load conductance of the ear canal and can be calculated as.

$$G_{ec} = \mathrm{Re}(\frac{1}{Z_{ec}}) \tag{4.2}$$

The calculated $I_{ec}$ is converted to sound intensity level in dB re 1 pW/m$^2$.

# Methods

## Subjects

*Scheperle et al. 2008*

In this experiment data was collected from 21 subjects, with an age between 14 and 49 years old. The subjects were included when they had (1) normal audiometric thresholds according to (ANSI, 1996) and (2) normal 226 Hz immittance test results before DPOAE measurements. Otoscopic examination revealed if there were contraindications to making a DPOAE. When both ears met the inclusion criteria, the ear with better behavioral thresholds and/or the easiest probe insertion was chosen.

*Souza et al. 2014*

In this experiment data was collected from 30 subject with an age between 21 and 35 years old. The subjects reported to have no hearing loss or history of middle ear surgery. Subjects who had a history of having an infection or ear-ventilation tube, were not excluded from the experiment. In this study an otoscopic examination was done on the subject to make sure there was no debris in the ear canal and that the TM was present. Each subject was screened for normal middle ear function and an intact TM on the day of testing with a standard 226 Hz probe tone tympanometry.

## Procedure

*Scheperle et al. 2008*

Measurements were obtained for two insertion depths. First the probe was inserted as deeply as possible in to the ear canal so that the pressure response showed a notch peak at the highest frequency (4-8 kHz) as possible, after applying the calibration chirp stimulus. For the second insertion, the probe was inserted approximately 2-3 mm less deep than the first insertion, and the measurements were repeated. Tape was used to prevent the probe from moving. Subjects were not excluded from the experiment when there was no notch peak found with the shallow insertion.

Pairs of primary tones ($f_1$ and $f_2$) with a fixed ratio of ($f_2/f_1=1.22$) were used to elicit DPOAEs with levels according to $L_1=0.4L_2+39$ (Kummer, Janssen, and Arnold 1998). For each calibration method and for each insertion depth the $f_2$ ranged from 1 to 8 kHz at $L_2$=20, 30, 40, 50 and 60 dB. The three in situ calibration methods were repeated before applying each stimulus.

For each individual subject, the incidental change in DPOAE levels resulting from a shallower insertion depth, were calculated before analysis of the data was done. These estimated changes should have minimized the effect of the volume change from deep to shallow insertion.

*Souza et al. 2014*

The subjects were seated in a silent room. Initially the probe was placed as deep as possible in the subjects ear, without discomfort for the subject. The deep insertion exceeded

typical placement of insert earphones used in clinical audiometry. The probe was as much as possible oriented toward the TM.

The same wideband chirp stimulus that was used in the Thévenin-source calibration was used to calibrate in situ. SYSRES, a program designed to measure system response to a wideband stimulus, was used for an acoustical estimation of insertion depth, using the half-wave resonance frequency. Leakage was checked using a low frequency pressure response. After the leakage check, a 2 minute recording of spontaneous otoacoustic emissions was done for an additional check of proper probe placement based on whether or not electrical noise was noted. When excessive noise was observed, the probe was replaced and the measurement was repeated.

Thresholds at half-octave frequencies ranging from 0.125 to 8 kHz, and additional frequencies of 10, 11.2, 12.5, 14, 15, 16, 17, 18, 19 and 20 kHz were obtained from each ear for shallow and deep insertion depths of the probe. All the threshold measurements began at 1 kHz and ascended to the highest frequency to which the subject responded. After that, the lower frequencies were tested. After the threshold measurements, the pressure response of the ear canal was measured, so that the ear canal impedance could be calculated, see section: *ear canal acoustical parameters*. Other measures were calculated after the experiment. When the deep insertion test was done, the same procedure was repeated with a shallow insertion. During this test, a good acoustical seal was confirmed using SYSRES.

