Individual fit-testing of earplugs: A review of uses

Theresa Y. Schulz

Sperian Hearing Protection, LLC 7828 Waterville Road, San Diego, CA 92154, USA

Abstract

Individual fit-testing of earplugs is an exciting new trend in hearing conservation. This article reviews how this technology is being used to protect noise-exposed workers. Earplug fit-testing systems are becoming more commercially available and more feasible for field use. Individual fit-testing is no longer used only for research investigations but is being incorporated in Hearing Conservation Programs (HCP) to improve training, document protection and evaluate the effectiveness of the hearing protector element of an effective HCP.

Keywords: *Attenuation, earplugs, fit-test, hearing protection, protected exposure*

Introduction

The purpose of a hearing protector is, of course, to protect hearing. Hearing protectors do this by blocking or attenuating the sound as it enters the ear. But, how much attenuation (noise reduction) does a given hearing protector provide for each individual who uses it?

The US Environmental Protection Agency (EPA)-mandated label for hearing protectors is the implementation of the requirement, stated in Section 8 (Labeling) of the Noise Control Act of 1972 (42 U.S.C. 4907). "These rules require manufacturers of hearing protection devices (HPD), that are entered into commerce in the United States, to provide the prospective user with information regarding the products' effectiveness in reducing the level of noise (unwanted sound) entering a user's ears."[1] This is one example of similarly mandated labeling requirements that exist in jurisdictions worldwide. Other examples include the Single Number Rating (SNR) used by the European Union and associated jurisdictions and Sound Level Conversion $(SLC)_{80}$ used by Australia and New Zealand. See Sound Source for a general summary of hearing protection ratings.[2]

These mandatory ratings, including both the current Noise Reduction Rating (NRR) and the proposed new NRR[3] as well as the SNR and SLC_{80}, can only measure the capability of a hearing protector to reduce the level of noise entering the user's ear. The focus is on the hearing protector itself, as it should be for the purpose of labeling the hearing protector. However, new technology allows users to individually measure the effectiveness of their hearing protection by individual fit-testing. This adds a dimension to the use of earplugs beyond population estimates of protection. Individual fit-testing takes the focus from the earplug to the person using the earplug.

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This article reviews studies in which fit-testing systems were used for a variety of reasons, including lab and field studies, and discusses how fit-test data can be used to improve hearing conservation programs. Unfortunately, many of the studies and evaluations are not published at this time. The author hopes that continued work in this area will result in additional peer-reviewed articles about both the methods of fit-testing and the practical applications of those methods.

Earplug fit-test systems produce a measurement called Personal Attenuation Rating (PAR), which is an individual measure of noise reduction of a given earplug *in situ*. Hager (in this journal) summarizes the types of hearing protection fit-testing systems that are available commercially, and his article serves as a companion piece to this article.

Labeling of Hearing Protection vs Individual Attenuation

Berger, Franks and Lindgren[4] reviewed the mounting evidence that hearing protection as used in the workplace, generally referred to as "real-world" performance, is not equal to or even predicted by the laboratory measurements that are used to test the capability of the hearing protector (NRR, SNR, SLC_{80}). They advocated an alternative laboratory method, the Noise Reduction Rating-subject fit

(NRRsf) for labeling hearing protectors. There has been extensive work over the last decade to develop a laboratory method to test hearing protectors that is a better predictor of the performance in the real world. The reader is referred to the work of the Acoustical Society of America Working Group S12/WG11 and their recent publications for details.[5-7] The labeling of hearing protectors is outside the scope of this review. The NRR, SNR and other ratings are a population statistic that suggests what a reasonably trained person ought to be able to achieve for attenuation. Although the work of the American National Standards Institute (ANSI) Working Group provides overwhelming evidence that in the real world many workers achieve much less noise reduction than is indicated on the label of a hearing protection, it is important for the reader to realize that some individual users should be able to exceed the published rating.

The wide range of attenuation provided by any given earplug is a primary reason for individual fit-testing of earplugs. The focus of this current review is individual fit-testing of earplugs. Berger *et al*.[4] reviewed 22 studies of how hearing protection is used in the real world by the end-user and found that earplugs provided an average of about 6 dB of attenuation and that earmuff provided a little over 14 dB of attenuation.

The development of individual fit-testing has focused on earplugs. In general, earmuffs provide a more consistent level of attenuation likely because they are easier to fit for a wide-ranging group of users. Assuming that the average attenuation provided by an earmuff is about 14 dB, as estimated in the Berger *et al*.[4] metastudy, and assuming that most of the workers need only 10–15 dB of attenuation, individual fit-testing of earmuffs is not a priority. However, the average attenuation that workers using earplugs received in the real world is often inadequate to meet even the modest goal of 10–15 dB of protection. The need for individual fit-testing and intervention with those users with inappropriate levels of protection is also evident in the continued hearing loss of noise-exposed workers.

The Validity of Fit-Testing Earplugs

The Real-Ear at Threshold (REAT) method is considered the gold standard to measure the capability of the hearing protector. It has been used throughout the world in laboratories and has been adapted for the field. The REAT method is codified in ANSI[8] and International Organization for Standardization (ISO) standards (ANSI/ASA S12.6-2008; ISO 4869-1).[9] Therefore, results from field REAT methods and the non-REAT fit-testing methods have been compared with the REAT results as a way to demonstrate the accuracy and validity of the fit-testing methods. In direct comparisons, the methods for individual fit-testing that are currently available have been shown to be valid methods to determine the attenuation achieved by individual earplug users. Some of those studies are summarized below.

