Assessing FPL calibration: Extended high frequencies and various cavity sizes.

Rachel A. Scheperle[1], James D. Lewis[1], Stephen T. Neely[2], Shawn S. Goodman[1]

1. Department of Communication Sciences and Disorders, The University of Iowa, Iowa City, Iowa 52242
2. Boys Town National Research Hospital, 555 N. 30th St., Omaha, NE 68131

INTRODUCTION

There is a growing need for accurate in-situ sound level measurements across the extended high-frequency range of human hearing, specifically for hearing aid verification[1] and otoacoustic emission (OAE) testing[2-5]. Forward pressure level (FPL) has been proposed as a preferred reference for in-situ calibration due to theoretical avoidance of standing-wave errors and practical advantages over placing a microphone near the tympanic membrane[6]. To date, the benefits of using in-situ calibrations based on incident pressure calculations include decreased test/retest variability of OAE measurements and behavioral thresholds, decreased evidence of standing-wave notches in behavioral thresholds, and slight improvements in OAE test performance[1,6-9]. While present evidence suggests that FPL is more accurate than sound pressure level (SPL) for in-situ calibrations, FPL has only been validated through 8 kHz in a single cavity[8]. The purpose of this study was to further investigate the accuracy of the FPL calculation through 18 kHz in brass tubes with lengths and diameters chosen to span a range similar to human ear canal sizes[10-11]. The effects of commercially available probe tips (Etymōtic Research: ER10-14, ER10D, and modified ER10D with tube extensions) on the calculation of Thévenin-equivalent source characteristics and FPL were also examined.

METHODS

Source Calibration: Thévenin-equivalent source impedances and pressures from 0.25 – 18 kHz were obtained for ER-2 loudspeakers coupled to an ER-10B+ probe assembly[12-13]. Loudspeaker tubing (standard length, 25.7 cm) was cut to 2.7 cm to increase high-frequency output. A modified version of the ER10D tip was created by cutting 2.5 mm from the back, allowing the loudspeaker tubes to protrude. A separate source calibration was performed for each type of probe tip.

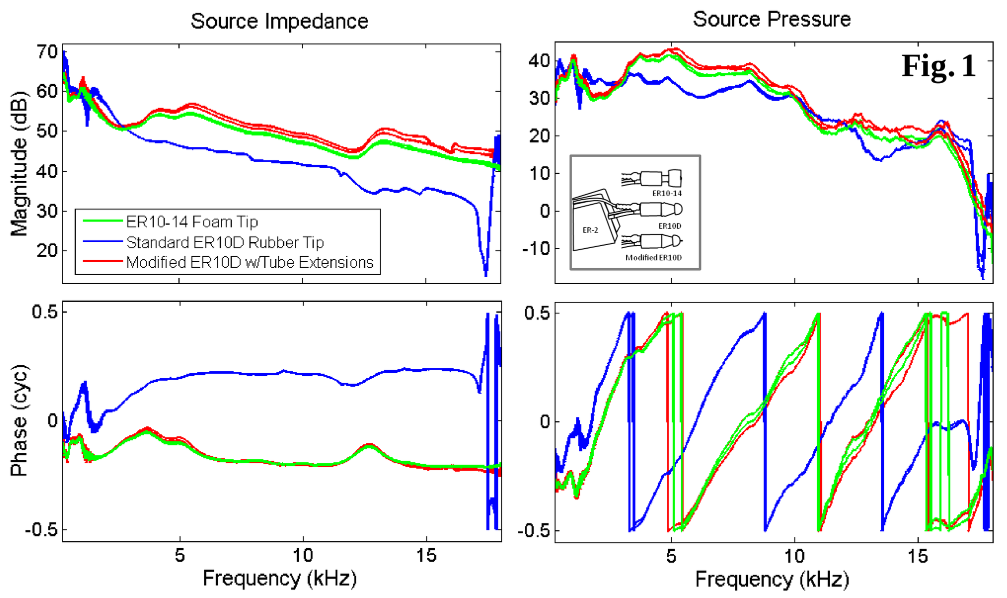


Fig. 1: Inset: Schematic of probe tips. Panels: Source characteristics as a function of frequency. Similar characteristics were observed using the ER10-14 (green) and modified ER10D (red) tips, with length-iteration errors typically below 0.1. It was more difficult to obtain acceptable source calibrations with the standard ER10D tip (blue), and errors were never below 1.0.