# Results

*Scheperle et al. 2008*

The average DPOAE and noise levels of the three calibration methods for three different stimulus levels are plotted in Figure 5. The noise levels never exceeded the DPOAE levels, except for the $L_2$=20 dB at a frequency of $f_2$=8 kHz for SPL and FPL calibration. This means that the DPOAE measurements were reliable, especially for higher values of $L_2$. For all the stimulus levels and calibration methods, a lower DPOAE level is present for the shallow insertion relative to the deep insertion. This decrease in DPOAE level is expected because of the inverse relationship between volume and pressure. For SPL calibration, the difference in DPOAE level is relatively equal for frequencies up to 5 kHz, for the three different stimulus levels. For frequencies above 5 kHz, where standing waves occur more frequently, the difference between the DPOAE levels is higher. The mean difference between shallow and deep insertion for the FPL and SIL calibration is relatively equal over the full range of frequencies, except for the SIL calibration with a stimulus level of 20 dB and 40 dB, where the difference is about 5 dB at 5 kHz and almost 0 dB at 8 kHz.

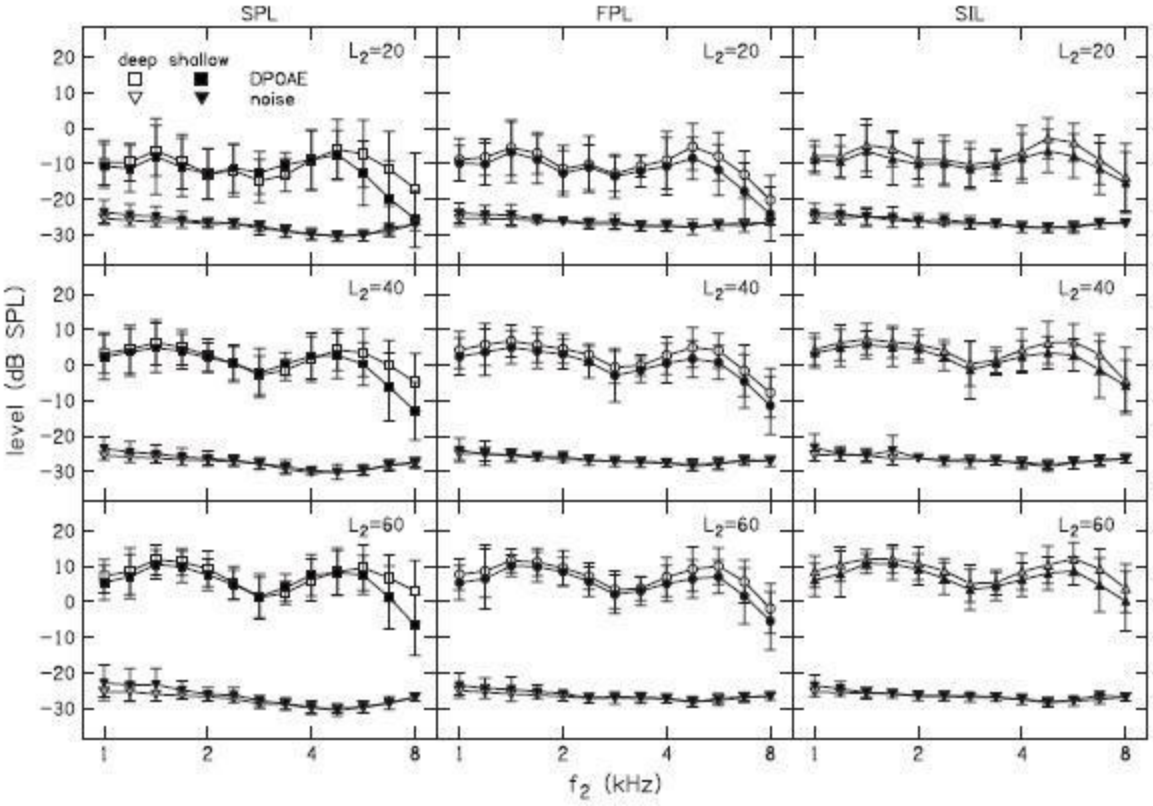


Figure 5. DP-grams for three calibration methods (SPL, FPL and SIL) with the means and standard deviations of the subjects. Plotted are the DPOAE and noise levels for three different stimulus levels (20, 40 and 60 dB). The upper two lines in each diagram show the DPOAE levels and the two lower lines in each diagram show the noise levels(Scheperle et al. 2008).

