

INTRODUCTION

Equivalent input noise (EIN), as specified in ANSI S3.22¹, is used by industry and clinics to evaluate internal noise levels of hearing aids (HAs). Questions regarding the validity and usefulness of the EIN measurement are raised by the following:

- 1) The use of EIN presupposes that the noise measured at the HA receiver is the internal noise multiplied by the gain, an assumption that may not be true.
- 2) The EIN was not intended to be predictive of the noise's audibility.
- 3) Measurements made in our lab show that the EIN is somewhat variable (Fig 1).

Accordingly, the purposes of this study were

- To assess the validity of the EIN noise assumption.
- To develop a method of measuring internal noise that
 - is insensitive to location of internal noise
 - is predictive of the noise audibility
 - measures noise during speech processing
 - measures noise with adaptive features enabled

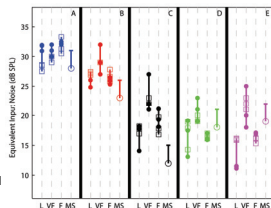


Figure 1. Variability in clinical EIN measurements. The EIN for two HAs (filled circles, open squares) of models A–E was measured using 3 different measurement systems (L, VF, F). Measurements were repeated 3 times, and obtained values were compared to manufacturer specifications (MS, open circle, error bar = +3 dB). Results showed higher than expected variability across repeated measures and across measurement systems. All HAs exceeded the ANSI tolerance of +3 dB for at least one measure.

METHODS

Figure 2. Top-end BTE HAs were obtained from six main manufacturers. HAs were programmed for a high-frequency sloping hearing loss using the manufacturer's software and "first fit" settings. Two conditions, Features Enabled and Features Disabled, were tested. "Features" here refers to feedback reduction, digital noise reduction, and directional mic scheme.

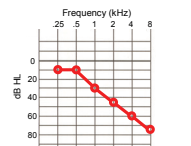


Figure 3. Stimulus waveform. A 5-second segment of the new International Speech Test Signal (ISTS) was presented through a loudspeaker positioned at 0° azimuth, 1 m from KEMAR. HA output was recorded for a no-input condition and for stimulus intensity levels of 20–80 dB SPL. For each test condition, the ISTS stimulus was presented repeatedly until 16 independent recordings of the HA output were stored.

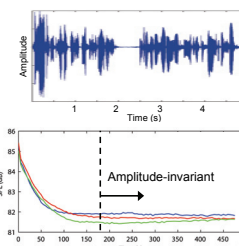
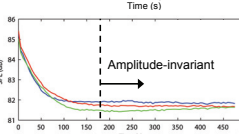


Figure 4. HA Settling Time. Prior to collecting 16 recordings, the HAs were engaged for 3 minutes using repeated presentations of the ISTS stimulus. This was done to allow the HAs time to "settle" to a consistent output amplitude. The HAs displayed a wide range of settling times, with the longest of these shown to the right. Each tracing shows HA output SPL assessed at 5-second intervals. The measurement sequence was repeated 3 times to check reliability.



NOISE CALCULATION

Discrete Fourier transforms were computed on each of the 16.5-second recordings (eq. 1). In eq. 1, x_k is the waveform in the k -th recording, and $X_k[m]$ is the DFT of the k -th recording and the m -th frequency bin. In the frequency domain, the mean signal was computed as the (coherent) average complex spectrum (eq. 2).

$$X_k[m] = \sum_{n=0}^{N-1} x_k[n] e^{-j2\pi mn/N} \quad (1)$$

$$\bar{X}[m] = \frac{1}{K} \sum_{k=1}^K X_k[m] \quad (2)$$

Noise was defined as any part of the measured waveform which was not repeatable (i.e. did not phase lock to the stimulus). By this definition, the energy of the hearing aid internal noise is the variance of the measurements (eq. 3). The variance was summed across 1/3 octave bands² and converted into dB SPL.

$$S^2[m] = \frac{1}{K-1} \sum_{k=1}^K (X_k[m] - \bar{X}[m])(X_k[m] - \bar{X}[m])^* \quad (3)$$

ASSUMPTIONS

- 1) HA output is time-locked to the input.
- 2) HA output amplitude is invariant for a given input.
- 3) Noise is random, stationary, and normally distributed.

If these assumptions are met, the variance will accurately describe the internal noise of the HA.

