

The objective measurement of individual earplug field performance

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This paper presents a field-microphone-in-real-ear (MIRE) method for the objective measurement of individual earplug field attenuation. This development was made possible by using a recently designed instrumented expandable custom earplug. From the measurement of the noise reduction (NR) through the earplug, this method predicts the attenuation that would be experienced by the wearer and that would be measured using the real-ear attenuation at threshold (REAT) method. Formulations presented include establishing the relationship between NR, insertion loss, and REAT, as well as defining the laboratory and field calibration procedures required to determine the correction factors to be applied to the measured NR. This method was validated experimentally by comparing the predicted field-MIRE attenuation values to the REAT values measured on a group of test-subjects. This method offers fast and accurate measurement of earplug field performance on an individual basis and could lead to further developments for effective hearing protection practices as well as for hearing protection device rating and labeling.

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I. INTRODUCTION

For several already well-documented reasons,^{1–4} current standardized methods⁵ dramatically fail to predict the attenuation of *hearing protection devices* (HPDs) for individual users in on-site applications. As recommended by the National Institute for Occupational Safety and Health (NIOSH) and many researchers, substantial efforts have been deployed to “find a laboratory method to estimate the noise attenuation obtained with hearing protectors worn in the field.”⁶ As a result, recent standards^{7–9} now include a “subject fit” method^{10–12} that provides a better estimate of the attenuation obtained in the field, even if some discrepancies still arise between laboratory and field attenuation values.^{13,14}

However, even if such laboratory methods better predict the average group field performance, it is still impossible to relate the individual field attenuation to this population-based, statistically-derived, laboratory-driven attenuation estimate. One solution to this fundamental problem, as Berger¹³ mentioned, would be to perform “individual fit testing” as it would provide the most accurate assessment for an individual user and could also afford an excellent opportunity to train and motivate the employee in appropriate HPD use and fitting.

Very few field measurement methods are currently available (see Ref. 15 for a recent review), despite the many attempts to adapt laboratory methods for field measurement use (see Ref. 16 or Ref. 17). The FitCheckTM (Refs. 18 and 19) system is probably the most used and documented²⁰ field measurement method. It relies on the real-ear attenuation at threshold (REAT) test, that is, the difference between open and occluded-ear hearing thresholds as measured on human

subjects. The REAT test, sometimes referred to as the “gold standard” since it was first standardized in 1957,²¹ is now part of many worldwide standards^{5,7,22,23} and takes into account all relevant sound paths to the inner ear. Unfortunately, REAT testing is not only time-consuming and very sensitive to the ambient background noise (making it often incompatible with practical field usage), but it is also hampered by two limitations: the first one is the well-known low-frequency masking error (caused by *physiological noise*), which leads to an overestimation of the low-frequency attenuation,²⁴ and the second one is the variability of the subjective response, i.e., the ability of a subject to track his or her hearing threshold levels. The authors’ experience is that a human subject will rarely report twice the same hearing threshold (even when tested at 5 dB steps) and hence there is inherently large variability in the REAT protocol since it requires two complete audiograms in order to determine real-ear attenuation.

Among the various laboratory methods available to measure HPD attenuation (see Refs. 25 and 26 for an extensive list), there is one method that would overcome these limitations and still enable individual measurement: the microphone-in-real-ear (MIRE) technique. It consists of inserting a miniature microphone (either wired or in a probe-tube form) in the ear to measure the actual sound pressure level at a given location, usually close to the tympanic membrane. The difference between two of these measurements on a given individual at the same location in open and occluded-ear conditions gives the classical insertion loss (IL). MIRE measurements techniques have been used successfully for earmuff IL (see Ref. 27 for a comprehensive review) and are now standardized for supra-aural or circumaural HPDs.^{28,29} Even if they cannot account for the bone conduction sound

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path, these laboratory MIRE techniques are fast, efficient, and reliable and do not suffer from the physiological noise bias.

A field method based on the MIRE approach has been developed for use in the fitting of hearing aids which may be adaptable to HPD attenuation measurements. The method is used to determine the so-called “insertion gain” and is sometimes referred to as the “substitution method” (see Ref. 30). However, existing measurement devices used to measure the insertion gain rely on a microphone probe inserted around the device and usually cannot be used when measuring IL for HPDs, as the soft tube of the probe microphone is not protected against outside noise contamination (i.e., the measurement is affected by the sound source itself, an effect sometimes described as “flanking pathway”²⁶), and the probe tube usually breaks the acoustic seal of the HPD.²⁶ Recent studies conducted on the use of MIRE as a field measurement device for earmuffs^{27,31,32} or for earplugs¹⁷ show promising results for in-field implementation of alternative attenuation tests. However, as mentioned by Mauney,²⁷ up to now, the equipment used was delicate laboratory equipment unsuited for regular field use and the procedure was complex, requiring that the subject be fitted and the microphone placed by a professional to avoid misplacement or tympanic injury. It is therefore necessary to develop more robust field-ready equipment and a simple procedure including HPD fitting by the subject.