The main objective of this study was to determine the difference in DPOAE levels for deep and shallow insertion for three different calibration methods, these mean absolute differences are displayed in Figure 4. These differences are corrected for each subject with

the expected change in emission levels due to changes in probe depth insertion, this was part of the study design. The SPL calibration method shows a larger difference in DPOAE levels than the other two calibration methods for a stimulus level of 20 dB. For a stimulus level of 40 dB, the emission levels are relatively equal for all the three calibration methods for frequencies just under 2 kHz, and SPL shows a larger difference than the other two calibration methods for frequencies above 2 kHz. With a stimulus level of 60 dB, the emission levels are relatively equal for frequencies up to 2.5 kHz, and show a larger difference for frequencies above 2.5 kHz for SPL calibration. Only at 5 kHz the emission levels of all the calibration methods is equal. The FPL and SIL calibration method show an equal level difference for all the three stimulus levels, except for three differences in emission level change. The first can be found in the 20 dB stimulus level at 6 kHz where the FPL shows a larger difference than SIL. The second can be found in the frequency range of 2 to 3.5 kHz with a stimulus level of 60 dB, where the change in emission level is slightly larger for FPL than for SIL. The last difference can be found at 8 kHz for all the three stimulus levels, where the SIL has a larger difference in emission level than FPL.

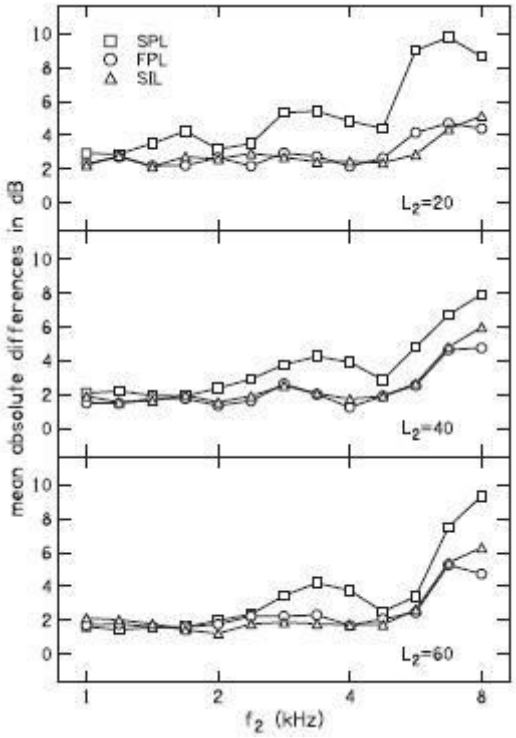


Figure 4. DP-grams of the mean absolute difference in DPOAE levels induced by insertion depth after correction for the expected change in emission level for each individual. The differences for three calibration methods are shown in this figure for three stimulus levels (20, 40 and 60 dB)(Scheperle et al. 2008).

The mean difference and standard deviation for each stimulus level and calibration method are shown in Table 1. The measured differences in DPOAE levels are averaged across frequencies. The table shows that for all stimulus levels, the change in emission levels was larger for SPL calibration relative to both FPL and SIL calibration, which suggests that the SPL calibration is less reliable than the other two calibration methods. This also applies to the standard deviation. When comparing FPL and SIL calibration, SIL shows a smaller difference in mean emission levels than FPL for the first two stimulus levels. For the other three stimulus levels, FPL shows a smaller change in emission level. The standard

deviation of the SIL is bigger than for FPL for all stimulus levels, except for a stimulus level of 20 dB.

