Field fit-testing and attenuation-estimation procedures

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Deanna – you wrote “The largest gap I see is an explicit section/paragraph outlining the different ways that PARs can be used to determine “adequacy” or “proper fit”. See if you think we have this covered now. See especially discussion in the sub-section “<H3> Verifying the proper attenuation of hearing protection.”

Tables 1 – 3 have been reorganized and the figures you requested updating were updated.

AIHA – Please lay out figures at whatever column width you feel works best.
Introduction
When properly selected and fitted, hearing protectors can be an effective means to attenuate noise to prevent hearing damage. This much is clear. However, the devil is in the details: how to train and motivate employees to correctly and consistently fit their hearing protection devices (HPDs), how to assign HPDs proportionately to noise exposures, and how to accommodate personal preferences and anatomical variations. Careful attention to detail is needed for individuals to accomplish these goals. Heretofore, proper selection and fitting have been complicated by the fact that in many cases those dispensing hearing protection in industrial environments have had little or no training in how to fit HPDs, and the only noise attenuation data available has been from group-average data based on laboratory measurements, as reflected in the Noise Reduction Rating (NRR) or similar ratings. Even if the laboratory data were representative of the actual group of subjects using the device, individual variability is large enough that attempts at predicting a person’s performance from group data can easily err by up to 20 dB (Gauger and Berger, 2004). One approach to solving these problems in industry is the development of systems to allow individual fit testing, and indeed such systems have proliferated. Fit-test technology has been available for research in many forms for over 40 years (Michael et al. 1976), but only in the past decade, as commercial solutions have become more broadly available, has the hearing conservation community started to look more closely at these issues (Hager, 2011; Witt, 2008).

Fit-test technology has been available in one form or another for over 40 years, but only in the past decade has the hearing conservation community started to embrace it. Today it is considered an emerging trend and best practice to train workers and verify individual attenuation.

Today, there are a number of field attenuation estimation systems (FAES), colloquially referred to as “fit-test” systems that provide field-test capabilities. Although the various fit-test systems have the same purpose and produce individual attenuation values that are presented in similar ways to one another, the underlying technology used to produce the personal attenuation rating (PAR) can differ substantially.

This chapter comprises five sections. In the first, the various fit-test systems developed by manufacturers over recent years are reviewed and categorized. Although such fit-test systems do enhance the prediction of individual protection performance, they are subject to their own errors and uncertainties inherent to the measurement process and user-fitting capabilities. Also included in this section is a brief discussion of the application of PAR. The second section of the chapter describes the use of fit testing as part of a hearing loss prevention program (HLPP). Research findings are reviewed and the many applications of fit-test methods within an HLPP are discussed. The concluding three sections briefly summarize the limitations of today’s fit testing systems, ongoing efforts in the United States at developing relevant standardization, and finally the future of fit testing with respect to best practices in HLPPs.

What is Fit Testing?

History of Individual HPD Fit Testing
Historically, the best of the laboratory procedures (see Chapter 11 on Measuring HPD Attenuation) were modified to reduce costs, improve portability and ruggedness, and were utilized under field conditions to estimate the amount of attenuation provided by HPDs in actual use (Berger, 1984). The procedure that was first successfully applied to test both earplugs and earmuffs under field conditions was real-ear attenuation at threshold (REAT)
conducted in a sound-field produced in a smaller acoustical chamber than the one used in laboratory testing. For earplugs, earphones mounted inside large circumaural cups instead of loudspeakers in a chamber have also been used to measure earplug attenuation in a similar manner (Michael et al. 1976), and for earmuffs, the microphone-in-real-ear (MIRE) procedure was used with microphones mounted on the inside and outside of earmuffs (Stewart and Burgi, 1979). These field-attenuation measurement procedures have been useful for research purposes and have revealed the significant difference in HPD attenuation obtained by users in the field versus test subjects in the laboratory. See Chapter 11 for more information on real-world attenuation and explanations for the observed discrepancies. Based on the field measurement systems previously developed, mostly for research purposes, commercial systems have more recently been made available to answer the pressing question within the hearing conservation community, namely, “What amount of protection can, or is, a given individual actually getting from his/her HPD?” (Hager, 2011; Witt, 2008). It is important to note that the term fit testing, as it is used in this chapter, refers to the process of conducting a measurement in order to estimate the acoustic attenuation of a given HPD, as for example would be measured according to ANSI/ASA S12.6-2016. Fit testing does not imply a casual physical or tactile assessment that a given HPD is properly inserted.

**H2> Fit-Test System Technology**

For the purpose of labeling hearing protectors as to their comparative capability, the attenuation of HPDs is typically measured using the REAT procedure as defined in ANSI/ASA S12.6 or ISO 4869-1 (ISO, 1990), described in detail in Chapter 11. While the REAT test method is known to have limitations, it is considered the “gold standard” for measuring an HPD’s attenuation. Figure 1 illustrates the REAT methodology, where the auditory thresholds are alternately measured for the unprotected (open) ear (Figure 1a) and for the protected (occluded) ear (Figure 1b). Attenuation is expressed as the difference between the open and occluded auditory thresholds at each test frequency as experienced by the test subject, from both ears simultaneously. In the field, the goal of a fit-test system is to quickly and accurately estimate an attenuation value that corresponds to that which would have been produced by REAT for a given fit of the tested individual.

**INSERT FIGURE 1 HERE**

**H3> Types of Fit-Test Systems**

Fit-test systems can estimate REAT using either physical measurements (also called objective) or psychophysical measurements (also called subjective). Physical systems use a measurement transducer, such as a microphone, accelerometer, or pressure sensor. For physical systems, the HPD used during testing is either a standard (unmodified) HPD such as the one the employee (also referred to as user) will later wear, or a surrogate (modified) HPD, which is a modified version of the standard HPD in order to facilitate the required measurement. Psychophysical systems actively involve a human test subject and rely on tasks such as measuring hearing thresholds or establishing a perceptual loudness balance. Within these psychophysical systems, a further distinction can be made, whether the method used is conducted at threshold sound levels or at greater sound levels (supra-threshold based methods). Consequently, to distinguish the types of measurements and test devices previously mentioned, four categories of measurement combinations are defined and presented in Table 1. A further distinction, not illustrated in the table, is that all four types of fit-testing systems may produce quantitative measurements and report an attenuation measurement value and/or a PAR, or may simply indicate, via pass/fail metrics, whether a given fit meets a pre-established criterion level of attenuation.
### Table 1 – Categorization of the four types of fit-test systems

<table>
<thead>
<tr>
<th>System type</th>
<th>HPD test device</th>
<th>Psychophysical Method type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measurement</td>
<td>Standard HPD</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Surrogate HPD</td>
<td></td>
</tr>
<tr>
<td>Psychophysical measurement</td>
<td>Standard HPD</td>
<td>Threshold-based</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supra-threshold based</td>
</tr>
</tbody>
</table>

### Commercially Available Fit-Test Systems
The fit-test systems commercially available at the time of writing are listed in Table 2. The table includes both the commercial information, such as the current brand name, distributor and/or manufacturer’s website, and the type of fit-test system with a short description of the underlying technology. The data in Table 2 are provided for illustrative purposes, ordered by type, then by technology, then alphabetically by brand, and are not intended as an endorsement by the authors. The list has been populated from references made in published literature, either through presentations during conferences (Hager and Voix, 2007; Murphy et al., 2010; Murphy et al. 2011b) or in refereed scientific articles and reports in North-America and Europe (Canetto and Voix, 2008; Dyrba et al., 2014; Trompette and Kusy, 2013).

