Thevenin-equivalent hearing aid calibration for verification of high-frequency gain

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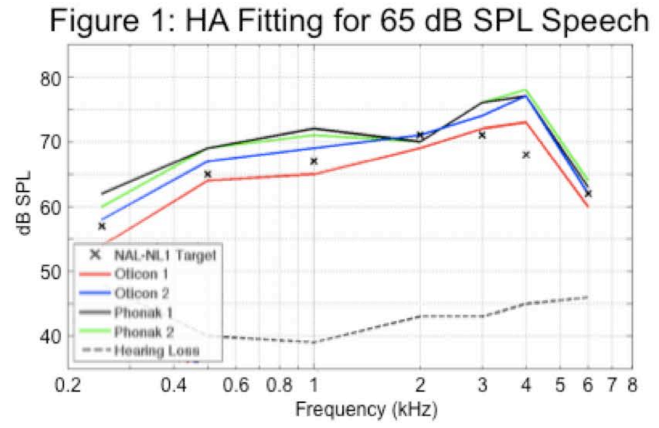
INTRODUCTION

Verification of hearing aid (HA) gain above 4 kHz is problematic when using traditional probe microphone measurements due to standing wave pressure nulls in the ear canal[1]. Ear canal pressure expressed in terms of forward pressure level (FPL) has been found to be insensitive to standings wave pressure nulls[2,3,4]. FPL measurements have been applied to in-situ calibration of otoacoustic emission primary levels[2] and behavioral pure-tone thresholds[3,4,5]. The purpose of the current study was to extend the use of FPL to HA fittings. The following questions were investigated: 1) Can a Thevenin-equivalent source calibration be applied to hearing aids to accurately derive in-situ FPL? 2) How well does a generic Thevenin calibration generalize across earmold types and HA models? The first question relates to accuracy while the second relates to clinical feasibility of implementation.

METHODS

Figure 1: HA Fitting for 65 dB SPL Speech

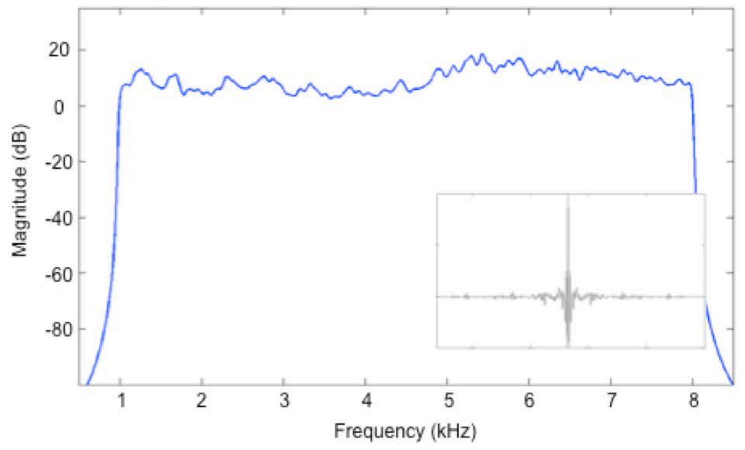


Subjects. Eight subjects participated in the study. All subjects had custom earmolds.

Hearing Aids. Four HAs (2 Phonak Exelia Art, 2 Oticon Epoq XW, bandwidths > 5 kHz) were programmed for a mild sensorineural hearing loss. NAL-NL1 amplification targets were approximated (**Fig. 1**) within 5 dB through 3 kHz and above 4 kHz. Targets were estimated within 10 dB at 4 kHz. Advanced processing features were disabled.

Calibration Procedure. Thevenin-equivalent source characteristics for an Oticon HA coupled to the subject's earmold were obtained using 5 brass cavities of varying lengths and known impedances (Z_0)[6,7]. Clicks (1 - 8 kHz bandwidth, 81 dB pSPL, **Fig. 2**) were presented in the free-field 1m from the HA. Cavity pressure was measured 4 mm past the earmold using an ER-7C probe microphone. Calibrations for each of the 4 HAs were also obtained using a Comply™ Canal Tip instead of the subject's earmold. These "generic" calibrations were performed once at the beginning of the study.

