

Individual Fit Testing of Hearing Protection Devices

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While hearing protection devices (HPD) have been the last and often only line of defense against noise-induced hearing loss in the workplace, their performance has been suspect. Laboratory evaluations have not proven to predict the actual performance of HPD in the field. Individual fit testing of HPD will allow the determination of HPD performance on individual workers, and this will improve the ability to select HPD appropriate for given noise exposures and intervene with workers to ensure sufficiency in HPD performance. A modified microphone-in-real-ear (F-MIRE) has been adapted to test a variety of HPD quickly and reliably in situ. A dual-element microphone and software combination permits reliable noise reduction measurements. Statistically developed compensation factors permit direct comparison of F-MIRE predicted personal attenuation ratings to traditional laboratory measures of HPD performance using real-ear-attenuation-at-threshold assessments.

earplug earmuff attenuation variability field measurement

1. INTRODUCTION

Determining, or even estimating, the real world performance of hearing protection devices (HPD) for individual users has proven problematic. Laboratory-derived rating systems, such as noise reduction rating (NRR [1]) and single number rating (SNR [2]) use analyses of test results from small sample populations, and attempt to extrapolate those findings to individuals and the population at large with statistical methods [3]. While the test protocols are valid, variability of the source data (i.e., individual test responses) underlying these calculations results in large standard deviations (commonly greater than 4 dB under Standard No. ANSI S3.19-1974 [4], and as much as 9 dB under other test protocols) [5]. Such broad standard deviations even in a carefully controlled laboratory test are an indication of the range of personal variability in HPD fit. In addition, even the compensation built into the number rating systems by applying generous “corrections” (e.g., the

NRR calculation applies two standard deviations to attempt to represent protection provided to 98% of the population) does not provide a valid indication of how well individual users will be protected in noise. Berger et al. found that not only do laboratory values severely overstate the amount of protection found in HPD field studies, but that a higher laboratory value does not equate with a higher real-use field value [6, 7]. It is clear that if the objective is to determine HPD performance on individual people, the appropriate approach is to test them on individual people. Various approaches have been taken to accomplish this end, with most adapting real-ear-attenuation-at-threshold (REAT) protocols, where the subject takes a hearing test with and without a HPD in place (see, e.g., Murphy, Franks and Harris [8]). The resulting insertion loss or difference is indicative of personal HPD performance. REAT-based field individual HPD fit testing approaches use protocols similar to laboratory testing, ostensibly making individual test findings directly comparable to laboratory results.

However, the time (up to 40 s per threshold at six frequencies in each of the ears with and without HPD), equipment (special audiometer headphones and software) and environment (a quiet test environment is required, typically generated via use of sound booths and/or noise-excluding headphones) can be challenging [9]. In addition, a REAT test is a subjective test: it requires the subject to hear, listen, and respond to test tones in an active fashion, and thus may be problematic for workers with impaired hearing, test anxiety, attentiveness issues or other confounders. REAT commonly results in 5 dB variability in any given threshold [10, 11].

This paper will discuss a novel microphone-in-real-ear (MIRE) test adapted to large-scale use. The first section will detail the field MIRE (F-MIRE) setup, calculations and third-party validation, while the second one will deal with the computation of a single number to represent the F-MIRE attenuation value. Finally, the third section will detail the various applications that this technique permits.

2. F-MIRE

The F-MIRE, relies on a modified MIRE process that has been originally adapted to test custom earplugs quickly and reliably in the field [12]. A dual-element probe microphone and a dedicated

spectrum analyzer—running on a proprietary digital signal processor (DSP)—measure under pink noise sound source the noise reduction (NR) of the earplug as fitted by the user. From this NR measurement, PC software runs algorithms to predict the individual attenuation when measured with the REAT, the current golden standard of attenuation measurement for HPD, used in numerous HPD attenuation rating standards [3, 4, 10, 12].