Despite its recognition as the gold standard, the REAT method has its limitations. Those limitations include physiological noise masking, which elevates the REAT values at 125 and 250 Hz, and REAT's inherent variability, as it is the difference between the two subjective thresholds, each of which has its own uncertainty. Field use of REAT has its challenges as it can magnify these limitations that affect REAT even in controlled laboratory environments.

REAT based systems include Michaels and Associates' FitCheck™, Workplace Integra's IntegraFit, NIOSH's HPD WellFit.

The loudness balance (LB) method of individual fit-testing is similar to REAT but uses an "above threshold" psychoacoustic measure of LB rather than threshold of hearing, and has been referred to as Real-Ear Attenuation Above Threshold. In studies at the House Ear Institute, where the LB method of fit-test was developed, Vermiglio[10] showed that LB estimates of attenuation agreed very well with REAT estimates [Figure 1]. The inter-subject variability associated with the LB procedure was significantly smaller than that observed in REAT measures [Figure 2]. The LB method is used in the VeriPRO® fit-testing system by Howard Leight, a Honeywell company.

Soli,[11] at the House Ear Institute, found that the LB attenuation estimates are less variable (average $s < 4.5$ dB) than the ANSI threshold attenuation estimates (average $s > 6.5$ dB). Based on unpublished studies by Larson,[12] using the VeriPRO® LB fit-testing method, LB estimates of attenuation exhibit a good test–retest reliability, with inter-subject standard deviations about 2 dB higher for VeriPRO® testing versus REAT testing. Using two sample earplugs, a comparison between the REAT values and the VeriPRO® results was made, which were within 2–3 dB, except at 250 Hz. Larson tested the repeatability of the LB results for an experienced earplug fitter using VeriPRO® and found that with no adjustment of headphones, the results were within 2 dB. With refitting of the headphone between trials, a mean difference of about 4 dB was noted. Larson further tested the repeatability of the VeriPRO® results within subject and found that differences in the within-trial repeatability were <2 dB in unoccluded LB results. When a trained subject reinserted the same earplug for 10 trials, the differences between multiple trials was about 3 dB, suggesting a high degree of reliability. Peer-reviewed studies are needed to continue to assess the variability of the LB method. The ANSI test standard for REAT uses 6 dB retest reliability; therefore, retest variability over 6 dB will trigger a "fail" within the VeriPRO® software and will require retest.

An independent test of the VeriPRO® system was performed by Ewa Kotarbinska of the Warsaw University of Technology, Institute of Radioelectronics. Figure 3 compares the average attenuation results of 16 trained subjects who were experienced earplug users for 10 different earplugs using the average PAR for each ear (left = blue diamond; right = red square) tested using the VeriPRO® system to

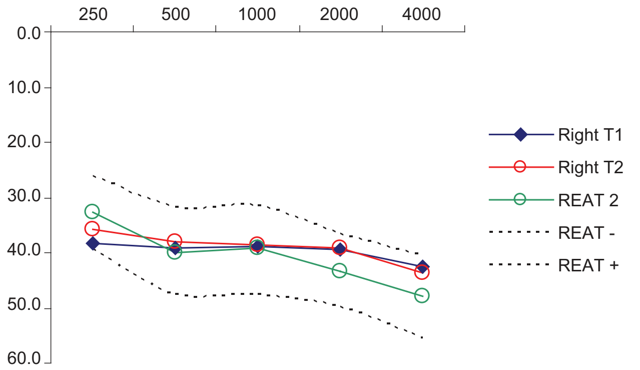

Figure 1: Right ear loudness balance means for 2 trials, T1 and T2) plotted with REAT mean and the mean ± 1 S.D. [From Larson's review of Vermiglio.[10] Used with permission]

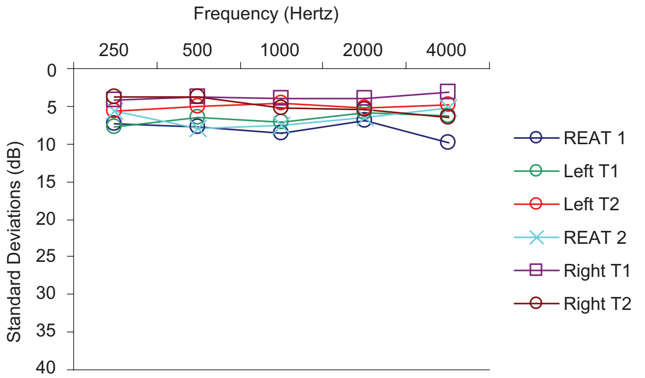

Figure 2: Standard deviations for loudness balance and REAT data for two trials. [From Larson's review of Vermiglio.[10] Used with permission]

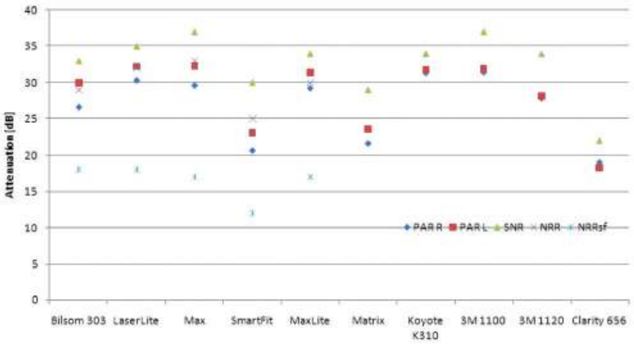

Figure 3: Comparison loudness balance attenuation (blue diamond = right ear PAR; red square = left ear PAR) with SNR (green triangles), NRR (purple x) and NRRsf (light blue *) for various earplugs. [From VeriPRO® fit-testing conducted by Ewa Kotarbinska, Electroacoustic Department, Warsaw University of Technology[13]]