Figure 2: Thevenin Calibration Stimulus



In-Situ Measurements. Measurements were obtained for various pairings of HA and Thevenin source characteristics (**Table 1**). Measurements consisted of a click train to obtain load pressure (P_{load}) and impedance (Z_{load}) followed by a chirp train (1 - 7.6 kHz, 70 dB SPL rms, P_{chirp}). Pressure was measured 4 mm beyond the subject's earmold (ER-7C). FPL was derived as:

$$corrections_{forward} = \frac{1}{2}\left(1 + \frac{Z_0}{Z_{load}}\right),$$

$$FPL = 20\log10\left(\frac{\left|P_{chirp} \cdot corrections_{forward}\right|}{0.00002}\right).$$

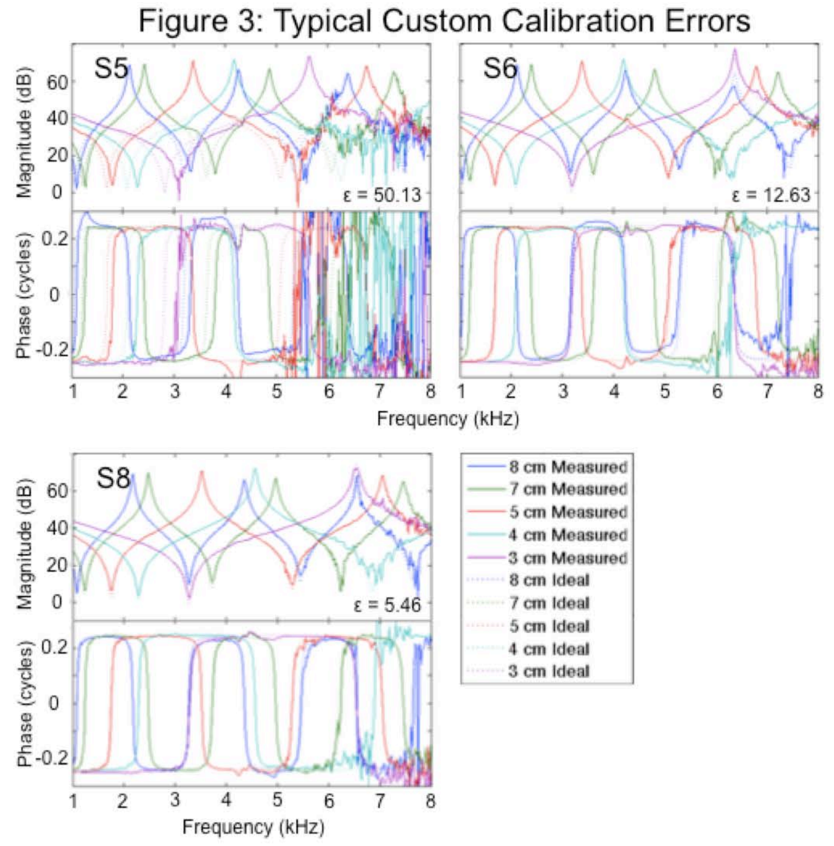
Table 1: HA Calibration Conditions

	Calibration Configuration				
Measurement Configuration	Oticon 1 (Comply)	Oticon 2 (Comply)	Phonak 1 (Comply)	Phonak 2 (Comply)	Oticon 1 (Custom EM)
Oticon 1 (Custom EM)					
Oticon 2 (Custom EM)					
Phonak 1 (Custom EM)					
Phonak 2 (Custom EM)					

Note: Only data from the "green" conditions were included in this poster.

RESULTS

Figure 3: Typical Custom Calibration Errors



Custom FPL. **Figure 4** shows in-situ pressure, dB SPL (black) and FPL (red), for all subjects. The difference between SPL and FPL is shown by the blue line. As expected SPL tracings demonstrated a standing-wave pressure null around 5 - 7 kHz that was not evident in associated FPL tracings. The relationship between SPL and FPL at frequencies away from the standing-wave null is dependent on the pressure reflectance (ratio of reflected pressure to forward pressure) of the measurement cavity (ear canal and middle ear) and described by:

$$FPL = SPL - 20\log10\left(1 + \frac{P_{reflected}}{P_{forward}}\right).$$

Accordingly, the difference between SPL and FPL at these frequencies should never exceed 6 dB. Using this criteria it is obvious that derived FPL for several subjects (S3, S6) is not entirely accurate away from the standing-wave null. Surprisingly, FPL for S5 appears relatively accurate despite a poor calibration while S6 is rather inaccurate despite the low-error calibration (see figure 3). Inaccuracies may be due to mismatch between characteristic impedance of the ear canal and the calibration cavities[8].