RESULTS

VARIANCE MEASURES OF INTERNAL NOISE

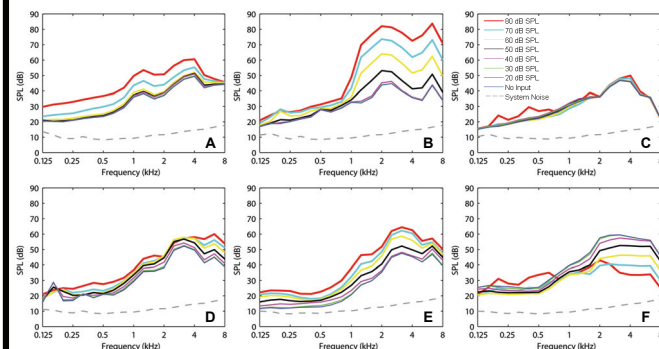
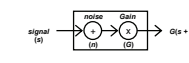
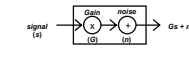


Figure 5. Measured variance as a function of stimulus level (Features Enabled condition). Three distinct patterns were seen. The different patterns suggest different models to explain the measurements of HA internal noise.

MODEL 1: Noise added to the signal prior to amplification. HA internal noise is constant; variance decreases as the stimulus level increases and gain decreases. This is the EIN assumption. Only HA F was consistent with this model.



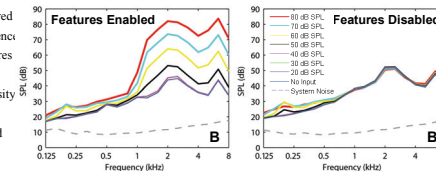
MODEL 2: Noise added after signal amplified. HA internal noise constant; variance constant across all stimulus intensity levels. HA C was consistent with this model.



OTHER MODELS: Noise Models 1 and 2 did not adequately describe the variance observed in HAs A, B, D, & E. The variance increased as stimulus level increased and gain decreased. This may be modeled using a variable noise source located prior to and/or after amplification. More study is needed to understand the underlying noise sources.

THE EFFECT OF HA FEATURES ON VARIANCE

Figure 6. Effect of features on measured variance. Only HA B showed a difference in variance between the adaptive features enabled and disabled conditions. The variance increased with stimulus intensity with features enabled but remained constant as stimulus intensity increased with features disabled.



Listening checks of HA B suggested that the high variance measured with features enabled was not audible to listeners. The high variance appears to have been the result of slow amplitude fluctuations across repeated presentations of the stimulus. In other words, with features enabled, HA B does not process the stimulus the same way every time, leading to high variability. This variability occurred across 5-second stimulus presentations, putting the fluctuations on the order of less than 1 Hz. The overestimation of the audible internal noise in HA B is due to a violation of the assumption that HA output is invariant for a given input.

Whether or not features were enabled did not affect the variance in the remaining 5 HAs. This suggests that, for the majority of HAs, adaptive features are not a significant source of internal noise. However, it should be noted that although the features were enabled, they were not necessarily activated by the test setup used in this study. Further studies should examine conditions in which the features are active.

LOUDNESS OF HA INTERNAL NOISE

ESTIMATION OF LOUDNESS: The HA internal noise will be audible to the user if the 1/3 octave band level exceeds the corresponding pure-tone threshold³ (circled areas in Fig. 7). For each HA, 1/3-octave band level loudness indexes (I) of audible frequency bands were obtained using ANSI S3.4-1980⁴. Total Loudness (S) was calculated according to (eq. 4), where I_m is the maximum of the indexes and $F = 0.15$. Total loudness was converted to calculated loudness in phons (eq. 5). HA were rank ordered from softest to loudest based on calculated loudness.

$$S_i = I_m + F(\sum I - I_m) \quad (4)$$

$$P = 40 + 33.219 \log_{10} S_i \quad (5)$$

SUBJECTIVE JUDGEMENT: The output from each HA in the absence of an input was recorded and filtered to simulate the high-frequency hearing loss used in this study (see Fig. 2). Normal-hearing pilot subjects were asked to make paired loudness comparisons between filtered HA noise samples (30 comparisons repeated three times each).