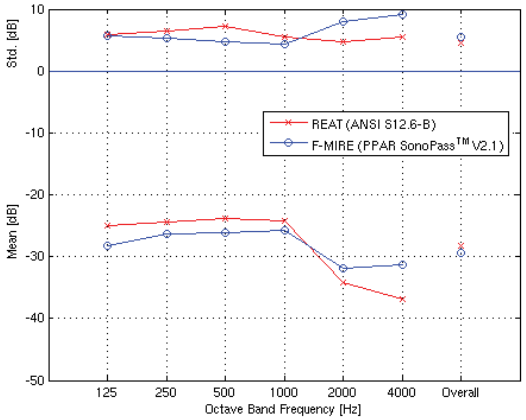

Figure 4: Average and standard deviation of the attenuation measured with REAT (red "x") and F-MIRE (blue "o") for the "per-earplug" approach. The overall values are computed from the 125–8000 Hz octave-bands. [From Voix, Hager and Zeidan.[14] Used with permission]

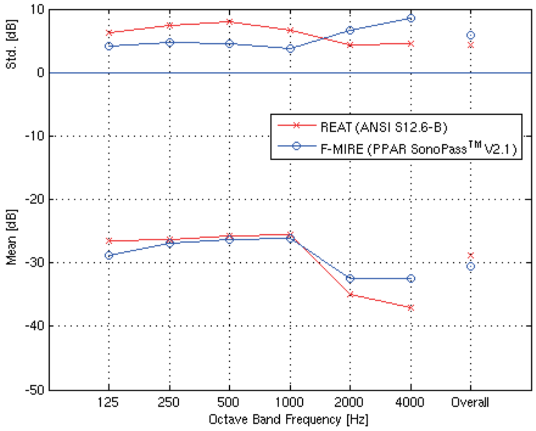

Figure 5: Average and standard deviation of the attenuation measured with REAT (red "x") and F-MIRE (blue "o") for the "per-subject" approach. Overall values are computed from the 125–8000 Hz octave bands. [From Voix, Hager and Zeidan.[14] Used with permission]

currently published SNR (green triangle), NRR (purple x) and NRR_{sf} (light blue asterisk).[13] The PAR closely estimates the NRR. The PAR underestimates the SNR, because SNRs are generally slightly higher than NRR, and overestimates the NRR_{sf} (as expected). The calculations for each of these ratings are slightly different. The calculation used to determine PAR in the VeriPRO® software is shown in Appendix A.

The E•A•Rfit™ Validation System by 3M and Sonomax systems use the technology detailed by Voix *et al*.[14] A similar system using Field-Microphone-In-Real-Ear (F-MIRE) technology is available as the SafetyMeter by Phonak. The calculation used by the SafetyMeter is shown in Appendix A. The F-MIRE method was independently validated using the E•A•Rfit™ by comparing its Predicted Personal Attenuation Rating (P-PAR) to REAT testing.[14] The experimental design allowed for comparisons "per-earplug" (the same earplug fitting measured via REAT and F-MIRE) and "per subject" (the same subject – with the earplug refit – measured via REAT and F-MIRE). Figures 4 and 5 show these comparisons, revealing that the average values predicted for the group with the F-MIRE are close to the REAT values (subject-fit).

The calculations of PAR for the various methods are shown in Appendix A. There is a need for clarification and standardization of PAR. Work is being initiated by the ANSI Working Group 12 to standardize the definition and calculation of PAR. It is important to understand the assumptions behind and the reasons for the factors that influence a PAR.

Low-frequency attenuation results will best predict whether an acoustic seal is attained with the earplug fit. The single test frequency that is most predictive of fit of hearing protectors is either 500 or 1000 Hz.[12] The VeriPRO® system uses 500 Hz in the Quick Check mode as it is a reasonable predictor of the overall attenuation. IntrgraFit, a REAT-based system uses 500 Hz only.

Individual Fit-testing in the Real World

The scientists and practitioners developing and using earplug fit-test systems have reported various uses for this new technology to improve hearing loss prevention efforts. Individual fit-testing can be a valuable training.[14-19] Voix and Hager[20] and Franks *et al*.[21] suggest that individual's ability to fit an earplug may be the largest single variable in HPD performance.

Applications suggested by the scientists, researchers, practitioners and other experts[14-19] include:

1. Training user to fit the earplug appropriately and training the trainer how to teach appropriate earplug fitting technique. Individual technique in fitting earplugs is probably the largest variable in overall attenuation results. Providing feedback to the users allows them to distinguish between a poor fit and a good fit.
2. Selection of earplug: Users often choose earplugs based on factors other than the real protection from hazardous noise. Those factors include convenience and ease of use, perceived comfort, color or other esthetics, etc. While these factors are important, knowledge of the effectiveness of a given plug for that person is one of the key factors in determining the right earplug for each person. Newly hired workers and workers who suffer decrease in hearing (even pre-standard threshold shift) can use fit-testing to help determine the appropriate earplug for their environment. Some workers may need more than one earplug in their arsenal of personal protective equipment (PPE) because they work in highly varied noise environments.
3. Sufficiency of protection: The goal of a hearing conservation program is to protect workers from hazardous noise. If noise controls and administrative controls have not removed the hazard, measuring the level of protection provided by personal protection (earplugs) can document that a worker is sufficiently protected from hazardous noise.
4. Awareness of possible "overprotection." European Union guidelines suggest that the optimal "protected level" or net exposure should be 75–80 dBA, with acceptable exposure ranging between 70 and 85 dBA.[22] Individual fit-testing can help the worker to find the "right" amount of protection without isolating himself from his environment. This is especially important for hearing-impaired workers.
5. Compliance to regulations: All jurisdictions have "Permissible Exposure Levels," and most have required follow-up procedures if an employee suffers from a change in hearing. Fit-testing allows employers to document their compliance with these regulatory requirements.
6. Evaluation of hearing conservation program effectiveness. The regulations in all jurisdictions call for an effective hearing conservation program. Fit-testing results are just one metric that can be used to track the effectiveness of a hearing conservation program.
7. Hearing test interpretation: A professional supervisor (an audiologist or physician) of the audiometric portion of the hearing conservation program must make a determination of work-relatedness for any "Recordable Hearing Loss." Documentation of the level of protection that earplugs provided an individual employee can serve as evidence as to the likelihood of a decrease in hearing being work related.
8. Prioritization of resources: Armed with fitting data, employers can focus their retraining efforts on the workers who need it, those with inadequate protection levels and on the areas where workers might still be at risk for overexposure.
9. Inventory control: Based on the earplugs that are documented to fit the workforce, employers can tailor their earplug inventory. A wider or smaller variety or more of one type and less of another may meet the requirement for "a variety of suitable hearing protectors" to be offered to the employee.

Examples of Application of Individual Fit-testing of Earplugs

Several studies have specifically used individual fit-testing to explore its value in hearing conservation programs. Examples continue to be reported as this technology gains use.

Michael and Bloyer[23] used a REAT-based fit-testing system, Fit Check™, to test workers at a worksite. They identified the workers achieving the lowest attenuation levels. Figure 6 shows a scattergram of each worker's attenuation results. The open circles are the initial attenuation levels, with the dashed line showing the average of those results of approximately 5 dB of noise reduction. The researchers then provided a very short (a couple of minutes) one-on-one training on how to fit the earplug and, in some cases, recommended a different earplug during that training. The filled triangles are the post-training attenuation results with the solid line showing the average of those results of approximately 19 dB of noise reduction. A Comparison of the vertically aligned open circles and filled triangtles shows the individual change in attenuation (a few examples are noted with dotted vertical lines). Not all workers showed improvement, but the average increase in PAR was 14 dB. This study used fit-testing to

- prioritize workers at risk for noise-induced hearing loss,
- allow one-on-one training as needed,
- help determine if another earplug might be needed and
- document metrics of improved hearing protection.

Joseph *et al*.[24] used Fit Check™ to measure the effectiveness of training methods. A small group training produced a significant improvement in the attenuation levels, and individual training provided even greater improvement in attenuation levels. Figure 7 shows that only with individual training were subjects able to obtain the targeted 8 dB improvement at every frequency tested.

NIOSH[21] researchers fit-tested workers in a metal stamping plant using the Fit Check™ system at approximately quarterly intervals over 1 year. Figure 8 shows a comparison of the estimated protected exposure level and the nominal exposure level for the initial session in February 2004. The fit of the protector was evaluated at 125, 500 and 2000 Hz using a REAT field fit-test system. About 90% of the workers were sufficiently protected, many of those overprotected. There was little change over the four visits for workers using traditional earplugs. One group of workers used custom-filtered earplugs, with the attenuation level controlled by the filter to match the overall exposure level (TWA). Over the year of the study, many of those workers, especially experienced earplug users, requested increased attenuation levels, preferring to be overprotected. The authors suggest that the preference for overprotection may be due to the impulsive nature of the noise exposures or experience with traditional earplugs that may have provided high levels of attenuation. This study addressed the sufficiency of protection and the awareness of overprotection.

Hager[25] used F-MIRE to fit-test 138 subjects at a metal can manufacturing plant, with noise exposures ranging from 80 to 105 dB TWA. The subjects used four different models of specially prepared earplugs but were instructed to "Put it in like you normally do." He found attenuation values ranging from 11 to 42 dB, which were essentially in a bimodal distribution. In general, the workers with high-noise exposures achieved more protective values and workers with low-noise exposures achieved lower attenuation levels. Almost all the workers (97%) had sufficient protection to 82 dB TWA.

A steel fabrication shop used LB fit-testing to determine the sufficiency of protection for its workers, with the goal of protecting workers to no more than 85 dB. Table 1 shows the protected exposure levels (PrEL) that were calculated by the fit-testing software. PrEL is calculated by subtracting the lesser PAR (of the two ears) from the Time-Weighted Average. After initial testing and short training, 12 workers did not achieve protection sufficient to decrease their exposure to below 85 dB, and were still at risk. Those workers were required to use double hearing protection until they could find an earplug that provided adequate attenuation. Post-training, most of those "at-risk" workers were in an area with a TWA of 103–104 dB and therefore required at least 20 dB of effective attenuation to achieve the target PrEL.

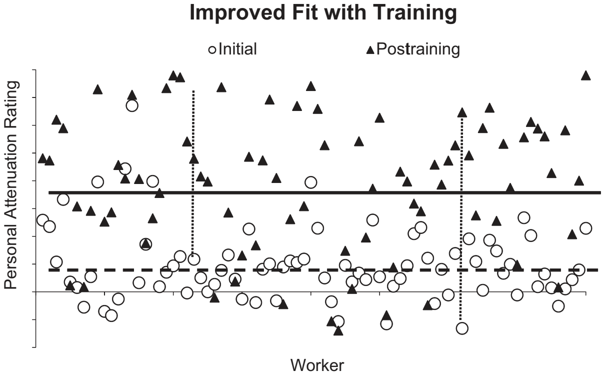

Figure 6: (reconfigured data). Mean (dotted line) of initial individual attenuation results (open circles) compared to mean (solid line) of post-training attenuation results for those individuals (filled trianges). [From Michael and Bloyer.[23] Modified with permission.]