Other commercial systems exist that measure effective noise exposure of a given employee. Often referred to as *in-ear dosimeters*, these systems are not considered to be fit-test systems but rather personal dosimeters that measure employee protected exposures to noise over an entire work shift. Data are retrieved at the end of each shift or work week and the results are analyzed on a personal computer. Some commercial solutions require the use of a small data logger that is worn by employees in a shirt pocket or on the back of a hardhat, protective eartips or earmuffs instrumented with microphones that record real-time in-ear noise levels, and a connecting harness (Michael et al., 2011, Rabinowitz et al., 2010). In another commercial solution, the electronic active earplugs are instrumented with outer- and inner-ear microphones and a belt-pack processing unit measures the effective accumulated noise dose of the user (Mazur and Voix, 2013).
Table 2: Commercially available fit-test systems circa 2017. F-MIRE denotes the field-microphone in real-ear method.

<table>
<thead>
<tr>
<th>Type</th>
<th>Technology</th>
<th>Testable Hearing Protectors</th>
<th>Manufacturer, developer or distributor</th>
<th>Brand or commercial name</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measurement using standard (unmodified) HPD</td>
<td>F-MIRE in sound field</td>
<td>Custom earplugs</td>
<td>CeoTronics AG</td>
<td>CT-EarGuard</td>
<td><a href="http://www.ceotronics.de">www.ceotronics.de</a></td>
</tr>
<tr>
<td></td>
<td>F-MIRE in sound field</td>
<td>Custom earplugs</td>
<td>Sonomax Technologies, Inc.</td>
<td>SonoPass™</td>
<td><a href="http://www.sonomax.com">www.sonomax.com</a></td>
</tr>
<tr>
<td></td>
<td>F-MIRE in sound field</td>
<td>Earmuffs</td>
<td>Michael and Associates, Inc.</td>
<td>FitCheck for earmuffs</td>
<td><a href="http://www.michaelassociates.com">www.michaelassociates.com</a></td>
</tr>
<tr>
<td></td>
<td>F-MIRE in sound field</td>
<td>Earmuffs</td>
<td>SVANTEK Sp.zo.o</td>
<td>SV 102A+</td>
<td><a href="http://www.svantek.com">www.svantek.com</a></td>
</tr>
<tr>
<td></td>
<td>F-MIRE under earcups</td>
<td>Custom earplugs</td>
<td>Elcea International B.V.</td>
<td>Elacin SI-Meter</td>
<td><a href="http://www.elacin.co.nz">www.elacin.co.nz</a></td>
</tr>
<tr>
<td></td>
<td>F-MIRE under earcups</td>
<td>Custom earplugs</td>
<td>Phonak Communications, AG</td>
<td>SafetyMeter</td>
<td><a href="http://www.phonak-communications.com">www.phonak-communications.com</a></td>
</tr>
<tr>
<td></td>
<td>Pneumatic seal test or airflow test</td>
<td>Custom earplugs</td>
<td>Bachmaier</td>
<td>Bachmaier leak test instrument</td>
<td><a href="http://www.bachmaier.de">www.bachmaier.de</a></td>
</tr>
<tr>
<td>Physical measurement using surrogate (modified) HPD</td>
<td>F-MIRE in sound field</td>
<td>Earplugs including canal caps and earmuffs</td>
<td>3M Company</td>
<td>3M™ E-A-Rfit™ Dual-Ear Validation System</td>
<td><a href="http://www.e-a-rfit.com">www.e-a-rfit.com</a></td>
</tr>
<tr>
<td>Psychophysical threshold-based measurement using standard (unmodified) HPD</td>
<td>REAT under earcups</td>
<td>Custom earplugs</td>
<td>Egger Otoplastik + Labortecnik GmbH</td>
<td>ePRO-Meter</td>
<td><a href="http://www.egger-labor.de">www.egger-labor.de</a></td>
</tr>
<tr>
<td></td>
<td>REAT under earcups</td>
<td>Earplugs</td>
<td>Cotral Lab, Inc.</td>
<td>CAPA®</td>
<td><a href="http://www.cotral.com">www.cotral.com</a></td>
</tr>
<tr>
<td></td>
<td>REAT under earcups</td>
<td>Earplugs</td>
<td>Inmedico</td>
<td>Oscilla</td>
<td><a href="http://www.inmedico.com">www.inmedico.com</a></td>
</tr>
<tr>
<td></td>
<td>REAT under earcups</td>
<td>Earplugs</td>
<td>Maico</td>
<td>MA 33</td>
<td><a href="http://www.maico-diagnostic.com">www.maico-diagnostic.com</a></td>
</tr>
<tr>
<td></td>
<td>REAT under earcups</td>
<td>Earplugs</td>
<td>Michael and Associates, Inc.</td>
<td>FitCheck Solo™</td>
<td><a href="http://www.michaelassociates.com">www.michaelassociates.com</a></td>
</tr>
<tr>
<td></td>
<td>REAT under earcups</td>
<td>Earplugs</td>
<td>Workplace INTEGRA, Inc.</td>
<td>INTEGRAfit®</td>
<td><a href="http://www.workplaceintegra.com">www.workplaceintegra.com</a></td>
</tr>
<tr>
<td>Psychophysical above-threshold measurement using standard (unmodified) HPD</td>
<td>Loudness Balance</td>
<td>Earplugs</td>
<td>Howard Leight by Honeywell International, Inc.</td>
<td>VeriPRO®</td>
<td><a href="http://www.howardleight.com">www.howardleight.com</a></td>
</tr>
</tbody>
</table>
Fit-Test Systems Specifications and Features

As seen previously, fit-test systems can rely on different types of technology. The underlying measurement approach and particular hardware used will have different effects on the PAR outcomes. Table 3 presents the various technologies and their general pros and cons, while Figures 2 to 5 illustrate the testing methodologies. Other considerations regarding the various types of fit-test systems include:

- The rapidity with which the test can be accomplished will affect the practical application of the fit-test system and the ability to address and potentially improve the problem of fit uncertainty by taking repeat measurements on multiple fits. Generally, objective systems provide more rapid data acquisition, using either standard (unmodified) or surrogate (modified) HPDs.

- For objective systems that use an acoustic stimulus presented via a loudspeaker for the measurement of the HPD attenuation (see Figure 2 and Figure 3), the test signal is clearly audible and may be annoying, although usually only for a few seconds.

- For systems employing a surrogate HPD (see Figure 3), the fitting and usability of the modified HPD must be comparable to the original HPD to ensure a user's ability to fit the surrogate HPD. For example, the use of a probe tube for the inner-ear microphone measurement also increases the stiffness of the earplug and may affect the earplug's insertion.

- For systems that rely on the use of surrogate HPD (see Figure 3), the HPDs are always new and may not show the effects of aging that would occur for such a product in real field use.

- Background noise in the test environment must be low enough so as to avoid masking the test signals, especially for systems relying on psychophysical measurements.

- For systems requiring a psychophysical response from a test subject, the subject's hearing must be sufficiently good so as to ensure that the signals are perceived even after the test signal is attenuated by the HPD being tested. So too, the presence of tinnitus may complicate employee responses, as well as can problems of comprehension for users for whom the fit-test interface’s language is a second language.

- Some psychophysical systems permit the measurement procedure to be performed on HPDs worn in situ, that is, employees taken from the workplace while wearing their HPDs so that they can be tested as worn. This can be useful for auditing, measuring earplug or earmuff slippage with time, and measuring earplugs that may have been used past their prime, etc.
Table 3: Summary of commercially available fit-testing technologies including potential pros and cons. Note: the term “auditing” in the table below refers to fit testing workers directly removed from the workplace without interfering with their HPD placement, so that the devices can be tested as worn.