Figure 5 shows the mean data using 1/3 octave band analysis (error bars indicate ± 2 standard deviations). It is evident that standing-wave nulls are a concern even for broader analysis bands.

CUSTOM CALIBRATION RESULTS

Custom Source Calibrations. **Figure 3** shows the calculated load impedances for the test cavities from 3 subjects' calibrations compared to the ideal values. These subjects' results were typical of all subjects. Subjects 6 and 8 showed good agreement between calculated and ideal impedance through 5 kHz. Above 5 kHz agreement declined likely due to limited gain and thus a poor signal-to-noise ratio (SNR). Subject 5 had the poorest calibration of all subjects. The earmold associated with this calibration was relatively large and did not couple well to the cavities which may have contributed to the error. The calibration error (deviation from ideal) is provided on each plot. Excluding S5, errors ranged from 1.06 - 12.13.

Figure 4: FPL Derived from Custom Calibration

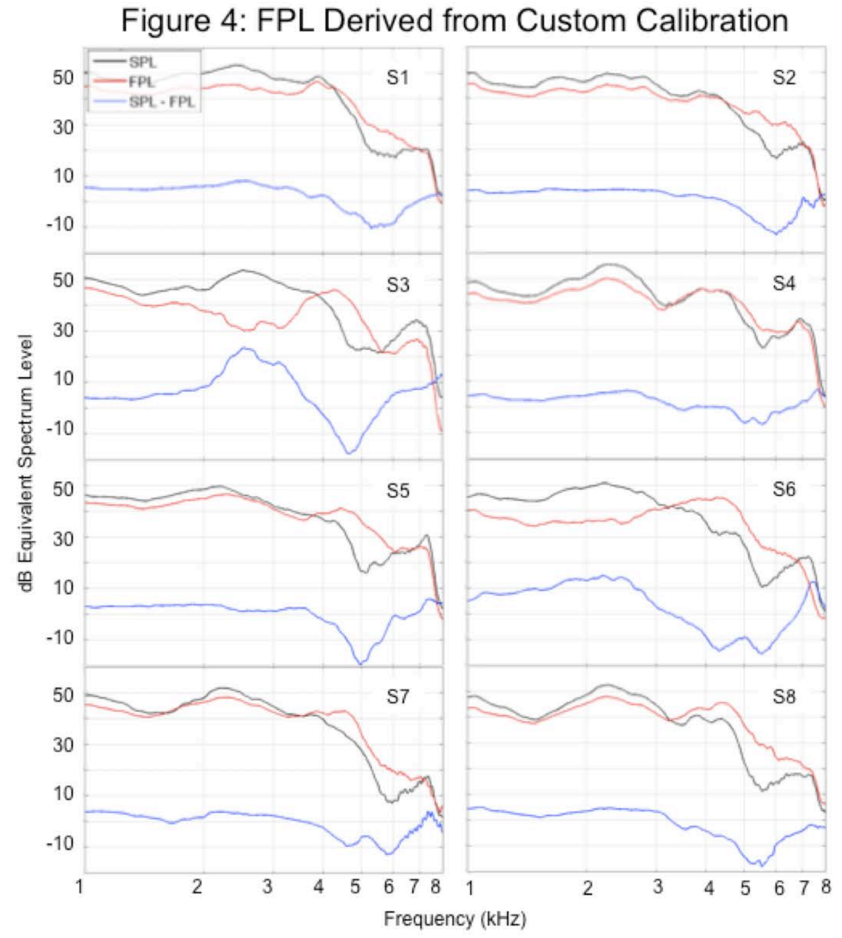


Figure 5: Mean 1/3 Octave Band Analysis

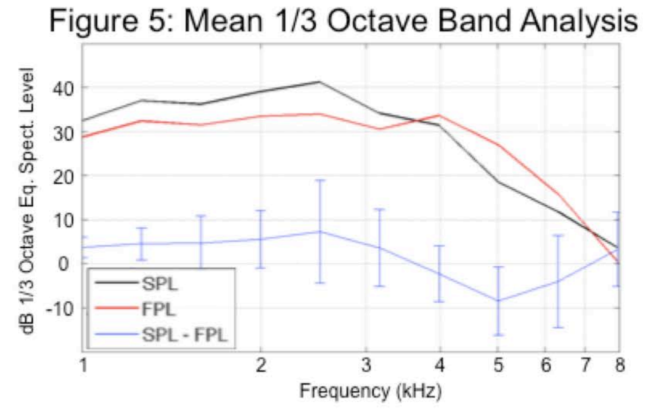
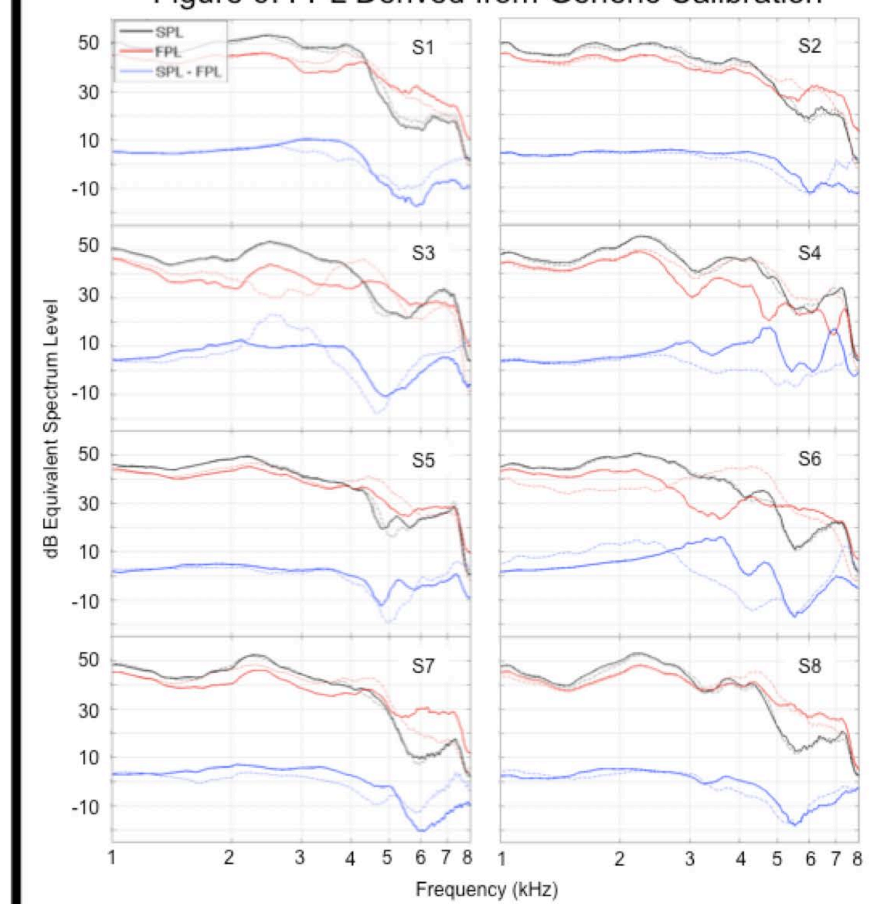


Figure 6: FPL Derived from Generic Calibration



Thevenin Source Characteristics. **Figure 7** compares source impedance (left panel) and pressure (right panel) for the generic (black) and custom (red) calibrations (dashed lines indicate 25th and 75th percentiles). The differences between generic and custom source characteristics are likely contributors to the differences in generic and custom FPL.