This paper describes the development of a field-MIRE method for measuring HPD attenuation. This development was made possible by using the recent design^{33,34} of an instrumented expandable custom earplug by Sonomax Hearing Healthcare Inc. (Montreal, Canada). This custom earplug has two main features: first, it is molded *in situ* by a trained technician and takes in a few minutes the shape of the wearer’s ear through silicone injection, which increases physical comfort, and, second, it includes a sound-bore that can be used either for field-MIRE measurements or the insertion of filters to improve the wearer’s auditory comfort, by letting a controlled amount of acoustical energy go through the earplug (see Ref.s 35 and 36 for details on the custom earplug filtered with acoustical dampers). Because custom earplugs are used, the need for a field-MIRE method could be questioned on the basis that custom earplugs have often been considered to be less prone to mis-fit by users, and it has even been suggested that they would not suffer from the discrepancies usually observed between laboratory and field performance. These assumptions do not withstand closer scrutiny and even if custom earplugs have some advantages over traditional HPD (like the fact that they provide increased comfort for some users and that they will fit certain earcanals that other plugs may not), they still require individual field attenuation measurements because they typically show the same inter-subject attenuation variability as other earplug types (pre-molded or roll-down foam plugs), as reported by Berger *et al.*³ or more recently by Murphy *et al.*³⁷

The instrumented expandable custom earplug is described in Sec. II. The proposed approach for the measuring of individual earplug field performance is formulated in Sec.

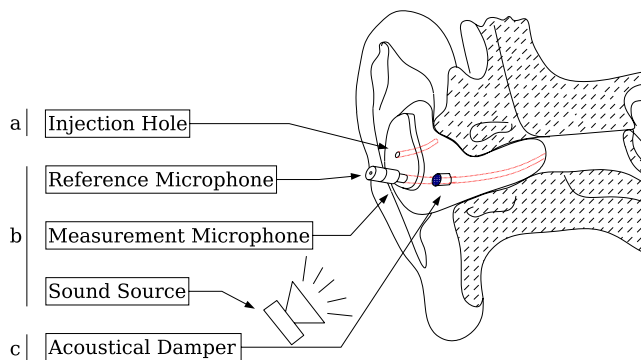


FIG. 1. (Color online) The custom earplug: (a) instantly-fitted by the injection of silicone; (b) instrumented with a dual microphone probe (external and internal pressure microphones with an extended probe tube inside the sound-bore) as well as the reference sound source; (c) filtered with acoustical damper for adapted protection.

III. An experimental validation follows in Sec. IV and conclusions are given in Sec. V.

II. THE DEVICE USED: AN INSTRUMENTED EXPANDABLE CUSTOM EARPLUG

As mentioned in Sec. I and as illustrated in Fig. 1, the earplug developed and used in this study is a re-usable custom earplug that is fitted *in situ* to the user’s ear in a few minutes.

A hole through the core of the earplug is used for the injection of a soft medical-grade thermosetting two-part silicon rubber between the rigid core—of generic shape—and the soft envelope that will expand to take the precise shape of the ear canal. Below the injection hole, a sound-bore through the earplug is used first for the field-MIRE measurements and then for the insertion of an acoustical damper. To perform field-MIRE measurement, a miniature microphone is temporarily inserted within the generic rigid core to measure sound pressure levels in the residual ear canal portion between the HPD and the eardrum. Attached to the back of this internal pressure microphone is an external pressure microphone so that sound pressure level difference across the earplug, noise reduction (NR), can be measured in the presence of loud pink noise generated from an outside reference sound source (frontal incidence, median plan). The two microphone elements used in the microphone probe assembly are miniature electret condenser pressure microphones manufactured by Knowles Electronics (Itasca, IL) and typically used in the hearing aid industry. These microphones offer a flat frequency response (within 0.1 dB) up to 10 kHz with omnidirectional directivity pattern. The NR measurement will be performed by the trained technician after the end-user removes and replaces the custom earplug in order to perform a “subject-fit” test. This subject-fit NR measurement will later be used to check the proper fit of the earplug and to predict the attenuation the user will achieve in an on-site situation (see Sec. III F). Finally, after the field-MIRE measurement, the microphone probe is removed and an acoustical damper (acoustic resistance resulting from a mesh of plastic fibers) is inserted in the earplug’s sound-bore, for regular use.