*Table 1. Means and standard deviations of the absolute difference in DPOAE levels between insertion depths for the three calibration methods (SPL, FPL and SIL), after correction of expected difference. The first five rows are averaged across frequency for each calibration method and the last row is averaged across all stimulus levels (Scheperle et al. 2008).*

| | 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 |

*Souza et al. 2014*

The pressure responses to a stimulus and behavioral thresholds from one subject are shown in Figure 5. In Figure 5.a it can be seen that the shallower insertion depth has a lower response relative to the deeper insertion for frequencies lower than approximately 4 kHz, for the SPL calibrated stimulus. The shallower insertion has a resonant peak with a lower frequency than the deep insertion (approximately 4 kHz and 6 kHz respectively), this is caused by standing waves, which occur on a lower frequency when the distance between the probe and the TM is longer. In Figure 5.b, it can be seen that the level difference in behavioral threshold correlates with the level difference in stimulus response. In Figure 5.c, it can be seen that the calculated forward pressure response shows a lower pressure level up to approximately 5 kHz. For both the pressure measured at the probe and the forward pressure, this lower pressure response can be explained by the inverse relationship between pressure and volume. The same drift of resonant peak that occured for the SPL calibrated stimulus was observed for the FPL calibrated stimulus, hower, the pressure nulls indicated with the arrows in Figure 5.a are not present in the FPL measured threshold. For FPL, the level difference for the behavioral threshold does not correlate with the difference in calculated forward pressure, see Figure 5.d. A threshold difference of 0 dB indicates no difference in the behavioral threshold. The thresholds are measured relative to the calibrated stimulus.