2.1. F-MIRE Setup

The F-MIRE system requires that the HPD under test have a consistent and reliable sound bore that enables the insertion of the measurement microphone. This can be accomplished internally in the design of the HPD (as with a custom earplug, Figure 1) or by inserting a probe tube with known and quantified acoustical performance properties (as with a roll-down foam or premolded earplug) [14], in which case the bias introduced by such tubing of the earplug has been carefully studied and its effect on the measured attenuation can reasonably be neglected.

NR measurement is performed on the earplug: loud pink noise is generated with the reference sound source—precisely located in the vicinity of the ears—and the magnitude of the transfer function between the outside and inside microphones is computed in real-time with the DSP.

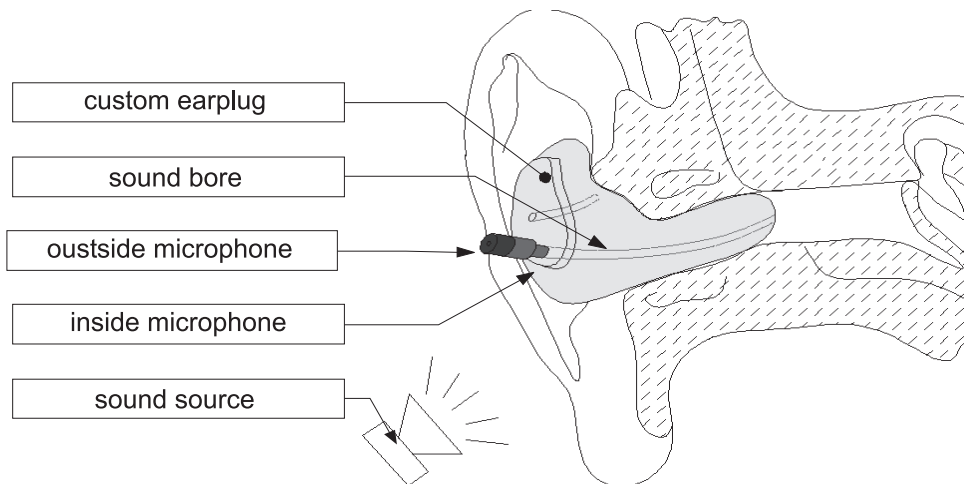


Figure 1. F-MIRE setup for a custom earplug featuring an internal sound-bore that allows the dual element microphone to be inserted for the noise reduction measurement under loud pink noise. Notes. Adapted with permission from SONOMAX, QC, Canada.

2.2. F-MIRE Calculation Basics

The first author's method is used to predict, from this octave-band NR measurement, the REAT (i.e., the difference between open and occluded-ear hearing thresholds) that would be reported by a subject if the subject was tested using the auditory thresholds method [12, 15].

The method is based on the concept of compensation factors (*COMP*) that links the corrected noise reduction (NR_c) to the predicted REAT (\widehat{REAT}):

$$\widehat{REAT} = NR_c + COMP. \quad (1)$$

The measured NR is first corrected for the microphone tip (in the case of a custom earplug, Figure 1) or probe tube length correction (in the case of a roll-down foam or premolded earplug), to obtain NR_c .

COMP is the sum of three corrective morphological or psychophysiological terms, which have been defined experimentally [12], and which include

- the correction between the free-field sound pressure level (which would be measured without the human head in place) and the sound pressure level that is measured by the outside microphone: this term includes essentially the head and torso diffraction as well as the pinna horn effect;
- the correction between the pressure on the internal face of the protector and the tympanic pressure; this term includes essentially the resonance of the occluded auditory canal; and
- physiological noise that is present during the REAT measurement, but which is not picked up by the inside microphone; this term also accounts for the occlusion effect.

These three corrective terms can be regrouped in "compensation by octave band" (indexed i) which is a normal distribution of average value \overline{COMP}^i and standard deviation σ_{COMP}^i .