<table>
<thead>
<tr>
<th>Fit-test system type</th>
<th>Technology</th>
<th>Testable HPD</th>
<th>Description</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measurement using standard (unmodified) HPD</td>
<td>Pneumatic seal test or airflow test on standard hearing protector</td>
<td>Custom earplugs</td>
<td>Small pneumatic pump builds up a static air pressure underneath the earplug and a pressure measurement assesses the leakage rate of the pneumatic seal through the earplug.</td>
<td>Fast. Simple.</td>
<td>Provides only an indication of a pneumatic seal but no measurement of the amount of acoustic attenuation achieved.</td>
</tr>
<tr>
<td>Physical measurement using standard (unmodified) HPD</td>
<td>F-MIRE on standard hearing protector (see Figure 2)</td>
<td>Earmuffs or customs earplug</td>
<td>Simultaneous direct measurements of SPL outside and underneath the earmuff or earplug in the presence of either ambient noise or a sound source generating a wideband or narrowband noise. The sound source can be an external loudspeaker or headphones.</td>
<td>Fast. Objective. Tests all frequencies simultaneously. Relatively insensitive to background noise. Not affected by hearing loss. Can be used for auditing. Can be used for any earmuffs</td>
<td>Must be used with manufacturer’s custom earplug. When accomplished with an external loudspeaker, noise from test is audible to others in the test environment. Microphone wires, underneath the HPD, might affect the acoustic seal of the earmuff cushion</td>
</tr>
<tr>
<td>Physical measurement using surrogate (modified) HPD</td>
<td>F-MIRE on surrogate hearing protector (see Figure 3)</td>
<td>Earmuffs or earplugs</td>
<td>Simultaneous direct measurements of SPL outside and underneath the modified hearing protector in the presence of a wideband or narrowband noise source. The sound source can be an external loudspeaker or headphones when testing earplugs, but an external loudspeaker is required when testing earmuffs.</td>
<td>Fast. Objective. Tests all frequencies simultaneously. Relatively insensitive to background noise. Not affected by hearing loss.</td>
<td>Must be used with manufacturer’s surrogate test HPDs. When accomplished with an external loudspeaker, noise from test is audible to others in the test environment. Employee cannot be audited, as the surrogate earplugs or earmuffs cannot be worn independently as an HPD.</td>
</tr>
<tr>
<td>Psychophysical threshold-based measurement using standard (unmodified) HPD</td>
<td>Earplugs</td>
<td>Can be used with any manufacturer’s earplug (not canal caps). Can be used for auditing.</td>
<td>Relies on employee’s subjective response. Employees with hearing loss may not be able to hear the test signal in the occluded condition or at all test frequencies. Employees with tinnitus may not be able to distinguish the test signals adequately. Test time increases with number of frequencies tested. When testing both ears simultaneously one loses the ability to determine if just one or both plugs are misfitted Cannot test earmuffs or canal caps.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
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<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REAT under headphones (see Figure 4)</td>
<td>Similar to the gold standard approach of laboratory-based REAT testing, but conducted in the field and performed under circumaural-type headphones. Hearing testing with and without earplug, each frequency separately, each ear tested separately or ears tested together, depending on the system and end-user choice.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REAT in portable booth</td>
<td>Similar to the gold standard approach of laboratory-based REAT testing, but conducted in field portable sound booth. Hearing testing with and without earplugs or earmuffs, each frequency separately.</td>
<td>Can be used with any manufacturer’s earplug and any type of HPD. Can be used for auditing.</td>
<td>Relies on user’s subjective response. Users with hearing loss may be unable to hear the test signal. Employees with tinnitus may not be able to distinguish the test signals adequately. Test time increases with number of frequencies tested. Calibration of the sound field requires high sensitivity ambient microphones to</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Other fit-testing technologies have also been tested over the years, from psychophysical techniques, such as the use of bone-conduction loudness balance (Rimmer and Ellenbecker, 1997) to the use of biophysical techniques using electroencephalography (Valentin and al., 2014). While further research is needed, they may have the potential to be commercialized in the future.

**<INSERT FIG 2 – 5 HERE>**

### <H3> Performance Criteria for Fit-Test Systems</H3>

To allow operators to properly select the fit-test system that is most suitable for their application, manufacturers should make performance statements and guidance available. Following are suggestions based both on the authors’ experience, and on material being drafted in the ANSI S12.71 standard that has been under development (Voix, 2011).

- For all fit-test systems, the manufacturer should specify:
  - Whether the fit-test system provides an overall attenuation measurement value and/or simply a pass-or-fail assessment,
  - In the case of an attenuation measurement value, whether the reported PAR is computed per the ANSI/ASA S12.71 standard or some other nonstandard type of rating,
- Which frequency or octave-band attenuation values are available in addition to the overall attenuation measurement value,
- Whether the attenuation measurements are presented for each separately (monaural), and/or as a single value combining both ears (binaural), closely resembling the attenuation measured using the REAT procedure as defined in ANSI/ASA S12.6 or ISO 4869-1 (see details in Chapter 11).
- An uncertainty statement regarding the measurement made by the fit-test system (see further subsection on “Fit-test system uncertainty” for details),
- The lowest and highest measureable attenuation, which might depend upon both the type and model of HPD tested, and the maximum permissible background noise level in which the fit test can be conducted accurately,
- The recommended periodic physical calibration intervals for the fit-test system,
- Any daily check that should be performed at the time of the measurement to ensure optimal fit-test system performance,
- Whether subjects shall or shall not wear eyeglasses, ear jewelry, or other accessories that might affect the ability of the fit-test system to operate in its intended measurement mode.

- For fit-test systems using physical measurement on surrogate HPDs, the manufacturer should provide guidance to the fit-test system operator on how the physical design of the surrogate HPD might affect the fitting of the HPD by the user.
- For fit-test systems using a physical measurement on a surrogate HPD, guidance should specify whether the manufacturer has designed the system to account for differences in attenuation performance between the surrogate and the actual HPD that it represents.
- For fit-test systems using a psychophysical measurement, manufacturers should provide guidance to the operator on how to estimate the subjects' maximum permissible hearing loss for testing and how to identify and handle the issue when users cannot hear test signals sufficiently to provide consistent responses. Manufacturers should also provide guidance to the operator regarding users with asymmetrical hearing loss and tinnitus and how this might affect test results.
- For fit-test systems that rely on the use of circumaural sound generation systems, manufacturers should advise users on how to properly position the test cups, and that the systems should not rest on or otherwise touch the pinna or the HPD, because this may affect the fit of the device and cause measured values to be unreliable.
- For fit-test systems that report only a pass or a fail, the criterion limit, i.e. the attenuation threshold at which a HPD attenuation test is passed, should be explained and presented as a PAR-like value.

**<H2> Fit-Test System Outputs**

Many fit-test systems can provide measurement results estimating REAT values at one or more frequencies, ideally the seven octave bands ranging from 125 Hz to 8000 Hz. However, the preferred output for most end users is a single-number rating, termed a PAR. This PAR combines the attenuation values of both ears, as does the REAT procedure that in practice measures the binaural attenuation of HPDs. The output, by most fit-testing applications, of a single binaural PAR value enables an end user to take measurements and to quickly make
recommendations for individual users’ noise exposure. Since employee exposure data are generally only available as single-number A-weighted values, a single-number PAR output is practical. However, some systems also report values for each ear individually as that can be useful in training for those instances in which workers may have more trouble fitting one ear than the other.

Numerous single-number ratings have been devised, and indeed the various fit-test systems have computed their own single numbers with differing approaches. The computational method currently being contemplated in the draft ANSI S12.71 standard is analogous to the Noise Reduction Statistic for use with A-Weighting (NRSA) as defined in ANSI/ASA S12.68 (ANSI, 2012). This standardized definition of PARs enables the cross-comparison of fit-testing results which will be briefly presented hereafter (Voix, 2011).

**<H3> Personal Attenuation Rating (PAR)**

The computation of the PAR described in this chapter relies on the calculation for a given fitting of the HPD on a single user, of the overall average A-weighted attenuation in a large ensemble of representative noise spectra. As the shape of the spectrum is part of the computations involving the various noises, this approach is only possible for fit-test system that report two or more octave-band attenuation values. The spectra used for the computation of a PAR have been commonly referred to as the NIOSH 100 Noises (Kroes et al, 1975). They are a sample of industrial noise spectra and are also provided in the ANSI S12.68 standard.