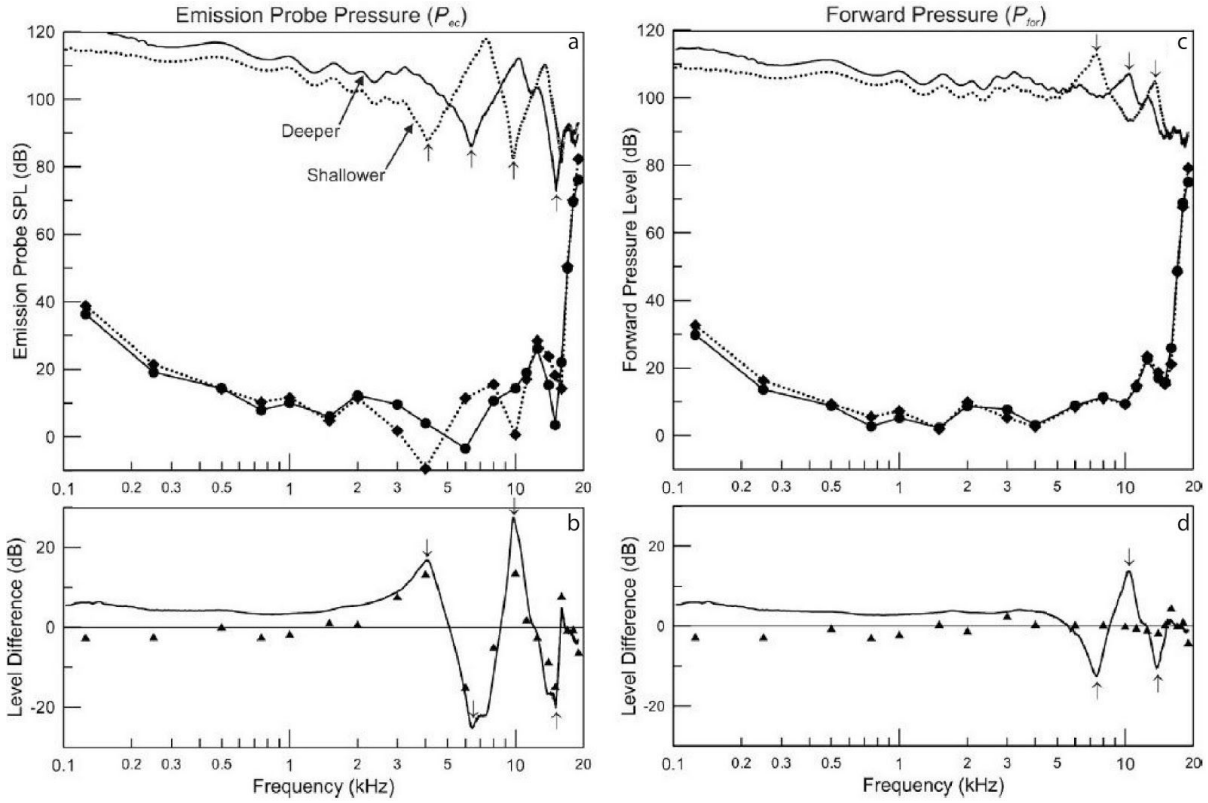


Figure 5. Example of measurements from one subject. The left column recasts the same sets of thresholds and their changes when referenced to the pressure measured by the emission probe ($P_{ec}$). (a) The measured Pec is depicted for the deeper and shallower insertions (solid and dashed lines, respectively) along with the thresholds. (b) The change in thresholds referenced to Pec is plotted as filled triangles and the change in $P_{ec}$ is plotted as the solid curve. The right-hand column recasts the thresholds by referencing them to $P_{for}$. (c) $P_{for}$ at the two insertion depths shows the change in the frequency of half-wave resonance from 10 kHz to 7.3 kHz that is also seen in $P_{ec}$ [panel (a)], but the pressure nulls at the quarter-wave frequencies in $P_{ec}$ are not present in $P_{for}$. (f) Thresholds referenced to $P_{for}$ are resistant to changes in insertion depth, despite changes in pressure at the half-wave frequencies that exceed 10 dB [arrows in (c) and (d)]. Thus, the input level to the ear is controlled well by the change in $P_{for}$ plotted in the solid curve (Souza et al. 2014).

Figure 6 shows the mean threshold difference and its deviation between deep and shallow insertion of the emission probe. Figure 4.a shows the threshold difference with a SPL calibrated stimulus. Figure 4.a shows that the threshold difference is close to zero for frequencies up to 1 kHz. From 2 kHz up to 20 kHz, the threshold for SPL calibrated stimuli shows a threshold level difference of approximately -4 dB to 8 dB with a standard deviation of 4 to 10 dB. This indicates a large variability in the threshold measurement, which is not favorable in these kind of measurements. The FPL calibrated stimulus, seen in Figure 4.b, shows a threshold difference of almost zero across the whole frequency range. The standard deviation of the threshold difference for the FPL calibrated stimulus is about 2 dB for frequencies up to 10 kHz and 4 dB for frequencies above the 10 kHz.