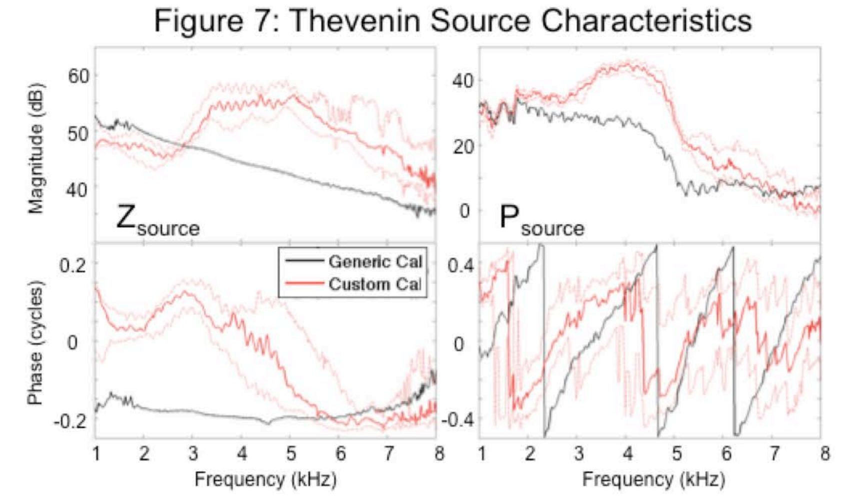
A surprising observation from figure 7 is the similarity between source characteristics across earmolds, especially for source pressure magnitude. It is probable that generic FPL would have been more accurate if a "model" earmold had been used as opposed to a Comply™ tip for calibrations.

GENERIC CALIBRATION RESULTS

Generic Source Calibrations. HA calibrations obtained using the Comply™ tips were similar in quality to those for S6 and S8 although errors were lower and never exceeded 3.5.

Generic FPL. **Figure 6** shows in-situ dB SPL (black solid) and FPL (red solid) for all subjects using the same generic calibration (Oticon 1 - comply). SPL and FPL using each subjects' custom calibration is also shown for comparative purposes (dashed lines). Generic FPL remains relatively insensitive to standing-wave nulls compared to SPL; however, generic FPL and custom FPL differ for all subjects when SPL is controlled (blue solid and dashed lines). Custom FPL should be considered the gold-standard when assessing the accuracy of the generic FPL since the source characteristics of the earmold and tubing are included in the calibration. These are approximated in the generic calibration by the Comply™ tip.

Figure 7: Thevenin Source Characteristics



Note: Generic source characteristics are from 1 Oticon HA (the same used in figure 6. Both Oticon aids had nearly identical source characteristics and the same was true for both Phonak aids.

CONCLUSIONS

Hearing aid source characteristics were determined using a Thevenin-equivalent calibration procedure. In-situ forward pressure level (FPL) was measured and found to be insensitive to standing-wave pressure nulls. Sound pressure level exhibited expected standing–wave effects even when analyzed over 1/3 octave bands. FPL offers a solution to the verification of high-frequency hearing aid gain.

The accuracy of FPL was greater for custom calibrations that included the subjects' earmold compared to generic calibrations using a Comply™ tip. Use of a "model" earmold may enable generic calibrations to be used in a clinical setting so that a calibration for each subject is not necessary. The observation that HA source characteristics were very similar within HA models further justifies the possibility of a generic calibration.

ABSTRACT

Ear-canal standing-wave pressure minima confound accurate estimates of eardrum pressure from more lateral locations. Hearing-aid (HA) real-ear verification is thus limited in its ability to ensure adequate high-frequency gain for the HA user. This study investigates the feasibility of utilizing a Thevenin-equivalent source calibration to isolate the forward-travelling pressure waves generated by HAs. HA source characteristics were calculated for two earmold conditions: 1) using subject's custom earmold and 2) using a Comply™ canal tip. Standing-wave pressure nulls were evident for in-situ sound-pressure level (SPL) but not for FPL responses. FPL was more accurately derived using the subject's custom earmold source characteristics compared to those for the Comply™ tip. Significant differences in the source characteristics derived using the custom and Comply™ earmolds were evident; however, characteristics were similar across all custom earmolds. Different HAs of the same model had similar source characteristics. The use of FPL as part of the HA verification process provides a means of ensuring adequate gain above 4 kHz. Results suggest the use of a generic earmold (but not a Comply™ tip) may allow for a single source calibration to be used for a given HA model.

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