The PAR is an NRR-like number, but since it is based on the data from one wearer who is the actual user of the device, instead of a group of 10-20 subjects, the between-subject standard-deviation correction that is included in the NRR computation is not needed. However, as with any single-number rating such as the NRR, the spectral variability must be accounted for. With the NRR this is accomplished using a constant 3-dB spectral safety factor, whereas the PAR accomplishes this with an explicit protection performance value (see Table 4) that results from the variability in the computations using the 100 NIOSH noises. The PAR can be directly subtracted from A-weighted noise measurements instead of requiring the use of C-weighted values, as is recommended with application of the NRR. The computational details of the PAR are beyond the scope of this chapter but can be found in Voix and Hager (2009) together with a comparison to other attenuation ratings and metrics. Ultimately, these calculations lead to the following equations:

\[
\text{PAR}_x = \text{FAES}_A - \alpha \cdot u_{\text{FAES}_A} \tag{1}
\]

where

\[
u_{\text{FAES}_A} = \sqrt{s^2_{\text{measurement}} + s^2_{\text{fit}} + s^2_{\text{spectrum}}} \tag{2}
\]

with \(\text{FAES}_A\) the overall A-weighted attenuation of the HPD estimated by the fit-test system, \(\alpha\) the coverage factor from Table 4, and \(u_{\text{FAES}_A}\) the combined uncertainty defined as the square root of the sum of the squares of the measurement, fit, and spectrum uncertainty components, later defined in the section Sources of Uncertainty.
As seen from Equation 1, PAR accounts for the combined uncertainty, $u_{FAESA}$, and is expressed at a protection performance $x$ (a percentile value), denoted as PAR$_x$. The desired percentile $x$ is usually expressed at 50%, 80%, 84%, or 98% and embeds a corresponding multiplicative constant, $\alpha$, as tabulated in Table 4, times the fit-test system combined uncertainty. In the case of a PAR$_{50}$, no contribution from the combined uncertainty is subtracted from the measured PAR value, while in PAR$_{84}$, twice the combined measurement uncertainty is subtracted from the measured PAR value. While PAR$_{50}$ represents the most statistically probable value, the use of PAR$_{80}$, PAR$_{84}$, or even PAR$_{98}$ is a safe practice when assessing the sufficiency of hearing protector attenuation for a given individual.

<table>
<thead>
<tr>
<th>Protection performance $x$ (%)</th>
<th>Value of $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.00</td>
</tr>
<tr>
<td>80</td>
<td>0.84</td>
</tr>
<tr>
<td>84</td>
<td>1.00</td>
</tr>
<tr>
<td>90</td>
<td>1.28</td>
</tr>
<tr>
<td>95</td>
<td>1.64</td>
</tr>
<tr>
<td>98</td>
<td>2.00</td>
</tr>
</tbody>
</table>

The use of PAR$_{80}$, PAR$_{84}$, or even PAR$_{98}$ is a safe practice when assessing the sufficiency of hearing protector attenuation for a given individual exposed to a known level of noise. These values are reduced by some fractions of the combined uncertainty to ensure a conservative estimate of the actual attenuation of the HPD. Just like a road patrol would reduce by a few miles per hour the measured speed of your vehicle, to account for its radar uncertainty, in order to be able to ascertain if you were indeed speeding.

PARs are based on measurements performed in a relatively short period of time, ranging from a few seconds to a few minutes, and provide a more direct estimate of the protection that a given individual is expected to receive from her or his HPD than does average data from a group of subjects in a separate laboratory experiment. However, PARs are still not based upon in situ measurements for actual users exposed to the noise they experience during a work shift. Thus, PARs reflect what users can achieve and have been shown to achieve, not necessarily what they truly achieve on a day-to-day basis, as will be discussed in the following section.

**Fit-Test Systems Uncertainty**

Regardless of the system type, a key performance metric is the comparison of attenuation data estimated via the fit-test system to a REAT measurement (Berger et al., 2011). Whether using an objective or subjective measurement approach, the fit-test system results may differ from REAT on a given fit of an HPD on a given subject. This should be assessed on a large group of test subjects under controlled conditions and reported in an uncertainty statement.
For those applications in which an explicit noise attenuation estimate is required, the specification of uncertainty is important. Measurement uncertainty may differ between the various systems. For the operator or user to appropriately apply the measured attenuation data, a clear statement of the uncertainty and how it should be included in the evaluation process should be provided. Uncertainty estimates are needed not only for proper application of the measured data but also to facilitate a comparison of the quality of the data from differing fit-test systems.

**<H4> Sources of Uncertainty**

There are three principal sources of uncertainty, assumed to be independent, that are inherent in the measurement and application of fit testing data and need to be considered in the computation of PAR (Berger et al., 2011).

*Measurement uncertainty,* $s^2_{\text{measurement}}$ in Equation 2, sometimes called prediction uncertainty, pertains to the difference between the fit-test system prediction of attenuation and the value measured by an accepted gold standard such as REAT. Since REAT values contain their own uncertainty (which is known from many published laboratory studies), a divergence on a single measurement between REAT and fit-test system does not necessarily indicate the fit-test system estimate is in error. Rather, multiple REAT and fit-testing measurements must be compared so that the quality of the fit-test system data can be determined by the amount of bias with respect to the REAT values and the spread of the data that exists (Voix, 2011).

*Fit uncertainty,* $s^2_{\text{fit}}$ in Equation 2, pertains to the variability in the attenuation of the HPD from one fit to the next. Fit uncertainty, which may often be the largest component of uncertainty, is substantially affected by the skill of the person doing the fitting, which may be the operator or the user, and also by the fitting characteristics of the HPD that is being evaluated. This component of uncertainty is largely independent of the particular fit-test system that is used for the measurement process.

*Spectral uncertainty,* $s^2_{\text{spectrum}}$ in Equation 2, arises when a fit-test system provides a single number such as a PAR that is to be applied to A-weighted sound level measurements of noises with unknown spectral content. Depending on the actual noise spectral content, there can be a variation between the attenuation predicted using an octave-band calculation applied to the actual octave-band noise data, versus that achieved with a PAR, which is analogous to the single-number approach described in ANSI S12.68 (ANSI, 2012). When the actual octave-band noise data are available and used for the computation of the attenuation, the spectral uncertainty component becomes null.

**<H1> Utilization of HPD Fit Testing in Industry**

**<H2> Implementing Fit Testing Within a Hearing Loss Prevention Program (HLPP)**

In the absence of regulatory directives and extensive FAES-applied research, reliance on practical experience provides the needed guidance to implement fit testing in an HLPP. Considering the “who, what, where, why, and how” fit testing is implemented will help maximize the benefits of integrating such a program into an HLPP.

The ways in which fit testing is implemented, as well as the types of HPDs to which it is applied, can vary widely. Though some fit testing systems currently exist that can estimate the attenuation provided by earmuffs (see Table 3), many fit-test systems feature circumaural cups for signal presentation and testing, and thus are limited to
estimating the attenuation of devices that will fit beneath those earcups, such as earplugs. The magnitude of this problem is limited, though, since earmuffs are more easily fit correctly than earplugs and thus are less in need of fit testing. However, there are other advantages to fit-testing earmuffs, such as the ability to measure them while wearing other PPE or clothing that may reduce attenuation, or to measure used and worn earmuff cups or headbands that may have degraded with use (Wells et al., 2013).