Load Calibration: Load impedance was calculated for brass tubes of various sizes using the ER-10B+ probe assembly at the cavity entrance. Each tube was terminated with a flat plate. An ER7-14C probe tube (used for validation recordings) was inserted into an opening (1.9 mm diameter) in the center of the plate. Load impedance was used to convert the load pressure into FPL.

Validation: The FPL of each tube calculated during the load calibration was inverted and converted into an impulse response. Five hundred FPL-shaped "clicks" were presented via the ER-10B+ probe assembly, and simultaneous responses of the ER-10B+ (entrance) and ER-7C (terminal end) microphones were obtained. An error term was calculated by comparing the dB SPL at the terminal end of the cavity with the dB FPL calculated from measurements at the entrance. Assuming unity pressure reflectance for each tube, it was expected that FPL would be 6 dB lower than SPL at the terminal end.

$$\text{Error} = FPL_{ER\text{-}10B+} - (SPL_{ER\text{-}7C} - 6\text{ dB}) \qquad \textbf{Eq. 1}$$

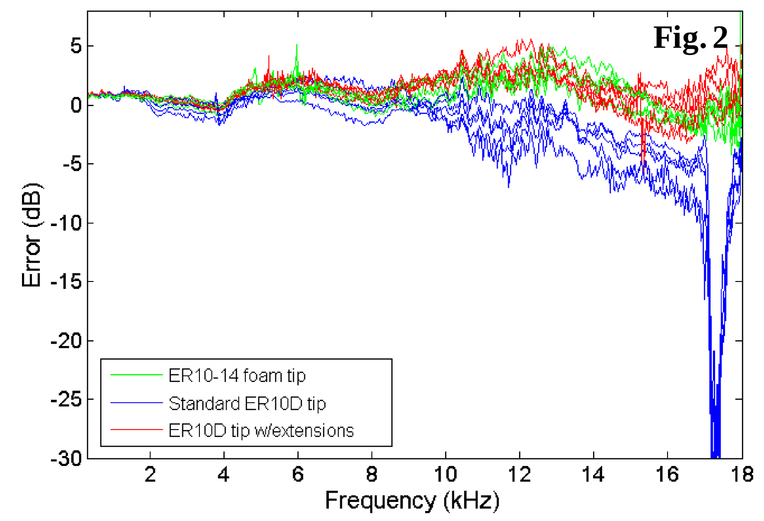
Estimating Characteristic Impedance: An initial set of measurements revealed larger errors than expected for the FPL calibration procedure (see **Fig. 3**). We hypothesized that the systematic error patterns were related to the value used to estimate characteristic impedance based on the relationship

$$Z_0 = \rho c / A \qquad \textbf{Eq. 2}$$

where Z_0 is characteristic impedance, ρ is the density of air, c is the speed of sound, and A is cross-sectional area of the cavity. Accurate in-situ FPL calibration is dependent upon an appropriate estimate of characteristic impedance. Our initial estimate was defined according to the source calibration cavities, which had diameters of 8.0 mm ($Z_{0,cal}$ = 81.55 acoustic ohms), based on the rationale that 8 mm is similar to average ear canal diameter. Rasetshwane and Neely (AAS poster, 2011), describe a method of estimating characteristic impedance ($\hat{Z}_0$) from load impedance by minimizing the corresponding time-domain reflectance (TDR) at t=0. We repeated the FPL calculations using this estimate. Additionally, we repeated FPL calculations using the appropriate ideal characteristic impedance values for each diameter ($Z_{0,d}$) determined from **Eq. 2**.

RESULTS

Fig. 2: Comparison of FPL calibration errors according to tip type for tubes with lengths and diameters ranging from 17.8 – 22.7 mm and 6.4 – 9.6 mm, respectively. Characteristic impedance was defined as $Z_{0,d}$. Error magnitude increased with frequency regardless of tip type. Errors were the largest for the standard ER10D tip, specifically above 8 kHz. Errors did not exceed 5 dB when using the modified ER10D and ER10-14 tips. The modified ER10D tips were used for subsequent measurements.