The field-MIRE measurement device, dubbed the “SonoPass™ System,”^{38,39} is a proprietary DSP-based spectrum analyzer that measures the octave-band sound pressure levels (auto-spectrum’s) from both microphones and calculates NR (using the magnitude of the transfer function (TF) between the external “reference” and internal “measurement” microphones) as well as the coherence function while generating a loud broadband sound (pink noise) through a loudspeaker. It can operate either connected to a computer or as a stand-alone unit (with LED indicators) and has successfully been used in the field since 2002.⁴⁰

III. FORMULATION OF THE PROPOSED OBJECTIVE MEASUREMENT OF INDIVIDUAL EARPLUG FIELD PERFORMANCE

The proposed approach relies on the objective measurement of NR to predict the REAT equivalent value. The general relationships between NR, IL, and REAT are derived in Sec. III A. The expression of REAT is then formulated, in Sec. III B, as the sum of two terms: the corrected NR (the raw NR value modified by several corrections specific to the test procedure) and a compensation term (that accounts for sound pressure TFs between the open and the occluded-ear as well as psycho-physiological effects, such as the physiological noise). These corrections on the raw NR value are obtained from laboratory and field measurements, as presented in Sec. III C. The procedure to obtain an equivalent binaural NR is presented in Sec. III D.

The compensation value is obtained statistically, detailed in Sec. III E, based on the fact that many of the corrections involved vary according to the geometry and dimensions of the human head; they can therefore be properly represented by a normal distribution. For example, the use of a statistically averaged TF of the outer ear (TFOE) value rather than an individual one has the advantage of avoiding the cumbersome and delicate measurement of tympanic sound pressure levels. It also makes such an approach highly compatible with practical field usage, as suggested by Mauney,²⁷ even though it increases the uncertainty associated with the prediction.

In a traditional hearing conservation program, the expected NR of a protector is determined through measurement REAT for a population of subjects to determine the noise reduction rating (NRR) defined by EPA (Ref. 41) based on attenuation measurements performed according to ANSI standard⁵ or the single number rating (SNR) as described in the ISO standard.⁴² In the proposed approach, the estimated NR is determined by individual NR measurement and determination of the predicted personal attenuation rating (PPAR); its formulation is provided in Sec. III F.

A. Relationship between NR, IL, and REAT

Figure 2 illustrates the pressure variables at different locations in the open and occluded-ear (the “prime” symbol is used in this latter case). Index 1 is not used in the current paper but is presented for reference, since it has been associated to the sound pressure at the ear canal entrance point.

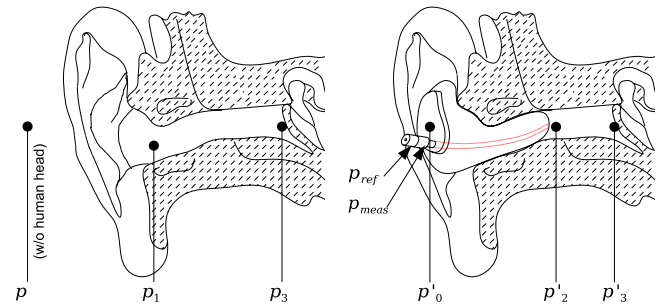


FIG. 2. (Color online) Schematics illustrating sound pressure variables at various locations for an open ear (left) and for an occluded-ear fitted with instrumented earplug (right)

The IL is defined as a ratio of the open tympanic sound pressure p_3 over the occluded-ear tympanic sound pressure p'_3 :

$$IL = 20 \log_{10} \left(\frac{p_3}{p'_3} \right). \quad (1)$$

Since IL usually represents a physical “loss,” it is usually a positive value (greater than zero); however, it can also be plotted as a negative one.

The theoretical noise reduction (NR_0) is defined as the ratio of the free field sound pressure p (at the tympanic membrane location, in the absence of a human subject) over the occluded-ear tympanic sound pressure p'_3 :

$$NR_0 = 20 \log_{10} \left(\frac{p}{p'_3} \right). \quad (2)$$

NR_0 is also a positive value often plotted as a negative one. The TFOE is defined as

$$TFOE = 20 \log_{10} \left(\frac{p_3}{p} \right). \quad (3)$$

A direct relation between these three figures is

$$IL = NR_0 + TFOE. \quad (4)$$

Such an expression for IL is commonly used when objectively measuring the attenuation of HPDs at supra-threshold levels. Indeed, for extremely high sound pressure levels (impulse or stationary), the HPD attenuation can no longer be considered to be linear or level independent (either purposely because of the non-linearity of the HPD’s design or unintentionally because of the intrinsic non-linearity of the HPD material for very high amplitude acoustical waves). Many studies^{25,32,43,44} rely on such two-part measurements where NR is measured on the device worn by an in-field user and TFOE is measured at a different time on the wearer in the laboratory to assess the overall HPD attenuation.