2.3. F-MIRE Third-Party Validation

The proposed validation concept for the F-MIRE method is straightforward: the predicted attenuation values per octave band, \widehat{REAT}^i ,

should be compared side-by-side for the same earplug on the same individual, to the attenuation that is measured using the REAT method. From these predicted and reported attenuation values, an uncertainty statement [13] could be produced, following the most recent Guide to the expression of uncertainties in measurements [16], for the proposed F-MIRE method. Such experimental validation has been conducted by an independent third-party laboratory [17] for custom earplugs and more recently on noncustom earplugs (roll-down foam and premolded earplugs) [18]. In both validations, the overall uncertainty of the F-MIRE was found to be lower than the uncertainty associated with subjective REAT attenuation measurement of earplugs [11].

3. Personal Attenuation Rating

From the predicted octave-band attenuation values, \widehat{REAT}^i prediction, a single number value representing the overall HPD attenuation can be computed. The computation can be done in a similar way to the NRR [1] or the SNR [2]. The main difference between the proposed F-MIRE single numbers as opposed to single numbers used in the aforementioned HPD attenuation rating standards is that this single value will now come from an objective measurement (not from a subjective evaluation of the attenuation) on a particular user (not on a population sample) under realistic wearing conditions for the hearing protector (not under laboratory conditions). The proposed single numbers for the F-MIRE method are the predicted personal attenuation rating (PPAR), that is computationally very similar to the NRR and SNR, and the personal attenuation rating (PAR) that is somewhat closer to the noise reduction level statistics (NRS) [19] and predicted noise level reduction (PNR) [2]. Both PPAR and PAR will be defined and detailed in the following sections.

3.1. $C - A'$ single number: NRR, SNR and PPAR

This section deals with single number rating that has to be applied on a C -weighted exposure value

to obtain an A -weighted protected value, hence denoted $C - A'$ single numbers.

3.1.1. NRR

The NRR is computed according to the Environmental Protection Agency requirements [1], by subtracting a two-standard deviation correction from the mean REAT attenuation values to estimate the minimum noise reduction theoretically achieved by 98% of the laboratory subjects:

$$NRR_{98} = 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+C^i}{10}} \right) - 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+A^i-REAT^i+2\sigma_{REAT}^i}{10}} \right) - 3, \tag{2}$$

where A^i and C^i are respectively the A - and C -weighting octave-band values.

The A -weighted protected level is then to be computed as

$$L'_{A98} = L_C - NRR. \tag{3}$$

3.1.2. SNR

The SNR is computed according to Standard No. ISO 4869-2:1994 [2] as

$$SNR_x = 100 - 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{L'_A - APV_x^i}{10}} \right), \tag{4}$$

where APV^i —assumed protection value.

Equation 4 can be rewritten in a very similar way to Equation 2, by realizing that the left term is simply the summation of octave-band sound pressure levels that have an overall value of 100 dB(C). Hence, after a few transforms, it is also possible to express the SNR as

$$SNR_x = 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+C^i}{10}} \right) - 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+A^i-REAT^i+\alpha\sigma_{REAT}^i}{10}} \right). \tag{5}$$

The factor α is a function of the protection performance m that is targeted. For example, for a protection performance of 98% (similar to Equation 2), $\alpha = 2$.

The A -weighted protected level is then to be computed as

$$L'_{A98} = L_C - SNR_x. \tag{6}$$

3.1.3. PPAR

The proposed PPAR is computationally very similar to the existing NRR and SNR: it is a single number, in decibels, which represents the attenuation achieved by the user for a given HPD. But while the NRR is obtained from a subjective REAT measurement on a population sample under laboratory conditions, the PPAR is obtained from an objective microphone measurement, on a particular user wearing the hearing protector under realistic conditions:

$$PPAR_x = 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+C^i}{10}} \right) - 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{100+A^i-ATT^i+\alpha\sigma_{ATT}^i}{10}} \right). \tag{7}$$