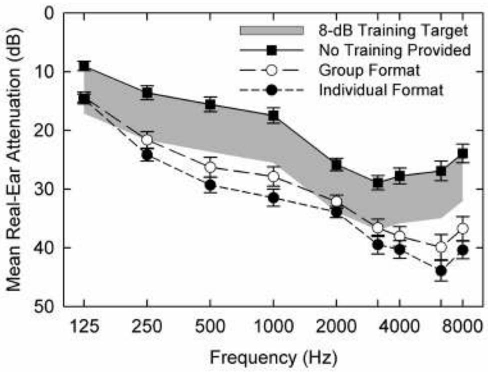

Figure 7: Mean binaural REAT data and standard errors for participants receiving no training, individual training and small group training, irrespective of the HPD group. An overlay of 8 dB is included for assessment of training effectiveness. [Used with permission for Joseph *et al.*[24]]

Table 1: Number of workers by Protected Exposure Levels (Prel) after initial fit-testing and training in a steel fabrication shop

	Protected exposure level					
	65–69	70–74	75–79	80–85	>85	>90
Number of workers	3	8	13	25	6	6

Tsukada and Sakakibara[26] trained workers on the use of earplugs using a fit-testing system (earplug checker AG-20A; Rion Co. Ltd.) that appears to use a Bekesy tracking style REAT method to compare the threshold of hearing with and without earplugs. They found that the prevalence of hearing protection use increased from 46% to 66% even 2 months after the training. They also measured the level of attenuation, and found that, before training, only 46% of

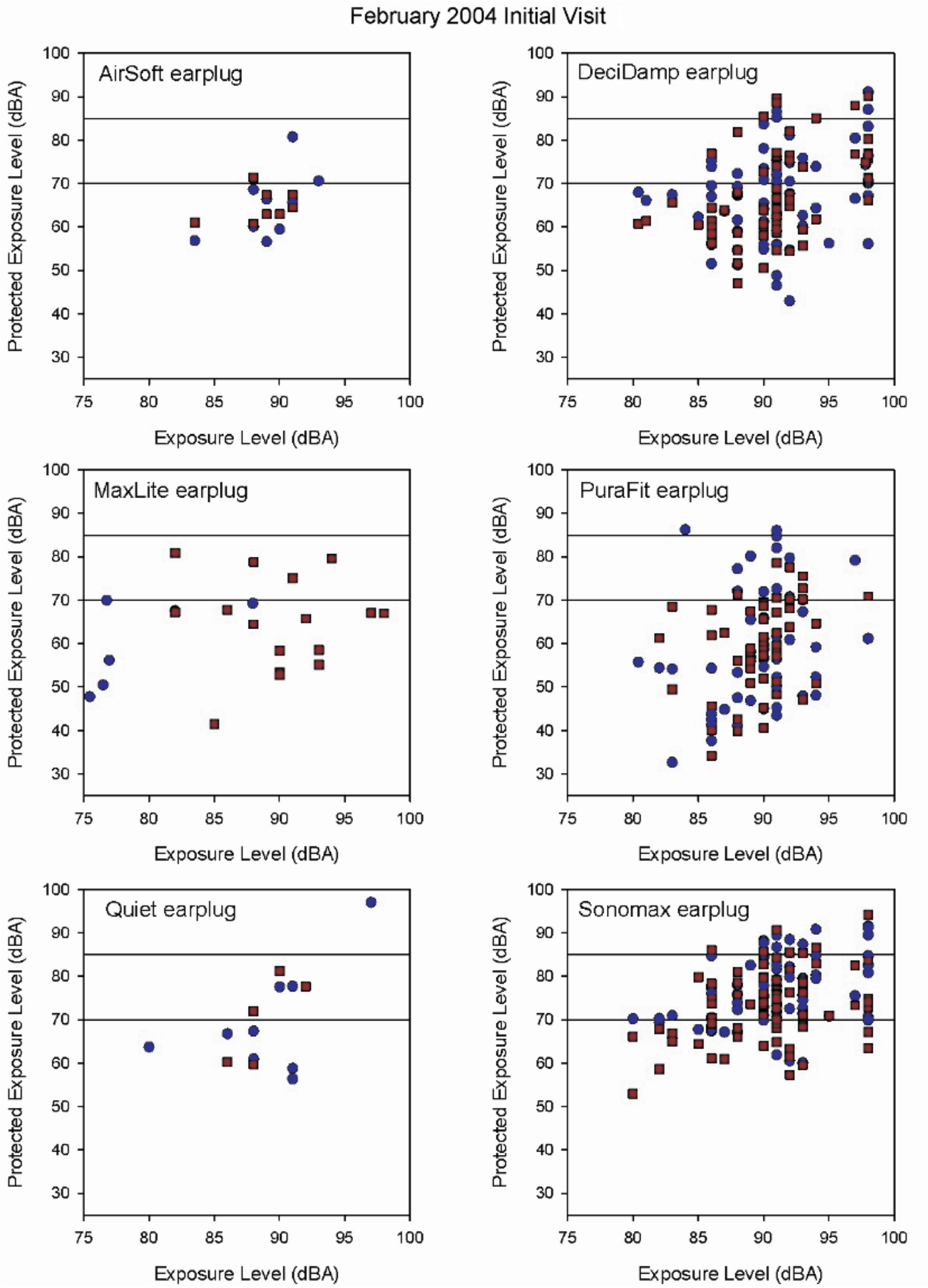

Figure 8: Attenuation results were used to calculate the "Protected Exposure Levels," and were plotted as a function of the unprotected exposure levels. The fit of the protector was evaluated at 125, 500 and 2000 Hz using a field REAT system. Red symbols depict the results for the right ear and blue symbols depict the left ear. The reference lines at 70 and 85 dBA indicate the ideal range between which a worker's protected exposure level should lie. [From NIOSH.[20] Used with permission]

the workers achieved at least 25 dB and, immediately after training, 72% of the workers measured attenuation of 25 dB or greater. The ability to attain 25 dB of attenuation was still present for 71% of the workers after 2 months.