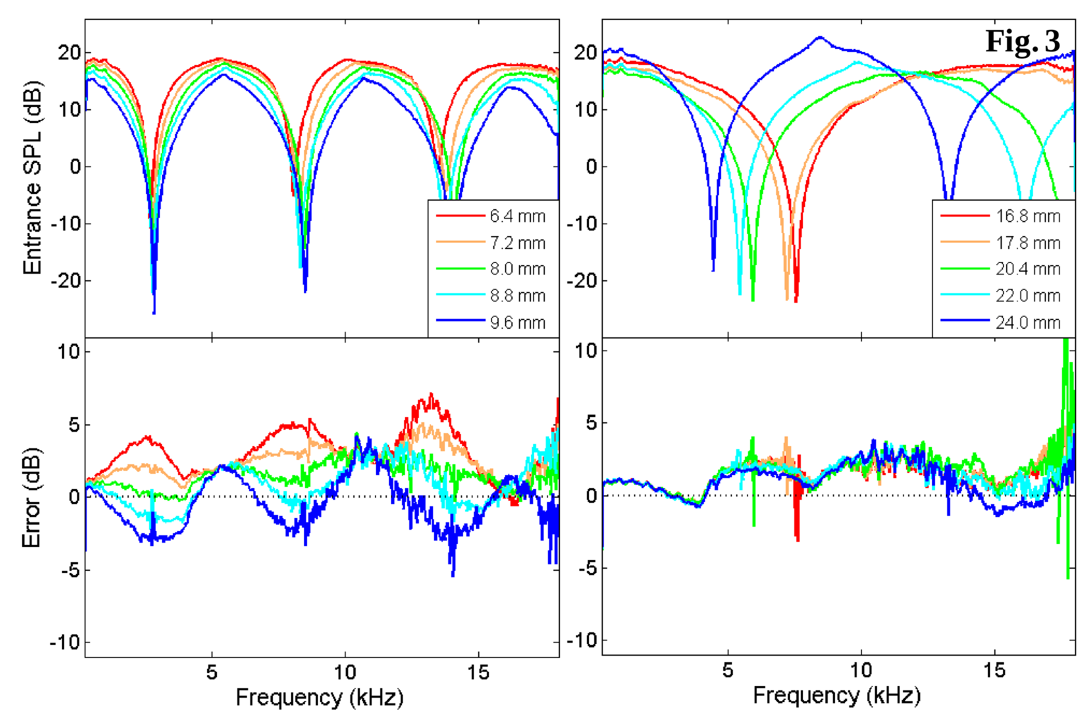


Fig 3. FPL calibration errors across various tubes using $Z_{0,cal}$. Left panel: Tube length = 30 mm. Diameter was varied (see legend). Right panel: Tube diameter = 8.0 mm. Length was varied (see legend). Notice that the y-scaling is different between top and bottom panels. FPL calibration errors systematically increased at null frequencies as tube diameters deviated from 8.0 mm. Errors did not systematically change as a function of tube length.

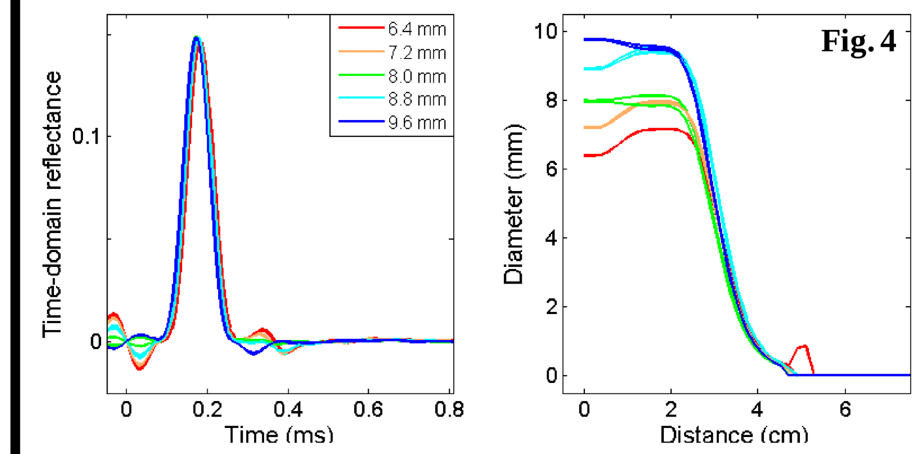
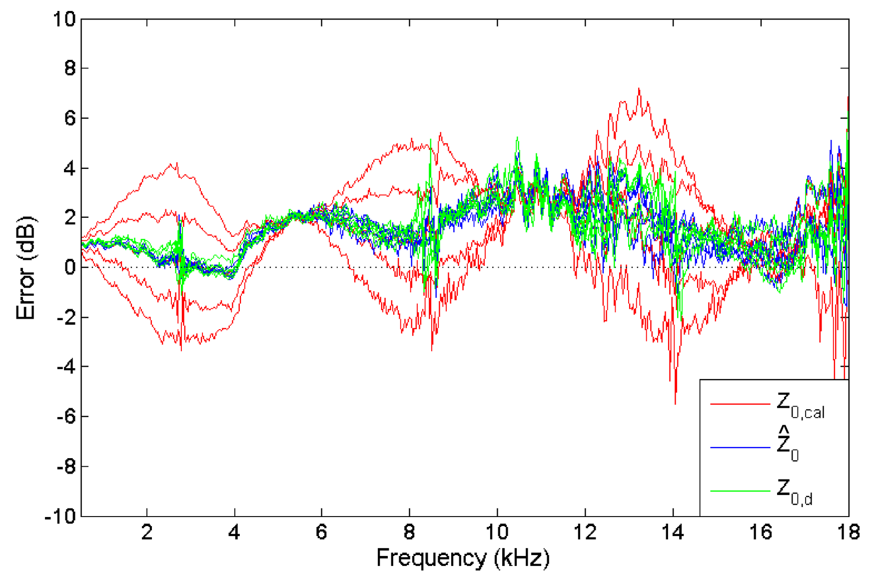