The REAT that would be measured on a subject is derived from the IL by adding the hearing threshold masking caused by the physiological noise (PN):

$$REAT = IL + PN \quad (5)$$

PN is device-related^{45,46} and depends on the earplug insertion depth and on the residual occluded-ear volume past the HPD. In our case, PN is considered a correction to be

applied for each frequency (even if it mostly occurs in the lower frequencies) on an individual basis. Using Eqs. (4) and (5), we obtain

$$\text{REAT} = \text{NR}_0 + \text{TFOE} + \text{PN}. \quad (6)$$

Equation (6) does not take into account the fact that the REAT measurements are affected by some bone-conduction (BC) pathways that flank the earplug and transmit energy to the inner ear, because those pathways are not modeled or measured with the field-MIRE approach described here. Though this is not necessary for the custom earplug of this study, it is conceptually part of the correction to be applied to the predicted REAT by representing the BC as a concurrent pathway to the earplug. In a recent implementations of the field-MIRE method⁴⁷ on high attenuation non-custom earplugs, an additional correction is applied to the prediction of the REAT of earplugs. For those high attenuation earplugs, the field-MIRE data need to be corrected by including an estimated BC pathway. The hypothesis behind this model is that the earplug and the BC are two independent paths (resulting in noncoherent sound pressures contributions at p'_3) and that no interference (resonance/anti-resonance) occur between them; hence that the sound pressure p'_3 can be expressed as an energy summation of the earplug and BC sound pathways. Such model has already been developed by the authors³⁶ for the prediction of the attenuation of the custom earplug filtered with the damper. When required, the “BC limited” REAT attenuation, REAT_{BCL} can be derived from REAT using the following equation:

$$\text{REAT}_{\text{BCL}} = -10 \log_{10}(10^{-\text{REAT}/10} + 10^{-\text{BC}/10}), \quad (7)$$

where BC is the attenuation of the BC sound pathway of the human skull, available in the literature.⁴⁸ Equation (7) shall be used twice, once to correct the measured REAT values used for the calculation of compensation in Eq. (16) and another time in Eq. (14) to correct the predicted REAT values.

B. Required corrections for the expression of REAT from the measured NR

Unfortunately, direct measurement of NR_0 in the field is problematic: it requires the measurement of p'_3 very close to the tympanic membrane and the measurement of p in the absence of a human subject. A practical alternative is to measure the NR between the outer and inner faces of the earplug, at pressure locations p'_0 and p'_2 , respectively. In practice, the device measures p_{ref} instead of p'_0 with the *reference microphone* located 19.5 mm away from the outer face of the earplug [i.e., approximately 20 mm from the ear reference point defined in ISO 11904 (Ref. 29)] and measures p_{meas} instead of p'_2 with the *measurement microphone* located at the aperture of a 18 mm long, semi-rigid (0.8 mm inside diameter) probe tube inserted into the sound-bore of the earplug. The NR that is practically measured (denoted NR_*) is therefore defined as

$$\text{NR}_* = 20 \log_{10}\left(\frac{p_{\text{ref}}}{p_{\text{meas}}}\right). \quad (8)$$

Three corrective factors need to be added to NR_* to obtain the previously mentioned NR.

- The use of p_{ref} instead of p requires the correction (p/p_{ref}) that will account mainly for head and torso diffraction and the pinna effect.
- The use of p_{meas} instead of p'_3 requires the correction (p_{meas}/p'_3) that will account for the occluded-ear canal shifted resonance, the microphone probe, and sound-bore tubing effects. This latter correction (p_{meas}/p'_3) can be split in two terms: a first term (p_{meas}/p'_2) that would account for the microphone probe-tube effect and a second one (p'_2/p'_3) that would account for the occluded-ear canal resonance.

The NR expressed as a function of these correction terms is expressed as

$$\begin{aligned} \text{NR}_0 &= \text{NR}_* \\ &+ 20 \log_{10}\left(\frac{p_{\text{meas}}}{p'_2}\right) \\ &+ 20 \log_{10}\left(\frac{p'_2}{p'_3}\right) + 20 \log_{10}\left(\frac{p}{p_{\text{ref}}}\right). \end{aligned} \quad (9)$$

Equation (9) is intentionally presented on three lines: the first line contains the measurement performed in the field, the second line represents the corrections associated with the measurement device, which can be determined in laboratory (i.e., probe-tube effect, etc.), while the third line contains the corrections related to human factors (i.e., morphology of the ear and psycho-physiological specificities of an individual’s hearing). This three-line writing convention shall be used throughout this paper.

Equation (6) can now be re-written using Eq. (9) and the same aforementioned three-line presentation convention.

$$\begin{aligned} \text{REAT} &= \text{NR}_* \\ &+ 20 \log_{10}\left(\frac{p_{\text{meas}}}{p'_2}\right) \\ &+ \text{TFOE} + \text{PN} + 20 \log_{10}\left(\frac{p}{p_{\text{ref}}} \times \frac{p'_2}{p'_3}\right). \end{aligned} \quad (10)$$

The first line of Eq. (10) is the measured NR_* , assuming the use of an ideal microphone probe for which both cells of the dual microphone probe are perfectly equal in sensitivity and frequency response. However, in practical situations, the microphone cells, although very similar, do not absolutely have the same sensitivity, nor is their individual frequency response constant over time due to sensitivity to ambient atmospheric conditions and other factors. In order to take such differences into account, the uncalibrated values are included in the equations and denoted with a tilde symbol above them to distinguish them from corrected values. The calibration factors required for the uncalibrated measurements $\widetilde{\text{NR}}_*$ are determined using, in the field, system *I* illustrated at the bottom of Fig. 3.