The A -weighted protected level is then to be computed as

$$L'_{Ax} = L_C - PPAR_x. \tag{8}$$

The question that immediately follows the definition of the PPAR proposed in Equation 7 is what value $\sigma_{\widehat{REAT}^i}$ represents in the case of an individual measurement. The answer that has been proposed [15] is that this value is the F-MIRE prediction uncertainty that is associated with the PPAR value, s_{FMIRE} . This uncertainty has been experimentally established during the side-by-side comparison, for the same fit of the same earplug on the same individual, between the F-MIRE predicted attenuation, \widehat{REAT} , and the reported REAT attenuation, $REAT$ (see section 2.3. for further details). The uncertainty component s_{FMIRE} is obtained from the group standard deviation of the P individual prediction errors:

$$s_{FMIRE} = \sqrt{\frac{1}{P-1} \sum_{p=1}^P (ATT_p - REAT_p)^2}. \tag{9}$$

Hence, the $PPAR_x$ is the value that users will obtain from their own HPD with a given probability x (where x can be seen in a frequentist

way as the expected percentile of measured REAT greater than predicted PPAR for an individual).

3.1.4. Issues associated with C – A' single numbers

The issues with C – A' single numbers, like the NRR, SNR or the proposed PPAR for the F-MIRE measurement, are twofold: (a) the single number has to be applied on a C-weighted exposure value, which is less common than A-weighted values; and (b) the frequency content of the noise used to compute is supposed to be uniform (pink noise), which is rare in industry.

3.2. A – A' single number: PNR (HML), NRS and PAR

On the contrary, A – A' ratings are straightforward: they predict, by simple subtraction from the A-weighted ambient noise levels, the effective A-weighted levels L'_{pA} when an HPD is worn. A – A' ratings, which by their very nature are easier to use and less prone to computational errors, are of sufficient precision for most applications considering the many sources of variability inherent in predicting protection [20].

3.2.1. PNR

The PNR from the high-, medium- and low-frequency attenuation values (H_x , M_x and L_x) values and the C- and A-weighted sound pressure levels L_C and L_A can be calculated according to Equation 10:

$$PNR_x = M_x - \frac{H_x - M_x}{4}(L_C - L_A - 2\text{dB}), \quad (10)$$

for noise with $L_C - L_A < 2$ dB.

For noise with $L_C - L_A > 2$ dB, the PNR_x is calculated according to Equation 11:

$$PNR_x = M_x - \frac{M_x - L_x}{8}(L_C - L_A - 2\text{dB}). \quad (11)$$

The H_x , M_x and L_x values are based on eight reference noise spectra with different $L_C - L_A$ values. The effective protected exposure level is hence obtained directly using

$$L'_{Ax} = L_A - PNR_x. \quad (12)$$

3.2.2. NRS

A substantial divergence in this standard from prior publications and other standards [2, 11, 21] is the recommendation that the simplified ratings be presented as pairs of numbers at the 80th and 20th percentile level. Furthermore, an exhaustive set of 100 actual industrial spectra, denoted NIOSH 100, will be used for the computation of this single number rating rather than only eight spectra, as in the previous section:

$$\Delta L_{A_{pn}} = 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{L'_n + A^i}{10}} \right) - 10 \log_{10} \left(\sum_{i=1}^7 10^{\frac{L'_n + A^i - REAT_p^i}{10}} \right), \quad (13)$$

where L'_n —sound pressure level, in decibels, for the octave centered on i for the n th noise in an industrial noise database; $REAT_p^i$ is the attenuation, in decibels, measured for the hearing protector on the p th subject at octave-band center frequency i , averaged across several trials (usually 2, as in Standard No. ANSI S12.6-1997 [3]).