PREDICTED AUDIBILITY OF HA INTERNAL NOISE

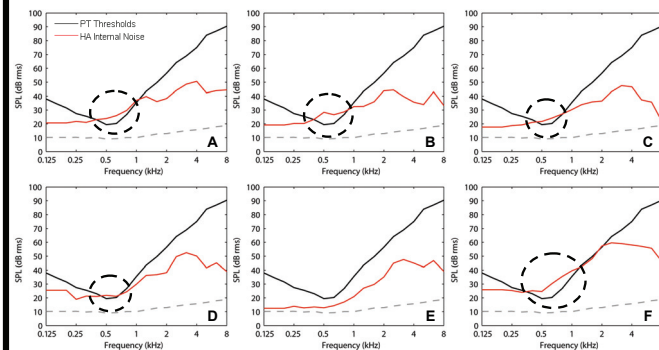
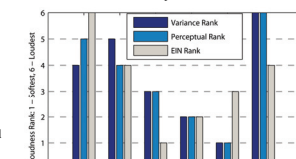


Figure 7. Predicted audibility of HA internal noise. The circled areas correspond to the frequency bands where the 1/3 octave band level of the noise exceeds the pure tone audiometric threshold. Noise in these bands is predicted to be audible.

RELATIVE LOUDNESS RANKING COMPARISON

Figure 8. Predicted and subjective relative loudness rankings. The predicted rankings of HA noise loudness (dark blue) were in close agreement with the subjective rankings of HA noise loudness (light blue). These rankings did not agree with a ranking of the manufacturers' reported EIN values, suggesting that the EIN should not be used to quantify the relative loudness of HAs' internal noise.



CONCLUSIONS

Variance measurements suggested that noise measured at the HA receiver is not simply the internal noise multiplied by the gain. This is contrary to the assumption made when using EIN, raising questions about its clinical and industrial utility.

Internal noise was quantified using the variance obtained by synchronous averaging. This procedure

- Measures internal noise regardless of noise location/source. Several different patterns were seen, indicative of noise acting at different locations.
- Predicts relative loudness of the internal noise. Perceptual rankings agreed with predictions based on the variance. This method has potential for predicting audibility and relative loudness of a HAs internal noise.
- Measures internal noise concurrent with HA processing while adaptive features are enabled.

ACKNOWLEDGEMENTS

Presentation of this work was supported by the Mentored Doctoral Student Research Poster Session Grant awarded by the National Institute of Health and the American Auditory Society.

CONTACT

james-lewis@uiowa.edu
shawn-goodman@uiowa.edu

This poster is available in pdf form on the Auditory Research Lab website:
<http://wendell.shc.uiowa.edu/wjshc/research/ar1/publications.html>

REFERENCES

1. American National Standards Institute. (2004). *American National Standards Specification of Hearing Aid Characteristics* (ANSI S3.22-2004). New York: American National Standards Institute.
2. American National Standards Institute. (2004). *American National Standards Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters* (ANSI S1.11-2004). New York: American National Standards Institute.
3. McKenzie, AR and Rice, CG. "Self-noise problems in hearing aids." *British Journal of Audiology* 21.1 (1987): 31-5.
4. American National Standards Institute. (1980). *American National Standards Procedure for the Computation of Loudness of Noise* (ANSI S3.4-1980). New York: American National Standards Institute.

ABSTRACT

Equivalent input noise (EIN), as specified in ANSI S3.22, is used by industry and clinics to evaluate internal noise levels of hearing aids (HAs). The use of EIN presupposes that the noise measured at the HA receiver is the internal noise multiplied by the gain, an assumption that we dispute. Using a synchronous measurement paradigm, we calculated the variance of HA output across repeated presentations of the new ISTS (speech) noise. Hearing aids from six manufacturers were programmed for a high-frequency hearing loss. Output was measured in response to no input and stimulus levels from 20 to 80 dB rms. Most of the HA responses indicated that 1) measured noise does not increase linearly with gain, and 2) the measured noise levels are likely to be audible to the listener (with the given audiogram) in quiet. The noise levels of the HAs were rank-ordered by predicted loudness measures and by perceptual rankings. Perceptual ranking was accomplished by filtering the output of the HAs to simulate the high-frequency loss and then having normal-hearing listeners make paired comparisons. Predicted loudness based on variance measures matched perceptual rankings. In contrast, EIN values were not accurate in describing the internal noise, nor were they predictive of listener's perception of noise.