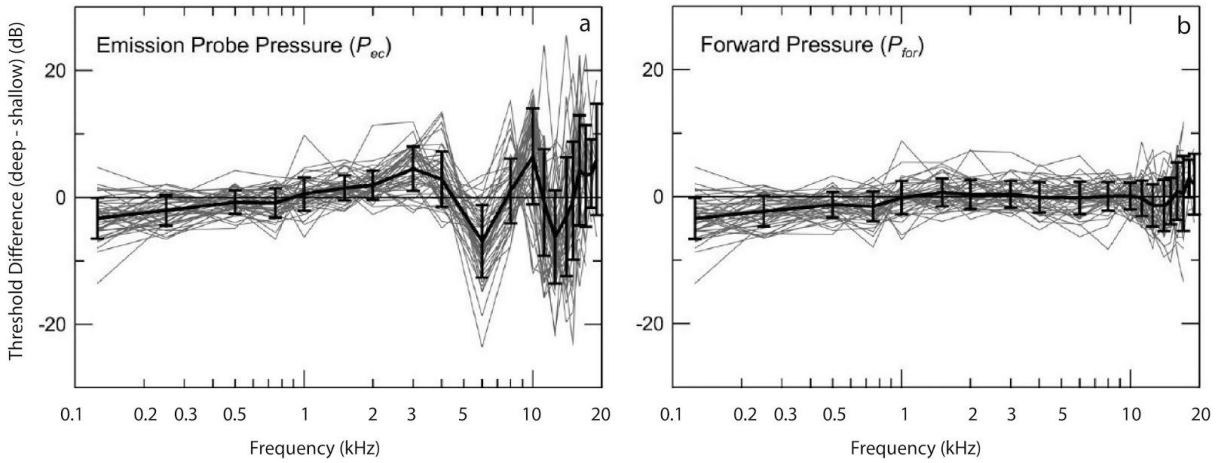


Figure 6. (a) Threshold difference between deep and shallow insertion depth referenced to $P_{ec}$. (b) Threshold difference between deep and shallow insertion depth referenced to $P_{for}$ *(Souza et al. 2014)*.

# Discussion and conclusion

The results of both studies confirm the previous findings (Stinson 1985; Siegel 1994; Neely and Gorga 1998) that SPL calibration of a stimulus results in a difference of measured pressure response with probe, induced by standing waves.

*Scheperle et al. 2008*

After applying the correction for incidental change following the change in volume, DPOAE levels still showed a large difference between deep and shallow insertions of ≥ 2 dB for all of the three calibration methods. (Mills et al. 2007) showed that DPOAE levels varied 1 to 2 dB when repeated measurements with the same setup were done. These variations were referred as intrinsic variability. This might explain the change in DPOAE levels for the SPL calibration up to 2 kHz and for the FPL and SIL calibrations up to 4 kHz, but they exceeded this value for higher frequencies. For the SPL calibration this can be explained by the standing wave problem, which occur above 2 kHz, but the FPL and SIL calibration should not be affected by standing waves. What causes this variability in DPOAE difference is till unknown.

Although the FPL and SIL calibration still show a DPOAE difference for frequencies above 4 kHz that exceed the intrinsic variability of DPOAE, these two calibration methods show better and more reliable results, when insertion depth is changed, over SPL calibration. In clinical use, the insertion depth of the probe in the patient can vary for different reasons. It depends on the experience of the clinician, the physical properties of the patient's ear and the its comfort. For this reason, FPL and SIL calibration might be more reliable for measuring DPOAE in the clinic.

From this study, FPL and SIL calibration showed similar results in DPOAE change induced by insertion depth. So for DPOAE measurements, both FPL and SIL calibration are favorable methods to use over SPL calibration. However, power measurements (such as SIL) are less closely related to behavioral thresholds than pressure, this was demonstrated by (Puria, Peake, and Rosowski 1997; Sivian and White 1933). While DPOAE levels are not directly related to behavioral thresholds, they are compared during clinical evaluations. Using FPL instead of SIL might be advantageous because it uses the same reference as

SPL (20 $\mu$Pa). This is favourable because several studies showed the relationship between SPL and behavioral thresholds across frequency (Puria, Peake, and Rosowski 1997; Sivian and White 1933; Robinson and Dadson 1957; Killion 1978). However the relationship between SIL and behavioral thresholds is not very well known. For these reasons, FPL calibration is favored over SIL calibration.

Souza et al. 2014

Behavioral threshold measurements referenced to the pressure measured directly by the probe showed large variability in the measurements when insertion depth was varied. This indicates that using SPL calibrated stimulus is not reliable for measuring behavioral thresholds. FPL calibrated stimulus showed less influence of insertion depth, on measuring behavioral thresholds.

According to (Green, Kidd, and Stevens 1987; Stelmachowicz et al. 1989) the intrinsic variability of behavioral thresholds is between 1.5 dB and 2.1 dB. The variability of the SPL calibrated stimulus exceeded these intrinsic variability for frequencies above 2 kHz. The variability of the FPL calibrated stimulus did not exceed the intrinsic variability, this is another reason for using FPL over SPL.

Combining the results from both studies, shows that using forward pressure, instead of pressure measured at the probe, results in more reliable measurements for both DPOAE levels and behavioral thresholds. This is especially the case for frequencies over 5 kHz.