Who Is the Target Population?
Who is chosen to be fit tested may be a matter of available time and human resources. The target population is presumably the group of employees expected to be at risk for noise-induced hearing loss (NIHL) and may either be limited or broadly defined. A company may prioritize a particular target population when first implementing a fit-testing program but then expand to other groups as time and resources allow. Examples of target populations include:

- **Newly hired employees** - This population benefits from a fit test as a means of initial training on the proper use of a hearing protector, selecting the best device for the noise exposure, and establishing a baseline for future comparison purposes.

- **Employees with a measured temporary threshold shift (TTS) or OSHA-defined standard threshold shift (STS)** – One of the follow-up steps for STS cases is to provide, if necessary, a hearing protector that offers greater attenuation. Currently, the NRR is used as an indicator of attenuation even though it is not typically an accurate measure of either group or individual performance in the workplace. Fit testing, which is a better indicator of individual performance, can be used to determine if the employee is not achieving adequate protection and remedy the problem via training or selection of an alternative HPD. Monitoring STS is a trailing indicator of a successful HLPP. Concentrating efforts solely on this population limits the ability to identify employees who have inadequate protection and to intervene before they exhibit damage to their auditory system. A proactive approach is preferable.

- **Subset of employees who work in the highest noise areas or are required to wear dual hearing protection** – With large populations of employees, companies may also opt to concentrate their fit testing efforts on the employees exposed to the most noise-hazardous areas or jobs in the workplace. Although this approach is more manageable in terms of time investment and staffing, the opportunity to identify high-risk employees exposed at lower levels is missed. Since 9 out of 10 workers are exposed to 95 dBA or less, this may mean that a large portion of the population would not be evaluated (OSHA, 1981).

- **Subset of employees who are at the margins of inclusion for mandatory hearing protection** – Rabinowitz et al. (2007) found that workers whose ambient noise exposure was less than or equal to 85 dBA were more likely to experience an STS of 10 dB compared to employees with higher exposures. Therefore, it may be prudent to include this group of workers.

- **Subset of employees exposed to ototoxic chemicals as well as to noise** – This population may be more vulnerable to hearing loss and may benefit from fit testing to ensure they have adequate protection.

- **All employees enrolled in the HLPP** – Ideally, every employee in an HLPP should be fit tested and can benefit from the experience. This provides the greatest opportunity for employer risk-management.

- **All employees regardless of noise exposure at work** – The most comprehensive HPD fit-testing programs include the entire worker population, not just those who qualify for the hearing conservation
program. Companies that offer fit testing for all employees understand that employees may participate in noisy activities outside of work and can benefit from knowing how to wear hearing protectors properly. Many companies encourage employees to take hearing protectors home—for example, to wear while using power tools, mowing the lawn, attending loud concerts, hunting, or shooting. Extending the fit-testing program to all employees regardless of their exposure at work supports HPD use at non-occupational events by reinforcing proper hearing protector usage and increasing NIHL awareness. Including fit testing for entire worker populations can be an important benefit to employees within a company's overall wellness program.

<H2> Who Conducts the Fit Tests and/or Manages the Fit-Testing Program?</H2>

In general, those responsible for the HLPP will manage the fit testing program. Examples of personnel typically responsible, previously referred to as operators, for conducting fit-tests include:

- Industrial hygienists,
- Occupational hearing conservationists certified by CAOHC¹,
- Safety professionals,
- Occupational audiologists
- Occupational health nurses,
- Vendor-trained personnel,
- Independent or authorized service providers.

<H2> What are the Benefits of Fit Testing and Why Include Fit Testing in an HLPP?</H2>

<table>
<thead>
<tr>
<th>What are the benefits of fit testing and why include fit testing in an HLPP?</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Identifying employees at risk of NIHL and benchmarking</td>
</tr>
<tr>
<td>- Verifying the proper attenuation of hearing protection</td>
</tr>
<tr>
<td>- Training and motivational tool</td>
</tr>
<tr>
<td>- Train the trainer tool</td>
</tr>
<tr>
<td>- Hearing protector selection tool</td>
</tr>
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</table>

<H3> Identifying Employees at Risk of NIHL and Benchmarking</H3>

Federal regulatory agencies require employee training. For example, OSHA (1983) requires that employers must "provide training in the use and care of all HPDs, ensure proper initial fitting and supervise the correct use of all hearing protectors" (29 CFR 1910.95 (i)(5)). Before fit-testing technologies became available in the market, employers were unable to consistently ensure a proper initial fit and document the attenuation achieved by an individual worker. Their only choice for product selection and estimation of attenuation was to rely on manufacturers' labeled attenuation values, which are of little value in making predictions for individual workers. For assuring good fit there have been many approaches to improve fitting and try to achieve a "best fit" as for example the section on tips for fitting hearing protectors in Chapter 11. But until the advent of fit testing, health and safety professionals did not have an effective means of measuring whether adequate protection was being achieved and if training had influenced behavior.

For newly-hired workers who have never worn hearing protectors, it is best to train them prior to the initial fit test with the strategies described in Chapter 11. For other workers, those who are familiar with hearing protector fitting, the fit-test operator should conduct measurements during their initial fit-test visit to establish a baseline value of

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¹ Council for Accreditation in Occupational Hearing Conservation
performance (not to be confused with the baseline audigram as required by OSHA for audiometric testing). Ideally, the operator should ask the workers to fit the hearing protector as they would while working in noise and carefully observe the fitting technique, without coaching or intervention. Then the operator should perform the baseline measurement fit test and record the results. The baseline measurements can identify the workers who, because of low or inadequate PARs relative to their noise exposures are presumably at risk for NIHL, and enable the health and safety professional to focus intervention efforts on this subgroup. The results of baseline fit-test measurements may be just one metric used to evaluate prior hearing conservation training and serve to judge program effectiveness. The 2012 recipient of the Safe-in-Sound Excellence in Hearing Loss Prevention award, Johns Manville, used the percent of employees achieving a criterion PAR as one of many metrics to evaluate their HLPP (NIOSH, 2016).

Michael and Byrne (2002) studied hearing protector fit testing in the steel industry using a mobile testing unit. The initial measurements were performed without additional training or assistance. They witnessed a wide range of fitting techniques resulting in a substantial variability in attenuation provided by the hearing protectors. Berger et al. (2008) found similar baseline results when conducting initial fit evaluations on 351 employees from 7 different industrial plants. The individual-employee PARs ranged from 6 to 43 dB. Although the average PARs were greater than 25 dB, the associated fit testing estimated real-world NRRs were 10 dB and 18 dB for the two earplugs tested, much lower than their labeled values. The wide range in individual PARs demonstrates how group-derived fit-testing attenuation data can substantially over-estimate or under-estimate an individual worker’s attenuation. For individual workers, PARs may even vary between their left and right ears. This phenomenon may be due to differences in ear canal shape and size, however, there is little evidence that handedness plays a role.

Gathering baseline measurement data and comparing it to subsequent measurements help to quantify the value of fit testing and the educational intervention that accompanies the fit tests. Furthermore, baseline measurements provide data for benchmarking between worker groups or with other industries, and can be used as one of the metrics to evaluate a company’s HLPP.

### Verifying the Proper Attenuation of Hearing Protection

The OSHA Hearing Conservation Amendment (29 CFR 1910.95(j)(1 - 4)) requires that employers evaluate the adequacy of attenuation for specific noise environments, verify noise exposure is adequately reduced to the targeted value, and determine when re-evaluation of hearing protection attenuation is warranted. Currently, employers must choose from a variety of NIOSH methods or the NRR, all of which are variants of using manufacturers’ labeled attenuation values to estimate protection achieved by groups of workers (See Using Attenuation Data to Estimate Protection in Chapter 11). Furthermore, the OSHA Technical Manual (Section III, Chapter 5, Appendix E), outlines the method for applying a 50% derating to the NRR as a safety factor when determining if engineering controls should be implemented (OSHA, 2013). However, not only do derating schemes vary around the globe, but there is no consensus as to which scheme best describes what an individual worker is achieving when the hearing protector is worn in practice, as seen in Chapter 11. Individual fit testing allows employers to set the target minimum attenuation based on noise exposure and helps to identify workers who are inadequately protected.