Witt[18] used individual fit-testing to determine

1. How close experienced hearing protector users were to getting the published NRR of their earplug of choice?
2. If users obtain low-attenuation levels with one plug, will they with another earplug?
3. What factors predict the level of attenuation workers obtain?

The amount of variation from the NRR is documented in Figure 9. About 100 workers who used a variety of earplugs were tested at eight work sites. Workers were fit-tested using VeriPRO® with the hearing protectors that they normally wear. No additional training instructions were provided prior to the testing. The attenuation levels achieved by workers were plotted as a function of the variation from the published NRR of that particular hearing protector. Therefore, zero (0) on the graph indicates the published attenuation ratings for each worker-selected hearing protector. Figure 9 reveals that about one-third of the workers (38 of 104, or 36%) obtained attenuation results that were higher than the published NRR. Another one-third of the workers (33 of 104, or 32%) were within about 5 dB of the published NRR. But, the bottom one-third workers (29 of 104, or 28%) obtained significantly lower personal attenuation than the rated attenuation on the package.[18]

To answer the second question of whether users with low attenuation with one plug would also get low attenuation with another earplug, the researchers provided a second or third type of earplug to the workers in the bottom one-third who were not reaching the capability of their earplug of choice. Figure 10 shows the attenuation levels of the workers' usual earplug (blue diamonds) compared with the attenuation level attained with a different earplug (horizontal black bars). Workers trying a different earplug often had major leaps in attenuation levels, bringing them closer to the published rating of the new earplug.[18]

In an effort to predict which workers would achieve levels of attenuation closest to those published for that earplug, Witt looked at various personal, product and program factors. Personal factors included gender, age, years in noise and ear canal size. Product factors included familiarity with earplug and type and model of earplug. Program factors included type of hearing protection training provided. He found that the only factor that correlated with attenuation levels that closely matched the published rating was individual training in use of earplugs.[18]

Neitzel and Seixes[27] used Fit Check™ fit-testing to report the percentage of the published attenuation attained [Figure 11] in a study of construction workers. Although the standard deviations of the averaged PAR results were large, they noted that the plug with the highest published rating did not obtain the highest binaural PAR. This finding adds evidence against derating of the population ratings to estimate real-world attenuation levels and for individual fit-testing.

Workers who get feedback are more likely to change their behavior. Zohar *et al.*[28] tested the hearing thresholds of workers before and after work shifts. Workers used hearing protectors for one work shift and did not use hearing protection for another work shift. The experimental group received information about their temporary threshold shifts when hearing protection was not worn. A control group received only standard lecture and disciplinary threats. After 5 months, 85–90% of the experimental group was using hearing protectors, and no more than 10% of the control group wore earplugs over the same 5-month period. The authors emphasize that workers continued to use hearing protection even after the feedback ceased.

Providing quantitative feedback helps the individual to recognize a poor fit compared with a good fit (Schulz and Bessette).[29] In a pilot study with 17 construction workers who were attending or teaching in an OSHA 10-h safety course, volunteers completed two to four QuickCheck LB earplug fit tests using VeriPRO®. In the VeriPRO® QuickCheck mode, only one frequency (500 Hz) is used to predict PAR. The volunteers were allowed to fit their own earplugs and then complete the QuickCheck multiple times (2-4), receiving feedback each time on their PAR, until they felt confident in estimating the attenuation provided by a given fit. As a final step they again fit their own plugs and performed their final QuickCheck and were asked to report the level of attenuation they thought they were getting by choosing between 5-dB categories prior to receiving the PAR feedback. Figure 12 shows that for 19 of the 34 ears, the user predicted their attenuation in the correct 5-dB category. Only four individuals (in one ear) were off by more than one category in their self-assessment of the amount of attenuation, and three of those were consistently achieving adequate attenuation. With improved self-efficacy in fitting hearing protection, it is possible that workers will be better protected.

Owens[30] used a portable audiometer with circumaural audiocups in a relatively quiet room to accomplish a fit-test for approximately 150 employees in a petrochemical refinery. He used three test frequencies (500, 1000 and 2000 Hz) to determine the unoccluded and occluded threshold measurements and averaged the results. Although this test method is make-shift and not definitive, Owen notes that the benefits include the opportunity for one-on-one guidance, feedback on the choices and availability of earplugs, identification of underprotected workers and emphasis on hearing conservation, both on and off the job.