The quantity NR_* defined in Eq. (8) is rewritten as the ratio of two measured pressure values for the earplug (index *III*) in the wearer’s ear, multiplied by a correction ratio ob-

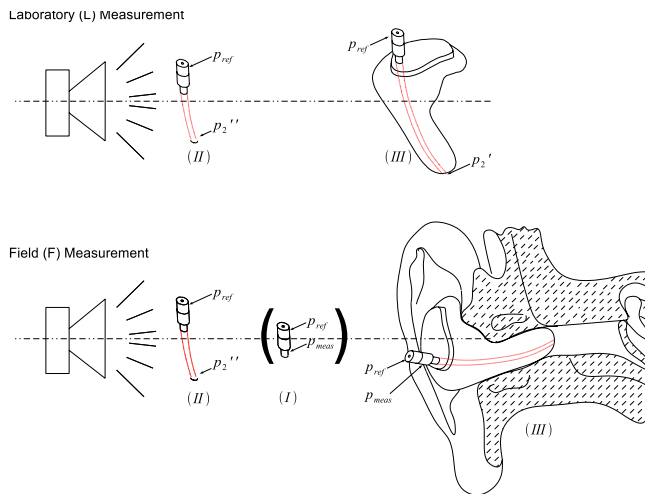


FIG. 3. (Color online) Scenario implemented to determine the sound-bore length and microphone sensitivity corrections. Top: Overview of the laboratory measurement of corrections $(\tilde{p}_{\text{ref}}/\tilde{p}_{\text{meas}})_{LII}$ and $(p_{\text{ref}}/p_2')_{LIII}$. Bottom: Overview of the field measurement of $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FII}$, $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FI}$ (between brackets because not used in actual correction calculation), and $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FIII}$.

tained by submitting the two microphone cells to the same pressure field the same day that the field measurement (index F) takes place, as illustrated at the bottom of Fig. 3:

$$\begin{aligned} \text{NR}_* &= \left(\frac{p_{\text{ref}}}{p_{\text{meas}}} \right)_{III} = \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}} \right)_{FIII} \times \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}} \right)_{FI} \\ &= \widetilde{\text{NR}}_* \times \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}} \right)_{FI}. \end{aligned} \quad (11)$$

The second line of Eq. (10) is the sound-bore length correction (p_{meas}/p_2') ; it is a fixed correction that depends solely on the overall length of the sound-bore and microphone probe tube. In order to measure this sound-bore correction, three different systems were set up in front of the speaker: system I is simply the microphone pair, system II is the microphone pair with the probe-tube, and system III is the microphone pair with the probe-tube inserted into the earplug, as illustrated in Fig. 3.

Three scenarios were studied⁴⁹ to determine the correction required for the first two lines of Eq. (10), in order to obtain the corrected NR, called NR_C , that represents the difference in sound pressure levels between the inner and outer faces of the earplug.

The *first scenario* would consist in performing the measurement of the microphone pair TF on a daily basis $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FI}$ and obtaining NR_* . The sound-bore length correction (p_{meas}/p_2') would be determined in the laboratory by placing the earplug in an acoustical field giving the same acoustic pressure at both microphone duct openings in free space. This first scenario is unfortunately not well adapted for field usage, since the two microphone cells that are used in the dual microphone probe cannot be easily dismantled on a daily basis for the field measurement of the microphone pair TF.

The *second scenario* requires no laboratory measurement, as the sound-bore length correction (p_{meas}/p_2') would be determined by means of a field measurement conducted

by inserting the dual microphone probe in the earplug and positioning the instrumented earplug in a homogeneous sound field. This approach is straightforward but unfortunately not adapted for field usage because of the following three practical limitations: first, it should be performed on every size of each earplug to be measured (the Sonomax SonoCustomTM earplug use to be available in three core sizes); second, the positioning of the relatively large instrumented earplug on the speaker grid was found to disturb the acoustical field in the vicinity of the loudspeaker; third, the orientation of the instrumented earplug in relation to the speaker is critical and difficult to achieve consistently because of the asymmetry of the earplug with respect to the sound-bore aperture. Consequently, it is not feasible to perform such measurement on a daily basis within subject.