Since FAES technologies were not available at the time the OSHA regulation was promulgated, they are not mentioned in the rule or included as an option to estimate attenuation. Although it is not currently a substitute for NRR according to the regulations, the fit-testing derived PAR can be an excellent supplement. If employers can use fit testing to determine the adequacy of hearing protector attenuation based on individual workers rather than group averages, it would appear a more reliable approach that makes derating unnecessary. Although current
regulations do not require fit testing, the data and information gathered during a fit-testing session may assist hearing healthcare professionals in assessing claims of worker-relatedness for OSHA recordability and workers’ compensation.

Companies differ in the way in which they use PAR to estimate worker protection. Ideally the binaural PAR (with or without uncertainty considered) should be subtracted directly from the worker’s exposure, as a single number A-weighted value to estimate worker protection. When the exposure in not known for a given worker, some companies may choose to subtract PAR from a representative exposure. If employees are highly mobile or are exposed to varying degrees of noise, some employers will opt to protect against the typical sound levels rather than use time-weighted averages and use the highest level measured for that job, or that individual worker. While seemingly more protective, this approach may introduce the risk of over protection, especially for jobs dependent on the ability to communicate in noise. Other companies may require that a worker achieve at least a minimum attenuation. This value can be set regardless of the worker’s noise exposure or can be set at a minimum attenuation that covers the worst-case scenario for exposure, resulting in a protected exposure below values of 90 dBA, 85 dBA or even 75 dBA. Depending on a company’s approach, the target minimum attenuation will be different and therefore pass/fail rates and triggers for intervention will vary.

**<H3> Training and Motivational Tool**

The OSHA Hearing Conservation Amendment (29 CFR 1910.95(k)(3)(ii)) requires employers to train workers on the advantages, disadvantages, and attenuation of various HPD types, and instruct on selection, fitting, use, and care. Simple instructions have been found to significantly improve hearing protector performance (Williams, 2004). Murphy et al. (2011a) found that individualized one-on-one training of employees in proper hearing protector fitting was superior to simply presenting video and/or the manufacturer’s written instructions. A meta-analysis of seven intervention studies found that “individual tailored education was more effective in improving HPD use compared with target education programs which address shared work characteristics (El Dib et al., 2012).”

Research studies as well as employer experiences have suggested that when individuals are involved in the fitting process and receive positive feedback on the proper fit of the earplug, they will be more likely to have a positive attitude about protecting their hearing and will be more apt to use hearing protection correctly and consistently in the workplace (Meinke and Morata, 2012; NIOSH, 2016; Smith et al., 2014). Given that fit-testing technologies provide one-on-one and tailored educational opportunities, it is not surprising that fit-test research has substantiated its usefulness. Smith et al. (2014) found that, despite having been trained annually on the proper way to fit a hearing protector, 30% of the workers discovered for the first time that they were not receiving adequate protection (i.e., protected exposures below 85 dB) and/or that the hearing protector they were wearing was not the right size or style to provide adequate attenuation (Figure 6). After retraining the employee and/or fitting them with a different size or type of HPD, every employee tested showed an increase in PAR50 from baseline to post-intervention and the average difference in PAR50 values increased significantly from baseline to post-intervention (95% CI: 10.3, 13.4) as shown in Figure 7.

**<INSERT FIGURE 6-7 HERE>**

A field study conducted on offshore oil rig inspectors by Murphy et al. (2015) found that 44% of the workers were not achieving adequate protection, but, after training, 89% improved their PAR to at least 25 dB (see Figure 8).
These findings are consistent with other studies that have analyzed PAR differences before and after training and over time (Cassano et al., 2013; Johnson, 2011; Kabe et al., 2012; Kunz et. al., 2013; Michael and Byrne, 2002; Murphy and Themann, 2012; Schulz, 2011; Tsukada and Sakakibara, 2008; Witt, 2008).

In many cases and depending on the technology, fit testing provides a teaching and motivational opportunity that is multi-sensory. First, workers can view the PAR values and watch them increase as they fit their hearing protectors more effectively. Some fit-test systems may also present other visual cues such as pass/fail indicator lights. Secondly, workers can compare their auditory experiences before and after a hearing protector is well fit. In the case of objective fit-test system that present a constant-level test noise, even the signals themselves will be perceived as quieter once the hearing protector is better fit. Finally, a well-fitted hearing protector will feel different in the ear and may often be more comfortable than a poorly fitted hearing protector. Emphasizing the differences between poorly-fitted and well-fitted hearing protectors helps to enhance the educational experience as well as to augment the training requirements of the regulation.

**<H3> Train the Trainer Tool**

Fit testing is a helpful training tool not only for workers but for the operators/trainers conducting the fit tests. Fit testing results provide data that help to guide the trainer’s intervention strategies. For example, low PAR values in combination with poor earplug fitting techniques can prompt the trainer to instruct the worker on proper roll down or use of the pinna-pull fitting technique (described in Chapter 11). Low PAR values in combination with seemingly well-fitted earplugs may prompt the trainer to consider a hearing protector better suited for larger earcanals. The trainer learns the best strategy for any given situation, and retesting helps to validate whether the interventions are successful or if further steps should be employed. With each fit test conducted, trainers gain more experience that adds to their “tool-box of tips and tricks” for future reference. Recently, educational institutions have been using fit-test systems to train health and safety students as well as audiology students in the proper use, fit, and selection of hearing protectors (Meinke, 2015). Students have incorporated fit-test systems as a means to gather personal attenuation data for research purposes that further expand the entire discipline’s understanding of real-world protection (Johnson, 2011; Kunz et al, 2013; Lerner, 2015).

**<H3> Hearing Protector Selection Tool**

Workers consider a variety of factors when deciding which hearing protector to select and wear. These factors include comfort, availability, ease-of-use, communication requirements of the job, the noise exposure, and/or the published NRR. Some workers may simply select and wear whatever hearing protector is available nearest the door of the hearing conservation area they are entering. Perceived comfort and attenuation played a key role in hearing protector usage in a study conducted by Davis et al, 2011. All too often, hearing protectors are purchased by employers with little consideration of their suitability for the individual worker. Although this approach may be fine for most workers, a percentage of the employee population will inadvertently select the wrong size or style. Fit testing can document the variety and mix of hearing protectors that are suitable for a given population.

As discussed previously, fit-testing data show that while some workers receive suitable protection, others fall short—as much as 44% of the workers—and therefore are at risk for NIHL (Murphy et al., 2011b, Murphy et al., 2015). Smith et al. (2014) found that remedial training alone did not help 11% of the study subjects, who instead required a different size or style of hearing protector in order to achieve adequate protection. Fit testing is...
essential to identify the subgroup of employees who need a different hearing protection solution than one that is chosen. An employee may need to be tested several times before finding the HPD offering attenuation required for their job. A western Australian mine found that in a group of 70 employees, many required multiple attempts to achieve a stringent proper fit criterion of 75 dBA exposure level (see Figure 9) (Hey, 2015). Murphy et al. (2015) found that the extra effort needed to achieve a proper fit and to find the right HPD amounted to an average test time of 10 minutes per employee. This is a rather small time investment given the benefit of identifying high-risk employees. Without using individual fit testing it may not be possible to identify this subgroup of high-risk employees.