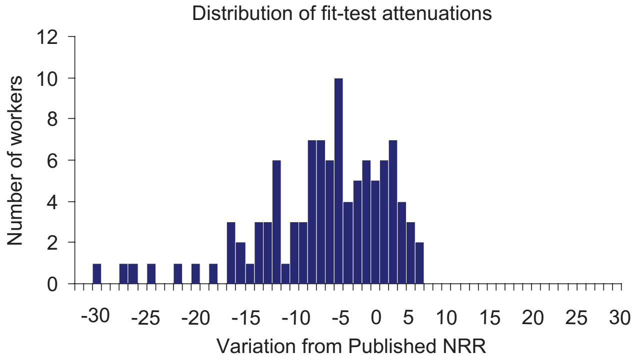

Figure 9: Individual variation from published NRR, as measured using the loudness balance method of individual fit-test. [From Witt.[18] Used with permission]

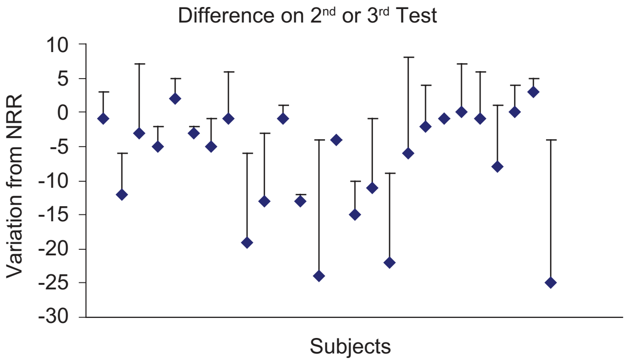

Figure 10: Amount of change in variation from published NRR when workers used a different earplug. [From Witt.[18] Used with permission]

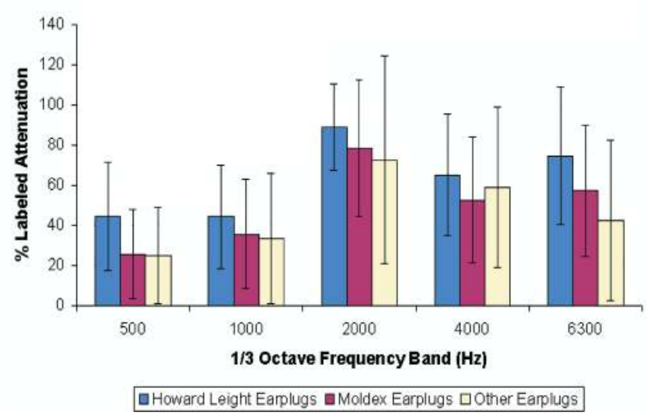

Figure 11: Percentage of frequency-specific labeled attenuation achieved. [From Neitzel and Seixas.[27] Used with permission]

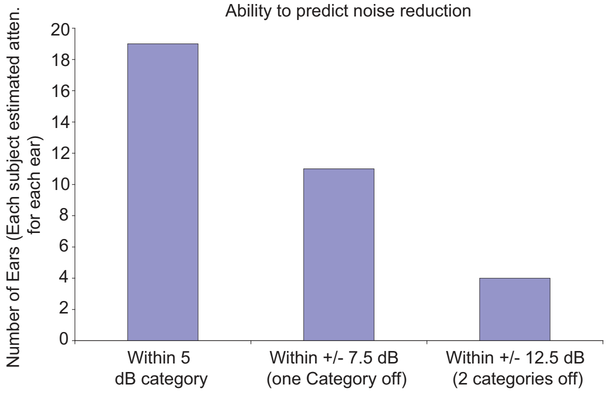

Figure 12: Worker efficacy in predicting the attenuation level of a given fit after a short training session. [From Schulz and Bessette.[29] Used with permission]

Discussion

The increasing availability and feasibility for companies to conduct individual fit-testing of earplugs is a major trend in the prevention of noise-induced hearing loss. The REAT method was developed as a laboratory method and has been adapted for real-world applications. However, it has seen limited acceptance in the workplace. As continued research[21,24,27] is conducted, the feasibility and viability of fit-testing is being demonstrated. Fit-testing focuses our efforts on prevention of hearing loss rather than on mere compliance with occupational safety laws.

Research projects continue to evaluate the various earplug fit-testing systems. But, it is clear that the benefits of individual fit-testing are real. It is vital that the hearing conservation community embrace this trend and help our constituents to improve their hearing loss prevention efforts.

All the systems that use psychophysical methods such as Fit Check™, VeriPRO® and REAT have an inherent variability in the human element of determining a threshold or equal level of loudness. Even the gold standard, in the case of fit-testing hearing protection, the ANSI Standard 12.6, allows for 6 dB differences in the threshold test–retest of a single subject. Therefore, we need to consider what we expect from individual fit-testing. Franks *et al*.[21] noted that variance of repeated thresholds showed that unoccluded thresholds were about 4 dB while occluded thresholds were larger (6–8 dB). Parsing the variance of the fit from the variance of threshold or suprathreshold measure is not trivial. The ISO standards for determining hearing protector attenuation do not address the issue of variance of fit with the variance of the occluded condition. Systems that use F-MIRE, such as E•A•Rfit™ and SafetyMeter, are less variable due to the exclusion of human response variability. There is, of course, a small variability for repeated measures with a microphone.

Differences of a few dB between tests or conditions or methods of testing are inherent in the methods that we use. However, individual fit-testing provides a vastly improved estimate of the real protection that workers can expect from their hearing protection devices.

Larson,[12] Kotarbinska[13] and NIOSH[31] show that the shorter version of fit-testing can accurately predict the PAR obtained for the various methods of fit-testing. The purpose of the fit-test will dictate the level of precision required. If documentation for compliance, workers compensation evidence or other legal reasons is needed, the full test should be performed, irrespective of the system being used. Abbreviated versions of the fit-test method may be adequate for training, earplug selection and identification of underprotected employees.