The *third scenario* was implemented because it did not have the practical limitations of the two others. This scenario is a variation of the second scenario where the field measurement is performed on the dual microphone probe before its insertion into the earplug. Because of its simple geometry and its small size, the probe is easy to position precisely and does not disturb the acoustical field in any critical fashion. However, it requires two additional laboratory measurements. One measurement is required of the earplug to address the sound-bore compensation, and the other of the probe alone to correct for microphone sensitivities that change with time. The measurement setups are illustrated in Fig. 3. The expression of the sound-bore length correction (p_{meas}/p_2') is

$$\begin{aligned} \left(\frac{p_{\text{meas}}}{p_2'} \right)_{III} &= \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}} \right)_{LIII} \times \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{meas}}(FII)} \times \frac{\tilde{p}_{\text{ref}}(LII)}{\tilde{p}_{\text{ref}}(FII)} \right) \\ &\quad \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}} \right)_{FI}. \end{aligned} \quad (12)$$

where

$$\left(\frac{\tilde{p}_{\text{meas}}(FII)}{\tilde{p}_{\text{meas}}(LII)} \times \frac{\tilde{p}_{\text{ref}}(LII)}{\tilde{p}_{\text{ref}}(FII)} \right) = \left(\frac{\tilde{p}_{\text{meas}}}{\tilde{p}_{\text{ref}}} \right)_{FII} \times \left(\frac{\tilde{p}_{\text{ref}}}{\tilde{p}_{\text{meas}}} \right)_{LII}.$$

As in the case of the second scenario, this approach eliminates the need for a microphone pair TF evaluation as the last term in Eq. (12) cancels the last term in Eq. (11) (this is the reason why the FI system has been placed between brackets in Fig. 3). Experience with this scenario has confirmed that the measurement of the dual microphone probe response $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FII}$ when clipped near the loudspeaker is a simple and repeatable measurement to cross-check laboratory and field measurements. First, it consists of simply using the “bare” dual microphone probe as used in practice without any specific preparation. Second, positioning of the dual microphone probe is fast and reliable: a “clip” similar to a fuse holder maintains the dual microphone probe in a vertical position onto the loudspeaker grid at a precise location. Third, such measurement of dual microphone probe response $(\tilde{p}_{\text{meas}}/\tilde{p}_{\text{ref}})_{FII}$ clipped near the loudspeaker is not susceptible to ambient noise nor the room’s acoustics.

Equation (10) can be rewritten using Eq. (12) using the same three-line writing convention, with the field NR measurement and its *field correction* on the first line, all the

laboratory corrections on the second line, and a compensation on the third line:

$$\begin{aligned} \text{REAT} = & \widetilde{\text{NR}}_* + 20 \log_{10} \left(\frac{\widetilde{p}_{\text{meas}}}{\widetilde{p}_{\text{ref}}} \right)_{FII} \\ & + 20 \log_{10} \left(\frac{\widetilde{p}_{\text{meas}}}{\widetilde{p}_{\text{ref}}} \right)_{LIII} + 20 \log_{10} \left(\frac{\widetilde{p}_{\text{ref}}}{\widetilde{p}_{\text{meas}}} \right)_{LII} \\ & + \text{TFOE} + \text{PN} + 20 \log_{10} \left(\frac{p}{p_{\text{ref}}} \times \frac{p'_2}{p'_3} \right). \end{aligned} \quad (13)$$

The measurement of the NR field correction $(\widetilde{p}_{\text{meas}}/\widetilde{p}_{\text{ref}})_{FII}$ is performed prior to the use of the measurement device, to discard any bias that would be introduced by small differences in the microphone sensitivity and frequency response during the measurement of the field noise reduction NR_* .

Given that the REAT method has been the “gold standard” for the past 50 years and in order to maintain consistency with current attenuation estimation protocols and standards, the proposed attenuation method aims to predict the attenuation value that would be measured on a human subject tested using the REAT method, for a given fit of a given HPD. In order to predict the REAT value, the previous equation (13) can be re-written as the sum of two terms:

$$\widehat{\text{REAT}} = \text{NR}_C + \text{COMP}. \quad (14)$$

The first term, NR_C , is the corrected NR, composed of the measured field NR and its field correction (first line) and laboratory correction terms (second line). The second term is the compensation factor COMP, and it is composed of the terms in the third line of Eq. (13). This term is detailed in Sec. III E.

Finally, this estimation of REAT attenuation is a monaural value. Since the NR measurement is performed on both earplugs, a binaural estimation of REAT is performed, with the “equivalent binaural approach” presented in Sec. III F.

C. Measurement of the field NR and its associated field and laboratory corrections

1. Measurement of the field NR

The NR values at octave-band index i , denoted $\widetilde{\text{NR}}_*^i$, are obtained from 1/3-octave bands filtered signals centered on the 125, 250, 500, 1000, 2000, 4000, and 8000 Hz frequencies. Such use of 1/3-octave band signals at octave-band center frequencies is common practice in the hearing protection measurement community, since the narrow band noise sources used for hearing threshold determination have precisely a 1/3-octave bandwidth (see Ref. 5 or Ref. 50).