This method of measuring forward pressure could also be favourable for experiments where suppression tuning curves are used to suppress SOAE, such as in (Manley and van Dijk 2016). In this study, a measure of cochlear frequency selectivity is studied by suppressing SOAE using a suppressor tone which has a frequency close to the SOAE frequency. This experiment was done using the pressure measured at the probe with SOAE frequencies mostly up to 5 kHz, with a few frequencies above 5 kHz. When the frequency selectivity of the cochlea is studied for frequencies higher than 5 kHz, forward pressure used to measure SOAE and calibration of a stimulus, is preferable over using pressure measured at the probe.

In the study from (Souza et al. 2014), a power measure like SIL is not used to measure behavioral thresholds. The study of (Scheperle et al. 2008), showed that SIL calibrated stimuli resulted in comparable DPOAE levels to FPL calibrated stimuli. (Scheperle et al. 2008; Oswald and Janssen 2003) showed a high correlation between DPOAE I/O functions, which can be derived from DPOAE levels, and behavioral thresholds. This means that there might be a close relationship between DPOAE levels and behavioral thresholds. For this reason, it might be useful to do more research on the relationship between SIL calibrated stimuli and behavioral thresholds, in order to use SIL in the future for experiments or in the clinic.

In experiments where only frequencies under 2 kHz are tested, it might be preferable to use pressure measured at the probe instead of forward pressure or sound intensity. This has two reasons, one being that the variability in measurements using pressure measured at the probe is not higher than the intrinsic variability, and the other reason being that an additional calibration (Thévenin-source calibration) is needed prior to the measurement.

# Conclusion

With this literature study, it is shown that forward pressure calibrated stimuli results in more reliable measurement for both DPOAE levels and behavioral thresholds over stimuli calibrated with pressure measured at the probe. This applies especially when a frequency range over 5 kHz is tested. For both experimental and clinical use, forward pressure measures are favorable over pressure measured at the probe. Before it can be used in the clinic, much more research needs to be done.

Even though the sound intensity calibration shows comparable results as forward pressure calibration, more research need to be done on this calibration method.

# References


Allen, J. B. 1986. “Measurement of Eardrum Acoustic Impedance.” In *Lecture Notes in Biomathematics*, 44–51.

ANSI 1996. “Specifications for audiometers,” ANSI Report No. S3.6-1996, *American National Standards Institute, New York.*

Dreisbach, Laura E., and Jonathan H. Siegel. 2001. “Distortion-Product Otoacoustic Emissions Measured at High Frequencies in Humans.” *The Journal of the Acoustical Society of America* 110 (5): 2456–69.

Green, David M., Gerald Kidd, and Kenneth N. Stevens. 1987. “High-frequency Audiometric Assessment of a Young Adult Population.” *The Journal of the Acoustical Society of America* 81 (2): 485–94.

Harris, F. P., B. L. Lonsbury-Martin, B. B. Stagner, A. C. Coats, and G. K. Martin. 1989. “Acoustic Distortion Products in Humans: Systematic Changes in Amplitude as a Function of f2/f1 Ratio.” *The Journal of the Acoustical Society of America* 85 (1): 220–29.

Killion, M. C. 1978. “Revised Estimate of Minimum Audible Pressure: Where Is the ‘Missing 6 dB’?” *The Journal of the Acoustical Society of America* 63 (5): 1501–8.

Kummer, P., T. Janssen, and W. Arnold. 1998. “The Level and Growth Behavior of the 2 f1-f2 Distortion Product Otoacoustic Emission and Its Relationship to Auditory Sensitivity in Normal Hearing and Cochlear Hearing Loss.” *The Journal of the Acoustical Society of America* 103 (6): 3431–44.

Lynch, T. J., 3rd, W. T. Peake, and J. J. Rosowski. 1994. “Measurements of the Acoustic Input Impedance of Cat Ears: 10 Hz to 20 kHz.” *The Journal of the Acoustical Society of America* 96 (4): 2184–2209.

