Using In-Situ Thresholds to Predict Aided Soundfield Thresholds

In a previous article, Kuk & Ludvigsen1 provided a justification and qualification for the use of the aided thresholds to verify the performance of nonlinear hearing aids. Briefly, for nonlinear hearing aids, the aided threshold allows one to predict the softest sound that a wearer may hear with the hearing aid. Such an index requires careful interpretation, and its value cannot be predicted from real-ear measures.

Despite the apparent usefulness of aided thresholds as a measure of audibility in nonlinear hearing aids, several authors2-4 reported significant variability on aided thresholds (and functional gain) obtained with linear hearing aids. Indeed, these studies suggest test-retest standard deviations of the aided threshold (and functional gain) ranging from 3 dB-10 dB.

Factors that may affect reliability include ambient room noise and circuit noise of the hearing aids, standing waves in the test suite, head and body movement of the test subjects, and artifacts from precipitous hearing loss.5 Interactions from the time constants used in nonlinear hearing aids with the timing of the stimulus presentation6 and loudspeaker placement may also add variability to this index.

Although measurement variability is an inevitable part of any clinical procedure, including real-ear measurements (eg, probe placement, loudspeaker placement, subject position etc.), it is nonetheless worthwhile to seek valid measures that can minimize variability. Indeed, it may be even desirable if the aided threshold can be predicted with minimal patient involvement. Such a task is possible today because of the application of digital signal processing in hearing aid design.

In-Situ Threshold Measurement

One of the many advantages of using digital signal processing techniques in today’s hearing aids is that the aids can be designed to generate acoustic signals. These acoustic signals have been useful in the calibration of the feedback cancellation systems7 and as stimuli to screen component defects (eg, microphones, receivers, amplifiers, etc) in digital hearing aids.8 Self-generated signals are also used in in-situ threshold measurement for accurate threshold determination9 and prediction of the aided threshold.

In-situ threshold measurement is the determination of the patients’ hearing loss using their own hearing aids as the transducers for delivering the test signals. As part of the evaluation and fitting process, the hearing-impaired person wears the actual hearing aids (or earmolds coupled to the hearing aids), listens to the acoustic stimuli that are generated from within the aids (ie, bypassing the microphone), and is instructed to respond in the same manner to the test stimuli as in routine audiometric threshold determination. The level of the stimuli is calibrated in an ear simulator (IEC-711) that has acoustic properties approximating the individual free-field to microphone (FF2Mic) transfer function.

Once the threshold is determined, one can specify output levels (and input-output curve characteristics) on the hearing aid relative to the threshold. Any appropriate target/prescription with suitable allowance made for the properties of the hearing aid may be used (eg, number of channels, time constants, hearing aid styles, etc).10 Using this approach, the aided threshold is determined as the lowest input level when the output of the hearing aid (input level + gain) exceeds the in-situ (or “unaided real-ear”) threshold of the wearer. The process can be simplified even further if one expresses the input-output relationship at the eardrum using the dB HL notation. (For more information, readers are referred to Kuk & Ludvigsen11 for a description of the steps necessary for this transformation.)

A numeric example may help clarify the description. Let’s assume that a wearer’s in-situ (or “unaided real-ear”) threshold is 60 dB HL at 1000 Hz. This means that the person may not hear the 1000 Hz tone unless the input to the hearing aid, when added to the gain on the hearing aid, yields a real-ear output that exceeds 60 dB HL. If one assumes that this hearing aid is linear and that it provides 40 dB of insertion gain, the 1000 Hz tone will be audible once it exceeds 20 dB HL (ie, 60 dB HL–40 dB gain = 20 dB HL).

Because the in-situ threshold is obtained with the hearing aid inserted in the ear canal without any amplification, it should be taken as the “unaided in-situ threshold.” Similarly, the aided threshold that is predicted from the in-situ threshold should be taken as the “aided in-situ threshold.” This aided in-situ threshold is similar but not identical to the conventional aided soundfield threshold. To change the aided in-situ threshold to the conventional aided soundfield threshold, one needs to use the individual free-field to microphone (FF2Mic) transfer function.