The NRS is defined as

$$NRS_{Ax} = m - \alpha \sqrt{s_{\text{subject}}^2 + s_{\text{spectrum}}^2}, \quad (14)$$

where m —average attenuation across subjects across spectrum, obtained as

$$m = \frac{1}{P \cdot N} \sum_{n=1}^N \sum_{p=1}^P \Delta L_{A_{pn}}. \quad (15)$$

and the standard deviations s_{subject} and s_{spectrum} are respectively, classically, defined by

$$s_{\text{subject}} = \sqrt{\frac{1}{P-1} \sum_{p=1}^P (m_p - m)^2} \quad (16)$$

and

$$s_{\text{spectrum}} = \sqrt{\frac{1}{N-1} \sum_{n=1}^N (m_n - m)^2}. \quad (17)$$

The effective A-weighted sound pressure level for protection performance x is computed from the NRS_{Ax} :

$$L'_{Ax} = L_A - NRS_{Ax}. \quad (18)$$

3.2.3. PAR

The *PAR* is defined, using a computation scheme very similar to NRS computation, in Equation 14:

$$PAR_x = att - \alpha \sqrt{s_{FMIRE}^2 + s_{fit}^2 + s_{spectrum}^2}, \quad (19)$$

where *att*—average attenuation across the *N* spectrum for the subject (who can have been tested up to *F* times in row), obtained as

$$att = \frac{1}{F \cdot N} \sum_{n=1}^N \sum_{f=1}^F \Delta L_{Afn}. \quad (20)$$

where $s_{spectrum}$ —spectrum uncertainty component, defined in Equation 17, and s_{FMIRE} —the F-MIRE uncertainty component, as defined in Equation 9. The uncertainty component, s_{fit} , is the intra-subject fit variability (rather than the inter-subject fit variability that $s_{subject}$ represented in Equation 14) and can be either assess individually if the number of consecutive refits, *F*, for the same HPD for the same subject is large enough (e.g., >4) or can be established from tabulated values obtained by laboratory subjects who tested the same product several times in row [14]:

$$s_{fit} = \sqrt{\frac{1}{F-1} \sum_{f=1}^F (m_f - att)^2}. \quad (21)$$

The effective *A*-weighted sound pressure level for protection performance *x* is computed from the PAR_x :

$$L'_{Ax} = L_A - PAR_x. \quad (22)$$

The advantages of using such a pair of PAR_x single numbers (like $PAR_{80\%}$ and $PAR_{20\%}$ values) are numerous:

- they represent an individual range of attenuation values, rather than a laboratory group statistics;
- they are obtained from an objective F-MIRE measurement, rather than a subjective REAT assessment;
- they can be measured on the actual wearers of the HPD, in a realistic way;
- they account for several variabilities and uncertainties encountered in the field (the uncertainty associated with the F-MIRE measurement method, the intra-subject fit variability, the spectrum variability, etc.).

The use of a single number pair like $PAR_{80\%}$ – $PAR_{20\%}$ greatly facilitates the use and deployment of the F-MIRE measurement approach, while permitting a rigorous uncertainty statement in the proposed attenuation values. The following section will detail the various applications that this approach makes possible.

4. Applications of F-MIRE

Applications of F-MIRE are just starting to be fully identified [18], they impact various fields, from training and motivation of the wearers to HPD selection.

4.1. Training

The individual fitting technique may be the largest single variable in HPD performance. F-MIRE provides a quick assessment of the performance of each user's HPD fit and performance, enabling intervention and training as required to improve individual fitting techniques and protocols. By providing documentation of HPD performance, F-MIRE can serve as a quantitative measure of individual fitting skill and ability. Individuals with insufficient protection are identified to facilitate counseling to either improve their fitting skill or to select an alternate HPD. Real-world attenuation is driven largely by how users wear the devices, and improvements in personal fit and use can be enhanced by giving them quantitative feedback on how changes in fit can affect performance.