As more workers are individually fit-tested, we must answer the question, what is meaningful? While evaluation of the reliability and precision of the various methods is an important issue to address, it must be understood that precision might be less important than value of self-efficacy and motivation of workers, who can better use their earplugs to protect themselves from hazardous noise both on and off the job.

Address for correspondence:
Dr. Theresa Y. Schulz,
Howard Leight
7828 Waterville Road
San Diego, CA, USA 92154.
E-mail: TSchulz@Sperian.com

Appendix A

VeriPRO® calculation method for personal attenuation rating (PAR)

From Larson, 2008.[12]

Attenuation for the two ears is computed from the loudness balance results. First, the quantity LD1 is computed by subtracting the level presented to the left ear from the level presented to the right ear, and represents the "imbalance" between the two ears with the ears unoccluded.

Next, the second loudness match is made with the right ear occluded by the earplug under the circumaural earphone. The level difference between the two ears in this condition is called "LD2," and the right ear attenuation is computed by subtracting the level difference (Left level – Right level) observed in this loudness match. Subsequently, the quantity "ATR" (representing attenuation for the earplug in the right ear) is calculated by adjusting LD2 by the amount of imbalance LD1 noted in the first balance. That is, because LD2 includes the imbalance between the ears, the attenuation for the right ear (ATR) is computed by subtracting LD1 from LD2 (i.e., ATR = LD2 - LD1).

Finally, the third loudness match is made with both the reference ear (right ear) and the comparison ear (left ear) occluded by the earplugs. The level difference for this match, LD3, is produced by the difference in attenuation of the right and left earplugs, ATD, plus the imbalance (LD1) between the two ears. Hence, LD3 is first adjusted by the amount of LD1 to obtain the attenuation difference ATD. Then, the attenuation of the earplug in the left ear, ATL, is calculated by subtracting ATD from ATR. This quantity is computationally similar to the NRR (EPA, 40CFR, Part 211), except that attenuation data at the extreme low and high frequencies are not available and, consequently, not used in its calculation. In addition, the VeriPRO® PAR calculation estimates the attenuation provided to the individual under test, rather than predicting the percentile of attenuation, as in the NRR calculation.

Fit Check™ calculation method for PAR

1. Assume flat exposure spectrum, similar to NRR calculation
2. A-weight flat exposure spectrum in each band
3. Logarithmically add across bands where fit-testing was performed to calculate overall dBA exposure level
4. Subtract Fit Check™ attenuation at each test frequency band
5. Logarithmically add across test bands to calculate overall protected dBA level
6. Subtract protected dBA level from dBA exposure level to arrive at PAR

Sample PAR calculation

Third-octave band center frequency in Hz	250	500	1000	2000	3150	4000
Assumed exposure in dB SPL	100.0	100.0	100.0	100.0	100.0	100.0
A-Weighting correction in decibles (dB)	-8.6	-3.2	0.0	+1.2	+1.2	+1.0
Assumed exposure in decibles, A-scale (dab)	91.4	96.8	100.0	101.2	101.2	101.0
Overall level = 107.4 dab						
Measured attenuation in dB (sample)	19.4	22.4	25.1	30.1	32.8	39.3
A-weighted exposure minus attenuation	72.0	74.4	74.9	71.1	68.4	61.7
Overall level under protetor = 79.8 dab						
PAR = 107.4-79.8=27.6dB						

Any of these frequencies can be omitted from the test without changing the method of PAR calculation.

E•A•Rfit™ calculation method for PAR

[From Voix and Hager, 2009.[20]]

The PAR is computed like the Noise Reduction Statistic for use with A-weighting (NRSA) that is defined in ANSI S12.68-2007, with the exception that the between-subject variability is replaced by the sum of the variances of the F-MIRE uncertainty and the within-subject refitting uncertainty. Thus, Equation 6 in ANSI S12.68 is replaced by Equation (1) below, where x is selected appropriately for the desired percentile, $\overline{\mathrm{ATT}}$ is the average corrected F-MIRE value across fits for a given subject (i.e., predicted REAT), α is 0.00 or +0.84, depending on whether the median or 80th or 20th percentile is selected, and spectrum is as defined in the ANSI standard. The F-MIRE prediction uncertainty (s2F-MIRE) represents the difference between the F-MIRE and REAT values averaged across the prior measurements with laboratory subjects that were conducted to establish the compensation factors as described in Equation (9) of Voix and Hager. Fitting uncertainty is given by Equation (2) below. In Equation (2), mf is the measured F-MIRE for each fit of the earplug, denoted by index f, and $\overline{\mathrm{ATT}}$ is the average F-MIRE across all F fits for that subject, as was defined for Equation (1).

$$\mathrm{PAR}_x = \overline{\mathrm{ATT}} - a_x \sqrt{s^2_{\text{F-MIRE}} + s^2_{\text{fit}} + s^2_{\text{spectrum}}} \quad (1)$$

$$s_{\text{fit}} = \sqrt{\frac{1}{F-1} \sum_{f=1}^{F} (m_f - \overline{\mathrm{ATT}})^2} \quad (2)$$

SafetyMeter calculation method for PAR

The Personal Attenuation Rating (PAR) is the "single user equivalent" of a Single Number Rating (SNR) measured as per the ISO 4869. The PAR is computed like an SNR, except that it is calculated individually for the user and does not include a standard deviation correction.

The [PAR-1.1 dB] is the "single user equivalent" of a Noise Reduction Rating (NRR), measured as per ANSI S3.19-1976. The [PAR-1.1 dB] is equal to an NRR calculated individually for the user, i.e. excluding standard deviation corrections and 3 dB spectral uncertainty factor."

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