<INSERT FIGURE 9 HERE>

In the absence of fit testing, environmental health and safety professionals rely on their visual assessment to determine if the HPD is appropriately selected and properly fit. Berger (2013) found with foam roll-down earplugs, depth of insertion predicted attenuation on average for a group of subjects. In general, if the hearing protector looks well inserted behind the tragus and into the earcanal, one may assume the worker is receiving adequate protection. Conversely, a hearing protector that appears to be fitted shallowly may be presumed to be poorly fit with low attenuation. Although this may be true for most employees, there will be the occasional worker who will have low PARs despite having a deeply inserted earplug, or have high PARs despite a shallow fit. The explanation for this phenomenon is a matter of unique anatomy; earcanals that are either extra-large or extra-small along with a HPD selection mismatch. Therefore, the best approach to understanding an individual worker’s hearing protector attenuation is not by visual assessment alone but by quantitative fit testing. Future research to further investigate the degree to which visual judgment of HPD fit correlates to PAR could yield interesting results.

The OSHA Hearing Conservation Amendment (29 CFR 1910.95(i)(3)) states that employers should provide a variety of suitable hearing protection options. However, employers frequently set a minimum NRR as the criterion to decide what is suitable and this policy may limit the variety of hearing protectors made available to employees. For example, a hearing protector with an NRR of 26 dB may actually perform better than one with a NRR of 33 dB for a given individual worker and yet may not be offered as an option, solely based on the lower NRR. PAR can be used to guide the selection of which hearing protectors are appropriate for the worker’s noise environment. If multiple hearing protectors are tested on each worker and are proven to adequately protect against the noise, the worker will have additional hearing protector options from which to choose, if their assigned hearing protector is not currently or no longer available. Furthermore, the results of individual fit testing can help companies manage hearing protector inventory and could conceivably result in cost savings.

<H2> Where and How Is a Fit Test Conducted?</H2>

The physical location and conditions for fit testing are dependent on the type of fit-test system implemented. Systems that require a relatively quiet environment, usually psychophysical systems based on threshold measurements, need a quiet office, medical clinic, or sound booth. Other systems may function well in an open area close to the worker’s work environment such as a lunch room or conference room. Regardless of the fit-test system(s) chosen, if testing large groups of employees, implementing fit testing is more efficient and effective if:

- The fit-test location is centrally located and easily accessible to the workers;
• Managers and supervisors are engaged in the process and can assist in assuring the workers can leave their workstations to be fit tested quickly and on a timely basis;

• A flexible schedule with individual time slots is employed;

• A “wrangler” is designated who can assist and ensure the efficient flow of workers to be tested.

• Educational materials and tools are available if additional training is required;

• A complete selection of hearing protector samples of all types that are used at the plant is available to give to workers, especially for cases in which they have been “reassigned” a different size or style based on fit test results.

**<H2> How Often Is Fit Testing Performed?**

In the absence of guidance documents, standards, or regulations that define how fit testing is implemented, it is the prerogative of the company to decide the interval between fit tests. As with other aspects of HLPPs, such as noise hazard assessment and audiometry, fit testing hearing protectors should not be considered a one-time event. Follow-up measurements on workers who achieve adequate protection during baseline measurements help to document that workers continue to wear their hearing protector properly over time. Follow-up measurements on workers identified as high-risk (low baseline PARs and higher noise exposures) are important for three reasons.

- **Access and assignment** - It is important to determine if the worker has access to and uses the assigned hearing protector. The assigned hearing protector must be readily available for use in order for the worker to have more fit and wear experience and to decide if the HPD is comfortable to wear over the course of his or her work shift. Commonly, workers “wear whatever is available” as they enter the noisy areas even if it is not their hearing protector of choice or the one assigned. Changing this culture for hearing protector selection may be challenging. However, as discussed earlier, hearing protector samples made available to workers after “reassignment” can help to ensure there is continuity between the assigned hearing protector during a fit test and the hearing protector worn in the workplace.

- **Comfort** - A good hearing protector choice is one that not only provides adequate protection but is also worn 100% of the time when the worker is exposed to noise. An uncomfortable hearing protector can affect wear time and overall effective attenuation as described in Chapter 11. Assessing comfort can be complicated given the subjective nature of the metrics used. Park and Casali (1991) reported that HPD comfort ratings established in a laboratory environment attempting to replicate the rigors of work may not predict user comfort and convenience in actual work conditions. The importance of comfort should not be underestimated when selecting hearing protectors, and arbitrarily assigning the highest-attenuation HPD without regard to comfort should be avoided. A newly assigned HPD that is first worn during a short fit-test session may not be representative of how comfortable the hearing protector will feel when worn for an extended period of time. One risk of assigning an uncomfortable HPD is that the worker will revert back to his or her original device despite learning it is not protective enough during the fit-testing session. Consequently, it is imperative to follow up with the employee to assess comfort and the acceptance of the assigned HPD before the worker reverts to a hearing protector offering inadequate attenuation.

- **Attenuation** – Conducting follow-up measurements will assist in documenting whether the employee continues to receive adequate protection over time. Smith et al. (2014) found that although the study
subjects showed a gain in PAR from baseline to post-intervention, it was not sustained at the same level when tested 6 months later. Note that a few subjects showed a marked decline compared to their initial baseline as shown in Figure 10. Meinke et al. (2015) utilized FAES to measure hearing protector attenuation on workers before and two hours into their shift. They found that attenuation of hearing protectors decreased somewhat over time, attenuation is variable among workers, and the variability is greater with preformed than with formable earplugs. Similar variations in hearing protector attenuation were found when FAES measurements were conducted multiple times over a representative duration of two or three hours (Le Cocq and Voix, 2014). Changes in hearing protector fit over a work shift, access to the assigned hearing protector, comfort concerns, and the need for repeat training may all be factors influencing PAR over time.

<INSERT FIGURE 10 HERE>

Given the issues with access and comfort, frequent follow up seems a logical approach to ensuring good attenuation over time, but it is less clear how this should be accomplished. The effect of a booster intervention to increase hearing protector usage has been studied. A booster intervention can be any follow-up action that serves to reinforce a health behavior, such as hearing protector usage, and may come in the form of follow-up phone calls, post cards, or electronic messaging. Hong et al. (2013) conducted a randomized controlled trial measuring the effectiveness of booster interventions and found that a booster given approximately two to three months after the initial intervention resulted in a significantly greater increase in hearing protector usage at two years as compared to a shorter-term booster given after approximately one to two months, and a longer-term booster given after approximately three to four months. Clearly, increased HPD usage is important but also validating the correct use is key. How often workers are fit tested may be dependent on the level of noise exposure, the worker’s hearing health status and baseline PAR values, and the protection that is recommended. The commitment of resources required may prohibit the ability to provide follow-up fit tests and booster interventions. More research may help to understand the optimal test interval and type of booster intervention that can be the most effective at maintaining PAR over time.

**<H2> Summary of Potential Benefits of Fit Testing**

Incorporating fit testing within an HLPP results in a multitude of benefits as discussed previously. The list below highlights the most compelling benefits of fit testing. Fit testing can be used to:

1. Identify workers with low PARs who are consequently at risk for developing NIHL.
2. Verify the attenuation of HPDs by individual measurements, instead of relying on derated laboratory-derived values that are based on group-average rather than individual-worker data.
3. Train and motivate employees on the proper use and fitting of HPDs.
4. Select and assign HPDs based on noise exposures, expected protection levels, and the anatomy of the workers’ earcanals.
5. Train personnel responsible for teaching employees the proper use and fitting of HPDs.
6. Provide an STS follow-up procedure to determine whether the problem may be related to either the fit or the selection of the HPD.
7. Provide data that may be accepted by regulatory agencies as a better alternative to using labeled attenuation values and derated NRRs, to assess HPD adequacy.

8. Audit departments to evaluate overall HPD effectiveness and suitability.

9. Provide documentation that may be useful to demonstrate hearing loss prevention efforts conducted by a company that go beyond regulatory requirements.