4.2. Selection

Individual users often choose HPD based on factors other than protection (e.g., ease of availability and use, and perceived comfort). Immediate feedback about personal HPD performance can enable workers to select a device that includes these factors as well as the sufficiency of a given HPD in a given noise environment. In addition, individual variability in physiology (earcanal size and shape, dexterity in preparing expandable foam earplugs for use) may make some devices more suitable for some users. By quickly determining sufficiency (HPD

performance compared to individual noise exposure), the F-MIRE process can aid the ease of selecting an appropriate variety of HPD sufficient for noise levels in a given facility as well as aiding individuals in selecting a device that works appropriately for their exposure and use.

4.3. Hearing Test Interpretation

While determination of noise exposure and hearing thresholds have been well understood for some time, inherent variability in HPD performance has made interpretation of hearing test results, and determination of work-relatedness of hearing loss, challenging. Regular collection of individual HPD fit testing data enables the professional responsible for the hearing conservation program to better assess “net” exposure (workplace noise exposure minus protection provided by the HPD) to determine the work-related component of hearing losses detected in the medical surveillance aspect of the hearing conservation program. Given the pervasive nature of noise exposure in the nonoccupational environment, estimation of the contribution of workplace noise to a given hearing loss or threshold can be greatly facilitated by better understanding of personal HPD performance.

4.4. Sufficiency

Maximal performance of the HPD is not necessarily the goal of an effective hearing conservation program. Selection of HPD sufficient to protect workers from the noise they are exposed to, with a conservative target protection level of typically 80–82 dB TWA, enables workers to be sufficiently protected from noise, and ensures that the HPD of choice and the fitting of that device will provide enough protection to keep the workers’ hearing safe from damage. Alternate methods for estimating HPD performance to determine sufficiency, such as derating or discounting labeled protection values, are as inaccurate as the underlying data, and may lead to overprotection (see section 4.7.). Related to selection, determination of the suitability of

a given HPD for a given individual in a given noise environment is facilitated by determining individual performance.

4.5. Documentation

Each F-MIRE test results in documentation of HPD performance for the individual tested at the time of the test. This data trail, with related net exposure determination, facilitates appropriate hearing loss apportionment and work-relatedness assessment by demonstrating the individual workers’ proficiency in fitting the HPD to obtain sufficient protection over time. The hearing conservation record contains then not only measures of hearing ability and noise exposure, but HPD performance as well, to permit longitudinal determination of hearing conservation program effectiveness.

4.6. Research and Demographics

Collection of demographic information in conjunction with F-MIRE tests facilitates decisions regarding what types and styles of HPD may be appropriate for workers based on noise exposure, gender, age and other factors. In addition, an analysis of F-MIRE test results can assist in determining what types of HPD are most consistent in performance, effective and easiest to use, enabling more effective product development and research.

4.7. Overprotection

Given the uncertainty in current laboratory-based HPD evaluation protocols, many employers default to selection of the highest possible labeled attenuation rating in HPD regardless of noise level or exposure to attempt to ensure that sufficient protection is provided. This practice results in overprotection for those workers who fit the devices properly, compromising their ability to hear critical communications, machine cues and warning signals. European Union guidelines indicate that the optimal “protected level” or net exposure should be 75–80 dB, with acceptable exposure ranging between 70 and 85 dB [22]. Individual assessment of HPD performance

enables selection of devices that meet this criterion, and permits workers to hear their machines and environment while still protecting their hearing from noise damage.

4.8. Compliance

Under Directive 2003/10/EC, the exposure limit value (87 dB L_{eq8h}) explicitly takes the effect of the HPD into account [23]. Assessment of HPD performance is critical to meet this aspect of the rule; in addition, nearly all jurisdictions have permissible noise exposure criteria that take HPD performance into account. Previous gross estimates of performance, such as SNR and NRR, are not accurate enough for application in this situation. Individual fit testing processes enable better understanding of HPD performance to meet these compliance needs.

5. CONCLUSIONS

The proposed F-MIRE method presented here appears to be “the next step forward in hearing conservation” (p. 6) [18]. It allows the individual fit testing of a HPD in the field, in an objective and simple manner and has an undeniable utility in one’s overall hearing conservation efforts.

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