Fig 4: Time-domain reflectance (left panel) for five uniform tubes of varying diameters and inverse-solution diameter (right panel) as functions of distance from the entrance of the tube[14]. Tube lengths were 3.0 cm. The constancy of reflectance peaks across widely varying diameters and the similarity of inverse-solution diameters (at x=0) to actual diameters (see legend) support using $\hat{Z}_0$ as an estimate of $Z_{0,d}$.

Fig 5: Comparison of FPL calibration errors using different values for characteristic impedance ($Z_{0,cal}$, $\hat{Z}_0$, and $Z_{0,d}$). Five in-situ calibrations were performed for each characteristic impedance condition using uniform tubes with diameters 6.4 – 9.6 mm. When $Z_{0,cal}$ was used, errors increased as tube diameters deviated from that of the source calibration cavity, exceeding 6 dB. When cavity-specific characteristic impedance was used, errors did not systematically increase with cavity diameter and were generally below 2 dB through 8 kHz and below 4 dB through 18 kHz. This is true for both the ideal calculation $Z_{0,d}$ and the estimate $\hat{Z}_0$.



SUMMARY AND CONCLUSIONS

- **Although FPL errors increase with frequency, FPL calibration appears valid through 18 kHz with the ER10-14 and modified ER10D tips.**
- **Standard ER10D tips appear adequate for source and FPL calibrations across frequencies ≤ 8 kHz.**
- **Estimating characteristic impedance from load impedance ($\hat{Z}_0$) resulted in lower FPL errors than found when using the characteristic impedance from the source calibration cavity ($Z_{0,cal}$).**
- **Estimating characteristic impedance from load impedance resulted in FPL error magnitudes similar to those obtained using ideal $Z_{0,d}$.**

FPL calibration errors obtained when using $Z_{0,cal}$ were ≤ 6 dB. Given that SPL calibration errors can approach 20 dB at null frequencies[2, 15, 16], it is not surprising that previous studies have shown benefits of FPL in-situ calibration over SPL[1,6-9]. However, it may be that the benefits of in-situ FPL calibration have been underestimated. The results presented here are encouraging because they suggest that (1) FPL errors are reduced by using accurate estimates of characteristic impedance and (2) accurate estimates of characteristic impedance are obtainable from measurements of load impedance, which are also available in human ears when calculating FPL. In other words, reducing FPL errors in human ears does not require ear-canal diameter to be known because characteristic impedance can be accurately estimated from ear-canal load impedance. It remains to be seen whether improving the estimate of characteristic impedance will improve FPL calibration in human ears.

ABSTRACT

The accuracy of FPL calibration was examined through 18 kHz in brass tubes of various lengths and diameters. Calibration errors were determined by comparing terminal SPL with FPL calculated from measurements at the cavity entrance. Three types of probe tips were used to couple the loudspeaker/microphone assembly to the tube entrance. Preliminary results suggested that using the diameter of the source calibration cavity to estimate characteristic impedance of the test cavity was insufficient for tubes with larger and smaller diameters; therefore, a new method of estimating characteristic impedance from load impedance was examined[14]. The FPL calculated using (1) source cavity and (2) load impedance based estimates were compared to the FPL calculated using (3) ideal characteristic impedance for each tube. Estimating characteristic impedance from load impedance reduced FPL errors to the same degree as seen when ideal characteristic impedance was used. While errors tend to increase with frequency, FPL calibration appears valid through 18 kHz for two of the three probe tips.

CONTACTS

rachel-scheperle@uiowa.edu

james-lewis@uiowa.edu

Stephen.Neely@boystown.org

shawn-goodman@uiowa.edu

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