Manley, Geoffrey A., and Pim van Dijk. 2016. “Frequency Selectivity of the Human Cochlea: Suppression Tuning of Spontaneous Otoacoustic Emissions.” *Hearing Research* 336: 53–62.

Mills, David M., M. Patrick Feeney, Eli J. Drake, Richard C. Folsom, Lianne Sheppard, and Noah S. Seixas. 2007. “Developing Standards for Distortion Product Otoacoustic Emission Measurements.” *The Journal of the Acoustical Society of America* 122 (4): 2203–14.

Neely, S. T., and M. P. Gorga. 1998. “Comparison between Intensity and Pressure as Measures of Sound Level in the Ear Canal.” *The Journal of the Acoustical Society of America* 104 (5): 2925–34.

Oswald, Johann A., and Thomas Janssen. 2003. “Weighted DPOAE Input/Output-Functions: A Tool for Automatic Assessment of Hearing Loss in Clinical Application.” *Zeitschrift Fur Medizinische Physik* 13 (2): 93–98.

Probst, Rudolf, Brenda L. Lonsbury-Martin, and Glen K. Martin. 1991. “A Review of Otoacoustic Emissions.” *The Journal of the Acoustical Society of America* 89 (5): 2027–67.

Puria, S., W. T. Peake, and J. J. Rosowski. 1997. “Sound-Pressure Measurements in the Cochlear Vestibule of Human-Cadaver Ears.” *The Journal of the Acoustical Society of America* 101 (5 Pt 1): 2754–70.

Rabinowitz, W. M. 1981. “Measurement of the Acoustic Input Immittance of the Human Ear.” *The Journal of the Acoustical Society of America* 70 (4): 1025–35.

Rasetshwane, Daniel M., and Stephen T. Neely. 2011. “Inverse Solution of Ear-Canal Area Function from Reflectance.” *The Journal of the Acoustical Society of America* 130 (6): 3873–81.

Robinson, D. W., and R. S. Dadson. 1957. “Threshold of Hearing and Equal-Loudness Relations for Pure Tones, and the Loudness Function.” *The Journal of the Acoustical Society of America* 29 (12): 1284–88.

Scheperle, Rachel A., Stephen T. Neely, Judy G. Kopun, and Michael P. Gorga. 2008. “Influence of in Situ, Sound-Level Calibration on Distortion-Product Otoacoustic Emission Variability.” *The Journal of the Acoustical Society of America* 124 (1): 288–300.

Siegel, J. H. 1994. “Ear-canal Standing Waves and High-frequency Sound Calibration Using Otoacoustic Emission Probes.” *The Journal of the Acoustical Society of America* 95 (5): 2589–97.

Siegel, J. H., and E. T. Hirohata. 1994. “Sound Calibration and Distortion Product Otoacoustic Emissions at High Frequencies.” *Hearing Research* 80 (2): 146–52.

Sivian, L. J., and S. D. White. 1933. “On Minimum Audible Sound Fields.” *The Journal of the Acoustical Society of America* 4 (3): 176–77.

Souza, Natalie N., Sumitrajit Dhar, Stephen T. Neely, and Jonathan H. Siegel. 2014. “Comparison of Nine Methods to Estimate Ear-Canal Stimulus Levels.” *The Journal of the Acoustical Society of America* 136 (4): 1768–87.

Stelmachowicz, P. G., K. A. Beauchaine, A. Kalberer, W. J. Kelly, and W. Jesteadt. 1989. “High-Frequency Audiometry: Test Reliability and Procedural Considerations.” *The Journal of the Acoustical Society of America* 85 (2): 879–87.

Stevens, Kenneth N. 2000. *Acoustic Phonetics*. MIT Press.

Stinson, M. R. 1985. “The Spatial Distribution of Sound Pressure within Scaled Replicas of the Human Ear Canal.” *The Journal of the Acoustical Society of America* 78 (5): 1596–1602.

Voss, S. E., and J. B. Allen. 1994. “Measurement of Acoustic Impedance and Reflectance in the Human Ear Canal.” *The Journal of the Acoustical Society of America* 95 (1): 372–84.