2. Measurement of the NR field correction

The measurement in the acoustic near-field of the correction $(\widetilde{p}_{\text{meas}}/\widetilde{p}_{\text{ref}})_{FII}$ is performed prior to any use of the measurement device in the field and is part of a daily calibration check procedure. This procedure requires that the dual microphone probe be clipped to the center of the reference sound source speaker grid (ensuring the same acoustical pressure on both microphones), and that a TF measurement

be performed between both microphones while the sound source is generating a moderate level pink noise (as shown at the bottom of Fig. 3). This procedure also serves two additional purposes, prior to any use of the measurement device: first to check that the sound source is functioning properly (since the sound pressure level measured at the reference microphone must be in a given range of levels), second to check that both microphones are working correctly and that the microphone probe is not clogged, altered in any way or incorrectly positioned on the speaker grid, since the measured TF magnitude must be within given bounds.

3. Measurement of the NR laboratory corrections

The acoustical length of the overall sound-bore depends on the type of earplug used: for example, at the time of writing, the earplug was available in three different sizes for the core. Consequently, the overall sound-bore length was set for a given earplug size. The associated correction was determined using the laboratory setup illustrated in Fig. 3: the TF $(\widetilde{p}_{\text{meas}}/\widetilde{p}_{\text{ref}})_{LIII}$ is measured in an anechoic chamber with the microphone probe placed into the earplug 2 ft away from the loudspeaker, and the TF $(\widetilde{p}_{\text{ref}}/\widetilde{p}_{\text{meas}})_{LII}$ is measured while the dual microphone probe is clipped onto the speaker grid.

D. Estimation of the equivalent binaural NR

The estimated REAT obtained from Eq. (14) is a monaural estimation, while the measured REAT is a binaural value. In order to estimate a binaural REAT value, an approach based on the protected hearing threshold has been successfully developed:⁴⁹ it considers that the test subject is able to detect the audio stimulus (that is, the test signal used for the hearing threshold determination) through the ear that is presenting a combination of the lowest HPD attenuation and the best hearing level. In practice, this approach consists of computing the protected hearing threshold for each ear by adding the respective right and left hearing thresholds level A_R and A_L of the test subject to the right and left corrected NR denoted $\text{NR}_{C(R)}$ and $\text{NR}_{C(L)}$; the equivalent binaural NR value to be used, denoted $\text{NR}_{C(B)}$, is the one that corresponds to the weakest protected threshold:

$$\begin{aligned} \text{NR}_{C(B)}^i &= \text{NR}_{C(L)}^i \quad \text{if } (\text{NR}_{C(L)}^i + A_{(L)}^i) < (\text{NR}_{C(R)}^i + A_{(R)}^i), \\ \text{NR}_{C(B)}^i &= \text{NR}_{C(R)}^i \quad \text{if } (\text{NR}_{C(L)}^i + A_{(L)}^i) > (\text{NR}_{C(R)}^i + A_{(R)}^i), \\ \text{NR}_{C(B)}^i &= \min(\text{NR}_{C(L)}^i, \text{NR}_{C(R)}^i) \\ &\quad \text{if } (\text{NR}_{C(L)}^i + A_{(L)}^i) = (\text{NR}_{C(R)}^i + A_{(R)}^i). \end{aligned} \quad (15)$$

E. Compensation calculation

Assuming the subject-related correction terms on the third line of Eq. (13) are all uncorrelated, their combining in a single compensation term COMP should lead to a normal distribution for large groups with average value COMP and standard deviation σ_{COMP} . Such an assumption, validated in

Sec. IV A, is supported by the fact that all the terms included on the third line of Eq. (13) originate from morphological or psycho-physiological variables.

Based on Eq. (14), the following expression of COMP can be obtained for each octave-band (index i):

$$\text{COMP}^i = \text{REAT}^i - \text{NR}_{C(B)}^i, \quad (16)$$

where REAT^i is the REAT attenuation measured on the human subject tested, while $\text{NR}_{C(B)}^i$ is the equivalent binaural corrected NR [detailed in Eq. (15)] as measured on the same subjects, in the same fitting conditions.

The experimental protocol for COMP^i determination includes six steps repeated for each of the 20 subjects.

- (1) Measurement of the octave-band REAT values according to ANSI S12.6-A.⁵
- (2) Measurement of $\text{NR}_{C(R)}^i$ and $\text{NR}_{C(L)}^i$; since the test-subjects are instructed not to touch the HPD after the audiometric tests, and the NR measurement is performed immediately after the REAT tests, the fit of the earplug can be considered to be the same except for the slight effect of the insertion of the microphone probe (probably enhancing the quality of the fit, as the strength applied to insert the probe is toward the ear canal and tympanic membrane). The same “bias” is introduced by the microphone insertion for every earplug tested, and consequently, such systematic error is automatically canceled later in the compensation computation, as detailed in Ref. 49.
- (3) The equivalent binaural $\text{NR}_{C(B)}^i$ is then computed per octave-band using Eq. (15).
- (4) The difference, per octave-band and per subject between the reported REAT attenuation values and the objectively measured $\text{NR}_{C(B)}^i$, will provide the compensation values using Eq. (16).
- (5) Repetition of steps 1–4 for a second test trial, leading to a second determination of REAT and $\text{NR}_{C(B)}^i$ on each subject.
- (6) This per-subject compensation can then be presented, per octave-band index, as a normal distribution $\mathcal{N}(\overline{\text{COMP}}^i, \sigma_{\text{COMP}}^i)$; hence this compensation can be given with a confidence interval that is useful in determining the uncertainty associated with the proposed field-MIRE measurement.