Group FF2Mic transforms12 for different hearing aid styles have been used for inclusion in the prescribed I/O curves to provide an unbiased estimate of the aided soundfield threshold. Although the use of average FF2Mic would not account for individual variations in FF2Mic values, its use is warranted since the range of individual variation in FF2Mic correction is less than 10 dB across frequencies in a CIC hearing aid.13 This corresponds to an inter-individual standard deviation of 2 dB-3 dB. This magnitude of variability is acceptable given that the variability in threshold measurement is of similar mag-

This article was submitted to HR by Francis K. Kuk, PhD, director of audiology at Widex Research Office in Lisle, Ill; Carl Ludvigsen, MS, manager of audiological research, Marianne Sonne, MA, research audiologist, and Trine Voss, research assistant, at Widex A/S in Vaerloese, Denmark.
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Predicting Aided Threshold

One of the design principles behind the Senso hearing aids (Senso+ and Diva) is that its fitting is designed to be simple and yet accurate. To achieve this objective, the unaided in-situ thresholds of the patient are first measured using a procedure called the “sensogram.” This procedure minimizes many of the variabilities inherent in threshold measurements. Accurate “real-ear” thresholds ensure an accurate specification of “real-ear” sensation level. Furthermore, the input-output characteristics of the hearing aids are referenced at the eardrum and reported in the dB HL notation for ease of understanding. Average FF2Mic transfer functions for adults were included. These steps improve the accuracy of the aided threshold prediction and make the prediction process straightforward.

It is recognized that some variability from the “unaided real-ear” or in-situ threshold may still exist. However, considering that this unaided in-situ threshold is measured with the hearing aids in the wearers’ ears, variability due to head and body movements, standing waves, sound leakage from the earphones, etc, will be minimized. Because no additional variability is introduced in the gain assignment, the accuracy of the predicted aided threshold is bounded by the accuracy of the unaided in-situ threshold only. For that reason, the predicted aided threshold should be as accurate (or even more accurate) than the measured aided threshold.

The ability to predict the aided soundfield threshold improves the accuracy of the measure and saves valuable clinical time. These benefits were the two major objections that have been levied against the aided threshold as a verification tool.

Validity of Predicting The Aided Threshold

An example of prediction: Figure 1 is an example of the Input-Output (I-O) curve shown in Compass, the fitting software for all Widex hearing aids. In this example, we’ll assume that this I-O curve is appropriate for someone with an unaided in-situ threshold of 60 dB HL measured at 1000 Hz. If one draws a horizontal line across the Y-axis where the in-situ output is 60 dB HL, one would recognize that output level above the 60 dB HL line would be audible, while that below the 60 dB HL line would be inaudible. Furthermore, the input level (in dB HL) at which the I-O curve intersects with the in-situ threshold is the lowest input level at which the output from the hearing aid exceeds audibility (ie, where threshold is reached). In other words, the input level at the intersection is the predicted aided threshold. In this case, the predicted aided threshold is 20 dB HL.

A preliminary validation study: In order to determine the validity of the prediction, we measured the soundfield aided thresholds of 10 trained subjects who had worn binaural Senso Diva hearing aids for at least 1 month and compared them to the predicted aided thresholds from the I/O curve. Eight of these subjects wore ITEs or ITCs, while 2 wore BTEs. The average age of the subjects was 57.1 years with a SD of 13.4 years. The audiogram showing the range and mean thresholds is included in Figure 2.

The sensogram (ie, unaided in-situ thresholds) and a feedback test were first determined with the hearing aid. The hearing aid was set to an omnidirectional microphone mode during aided threshold measurement. Subjects sat 1 meter directly in front of a loudspeaker in a sound-treated room and their monaural (right ear) aided soundfield thresholds were determined using warble tones at 300 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. The non-test ear was occluded with a foam plug. An ascending approach was used, and subjects were instructed to refrain from any head or body movement during threshold determination.

Subjects’ monaural soundfield aided thresholds at the 4 frequencies were compared to their soundfield aided thresholds predicted from the I-O curve in Compass. Figure 3 shows the individual deviation between the measured and the predicted aided soundfield thresholds across frequencies. Each symbol represents a different subject. Data points that are above the “0” line would suggest that the measured aided thresholds are higher than the predicted thresholds, whereas data points...
below “0” would suggest the opposite (ie, measured aided thresholds are lower than predicted). The dotted line around “0” is the mean deviation across frequencies, and the two solid lines represent the 25th and 75th percentile.

Most of the subjects showed less than 5 dB deviations between the measured and the predicted aided soundfield thresholds. This is especially true for frequencies at 1000 Hz and 2000 Hz. At 500 Hz, the mean measured aided threshold is about 3-4 dB higher than the predicted threshold. At 4000 Hz, the average measured aided threshold is about 4 dB lower than the predicted aided threshold. On the other hand, two subjects showed deviation as much as 15 dB at some frequencies. Taken together, these observations suggest that, on average, the aided soundfield threshold can be predicted with fair reliability (±5 dB) from the I-O curve used in the Compass software.

**Conclusion**

The aided threshold provides important information about the wearer’s performance with any nonlinear hearing aid (ie, audibility of softest sound). Such information cannot be predicted from real-ear measures. Concerns against its use as a verification tool (namely, time and reliability) may be eased by the ability to reliably predict the aided threshold. The use of in-situ threshold measurement (with suitable data transformation), an advantage of the application of DSP in hearing aids, makes this possible.

**References**