**<H1> Limitations of Current Fit-Testing Systems**

Individual fit testing offers great potential and advantages for hearing conservation, but fit-test systems have inherent limitations that should be considered. One limitation is that the measurements performed are only a “snapshot” revealing the attenuation of a given HPD at the time of measurement. Education and motivation, supervision and enforcement, attention to detail and ergonomics, etc. (see Individual and Group Training section in Chapter 11) will help assure that the measured attenuation value will later be achieved by the user in the field. While this may seem obvious, the argument is worth mentioning, as studies have demonstrated that earplugs are not always consistently fitted (Voix and Le Cocq, 2010) and also that earplugs may work loose with time and require periodic reseating (Kusy and Chatillon, 2012; Meinke et al., 2015; Nélisse et al., 2012). In this regard, field measurement systems that provide continuous monitoring of an individual user’s actual noise exposure under the HPD (Bessette, 2012; Gallagher et al., 2014; Mazur and Voix, 2013 Michael and al., 2011; Rabinowitz and al., 2010; Theis et al., 2012) have merit in answering the question, “Is this worker properly protected against noise exposure?”. One of the push backs on applying such systems today is the time-consuming and administratively burdensome nature of their current implementation, but this might change in the future with the rapid technological developments in electronic hearing protectors and wearable electronic devices.

Another issue relates to the fact that measurements obtained by FAES, as with any metrological device, have an inherent uncertainty, i.e. the reported attenuation values may differ from the “true” physical attenuation. As already mentioned several times, this uncertainty should be reported or otherwise accounted for by the fit-test system so that it may be taken into account by the operator, especially in applications in which a specific HPD noise attenuation is required. Several third-party independent validation studies have been conducted on existing commercial systems. Some of these studies report that certain fit-test systems on the market may present results that substantially differ from a REAT evaluation on that same subject following ISO 4869 or ANSI/ASA S12.6 (Brueck, 2013; Trompette and Kusy, 2013; Dyrba et al., 2014).

**<H1> Efforts at Developing an American National Standard Pertinent to FAES**

The number and variety of commercially available FAES have been rapidly increasing since the early 2000s. Because of the wide range of technologies used, it was determined that a standard would be helpful to ensure quality of FAES measurement outcomes. The development of such a standard, designated ASA/BSR S12.71-201x, is in process under the auspices of the Acoustical Society of America (ASA) and the American National Standards Institute (ANSI). The ASA Working Group S12/WG 11, Hearing Protector Attenuation and Performance, has prepared an initial draft of a standard as of 2017 and is continuing to work to finalize this for balloting and approval.

In its current draft format, ANSI S12.71 specifies minimum performance criteria for systems designed to estimate the real-ear attenuation provided by HPDs on individual users. The performance criteria are intended to ensure that FAES complying with the standard provide comparable test results to a reference laboratory procedure. As
such, the quality of the data are assessed by comparison of FAES data to those from the standard REAT procedure (ANSI, 2016) for the same fit of the device on an identical group of test subjects. This standard will also provide guidance to manufacturers of FAES in the development of systems and how to specify their performance in a standardized manner, including reporting FAES provide data that are both useful for estimates of the attenuation obtained by individual users and are comparable between systems. This standard also contemplates specifying procedures for the computation of a PAR. Individual fit-test data do not replace the laboratory, controlled, group attenuation data from ANSI/ASA S12.6 or the insertion-loss data from ANSI/ASA S12.42 (ANSI, 2010), nor are such data suitable for use as input data for ANSI/ASA S12.68 (ANSI, 2012). Furthermore, such data are not suitable for labeling the attenuation of HPDs.

**<H1> The Future of Fit Testing with Respect to Best Practices in Hearing Loss Prevention**

The positive impact of fit testing in the efforts to reduce noise-induced hearing loss in the workplace is now widely documented in a variety of industries and across different territories, as described throughout this chapter, as well as in Berger et al. (2008), Hager and Smith (2010), and Witt (2006, 2007a, 2007b, 2008). For these reasons, the use of fit testing is now becoming increasingly accepted in HLPPs such as by many of the award-winning hearing loss prevention programs which have been recognized with the NIOSH/NHCA Safe-in-Sound award (NIOSH, 2016). Furthermore, the OSHA-NHCA-NIOSH Alliance has identified individual fit-testing as an emerging trend and best practice (OSHA, 2008). Other regulatory initiatives are currently underway around the globe as countries are considering including fit testing as a best practice in hearing protection use standards and guidance documents. Currently, individual fit testing is included within the standards on hearing conservation and the selection of HPDs in the U.S., Canada, and Europe (ANSI/ASSE A10.46, 2013; CSA Z94.2, 2014; CSA Z1007 2016; EN 458, 2015). Furthermore the U. S. military has recognized the importance of fit testing by including recommendations to fit test when feasible (Mil Standard 1474E Section 4.2.1.1, DoD, 2015) and in the case of the Army, when STSs are detected (Department of the Army, Pamphlet 40–501, 2015). In addition, several countries, including Germany, are planning or have already included fit testing in upcoming revisions to existing standards and requirements.

Despite some limitations, additional research and refinements in commercial systems can be anticipated, and standards and policy developments continue to help refine the use of individual fit testing. Individual fit testing of hearing protection represents HLPP best practice in the early 21st century, and is a valuable step toward the goal of preventing occupational noise-induced hearing loss.

**<H1> References**


Hey, K. (2015). Personal communication regarding testing at Newmont Mining, Western Australia.


FIGURES

Figure 1: REAT measurement on an earplug (psychophysical measurement using a standard HPD) in a sound field in a laboratory: (a) Measurement of open ear auditory threshold; (b) Measurement of protected ear auditory threshold
Figure 2: Field-MIRE on custom earplug (physical measurement using a standard earplug): Measurement of SPLs outside and underneath the HPD in the presence of a loudspeaker sound source or alternatively a headphone sound source (not represented here).
Figure 3: Field-MIRE on an HPD (physical measurement using a surrogate HPD): Measurement of SPLs outside and underneath the surrogate HPD, here an earplug (but some systems also support earmuff testing), in the presence of a loudspeaker sound source
Figure 4: REAT on an earplug under headphones (psychophysical measurement using a standard earplug): (a) Measurement of open ear auditory threshold; (b) Measurement of protected ear auditory threshold
Figure 5: Loudness balance on an earplug (psychophysical measurement using a standard HPD): Subjective equalization of loudness between both ears using headphones, under sequential tests with the conditions of open ears, an earplug in one ear, and then earplugs in both ears.
Figure 6: Baseline binaural PAR results for initial fit testing for a group of manufacturing workers ($n = 327$) with protection exposure goal $< 85$ dBA (Smith et al., 2014).
Figure 7: Baseline PAR$_{50}$ vs. post-intervention PAR$_{50}$ (n=91) for workers identified as failing initial testing criteria based on minimum PARs, binaural disparity in PARs, and lacking low-frequency attenuation (Smith et al., 2014).
Figure 8: Initial and final PAR results for offshore oil rig inspectors (n = 75 for the 2012 survey and n = 86 for the 2013 survey with 35 workers tested during both surveys.) The solid symbols indicate the initial fit-test PAR based upon measurements of attenuation at 500, 1000, and 2000 Hz. The open symbols indicate the final PAR values that workers achieved after retesting or training. In 2013, four workers (a, b, c, and d) were fit-test with different protectors to see whether those devices might be appropriate, but they failed to meet the target PAR of 25 dB (Murphy et al. 2016 used with permission).
Figure 9: Number of earplug types tested before achieving a protected exposure of < 75 dB for a group of mining workers. “No fit” indicates that all 8 earplug choices failed to protect < 75 dB (5.6% of the employees tested). Courtesy of K. Hey (2015).
Figure 10 – Initial visit, post-intervention \( \text{PAR}_{50} \) vs. follow-up \( \text{PAR}_{50} \) six months later \((n = 70)\) for a subset of the set of workers whose data appear in Figure 7. Twenty-one workers were not available for testing at the follow-up visit (Smith et al., 2014).