F. Predicted personal attenuation rating

The PPAR is computationally very similar to the existing NRR and SNR: it is a single number, expressed in decibels, that represents the attenuation achieved by the user for a given HPD. While the NRR and the SNR are obtained from a subjective REAT measurement on a sample of individuals under laboratory conditions, the PPAR is obtained from an objective NR measurement, on a particular user wearing the hearing protector under more realistic conditions (since the HPD is fitted by the user). Furthermore, the NRR is a percentile value that is computed, according to EPA requirements,⁴¹ by subtracting a two-standard deviation correction from the mean REAT attenuation values in order to

estimate the “minimum NR theoretically achieved by 98% of the laboratory subjects.”⁴⁴ The PPAR_x is the value that the user will obtain from his own HPD with a given protection performance x , where x , based on the definition of ISO 4869 standard,⁴² represents the percentage of situations for which the effective personal attenuation is greater than or equal to the predicted value. Just like the SNR_x , defined in ISO 4869, is the minimal attenuation value that $x\%$ of a group should meet or exceed, the PPAR_x is the individual lower bound on the individual attenuation value such that $x\%$ of individual’s attenuation in a group will meet or exceed their own PPAR_x value.

Although the PPAR is a personal value, the uncertainty that will be used to compute the PPAR_x value comes from the prediction error obtained on a group of subjects. Per octave-band i (from $i=1$ for 125 Hz to $i=7$ for 8000 Hz), Eq. (14) can be written as

$$\widehat{\text{REAT}}^i = \text{NR}_C^i + \text{COMP}^i, \quad (17)$$

where COMP^i is the octave-band compensation factor, detailed in Sec. III E.

The equivalent binaural predicted attenuation can be expressed, respectively, by

$$\widehat{\text{REAT}}_{(B)}^i = \text{NR}_{C(B)}^i + \text{COMP}^i. \quad (18)$$

The PPAR is essentially the REAT value obtained in Eq. (19) reduced by an uncertainty factor that is the product of the prediction uncertainty $u_{\widehat{\text{REAT}}^i}^i$ and the coefficient α :

$$\text{PPAR}_x^i = \widehat{\text{REAT}}_{(B)}^i - \alpha \times u_{\widehat{\text{REAT}}^i}^i. \quad (19)$$

The coefficient α is a constant associated with a given protection performance, values of which are given in ISO 4869.⁵⁰

The overall PPAR value is obtained in a very similar manner as the existing NRR or SNR, by taking the difference between the C -weighted overall exposure level and the A -weighted overall protected exposure level, for a theoretical pink noise with a 100 dB in each octave-band:

$$\begin{aligned} \text{PPAR}_x = & 10 \log_{10} \sum_{i=1}^7 10^{(100+C^i)/10} \\ & - 10 \log_{10} \sum_{i=1}^7 10^{(100+A^i-\text{PPAR}_x^i)/10}, \end{aligned} \quad (20)$$

where A^i and C^i are, respectively, the C - and A -weighting coefficients.

Alternatives to the computation presented in Eq. (20) are possible: for example, instead of using a pink noise spectrum and computing the C - A' attenuation value like the NRR (where the prime symbol represents the protected level), the PPAR could be computed on the basis of the noise level reduction statistics (NRS_A) from the recent ANSI S12.68-2007 (Ref. 51) standard: the personal attenuation rating would hence be computed from the difference between A -weighted exposure values and A -weighted protected values for real industrial spectrums (see Ref. 52 for details).

IV. EXPERIMENTAL VALIDATION OF THE PROPOSED APPROACH

The validation of the measurement device has been successfully completed, by assessing its electrical floor noise, dynamic range, linearity, and time stability, and the current paper will focus in this section on the validation of the proposed method by comparing predicted and reported attenuation values.

The prediction method is validated using results of tests conducted by a third-party research laboratory.⁵³ Two groups, denoted α and β of 20 subjects, were tested with the instrumented expandable custom earplug (presented in Sec. II). The compensation for group α is evaluated according to Eq. (16) and the experimental procedure described in Sec. III E, on 17 of the 20 subjects. For three subjects the dual microphone probe was impossible to insert properly inside the sound-bore with the earplug in the ear (whereas in the usual measurement, the probe would be inserted in the sound-bore with the earplug outside the ear) because a pronounced bend of the earplug canal portion had distorted the sound-bore.

Then, the same measurement and calculation (as described in steps 1–5 in Sec. III E) are performed on the 20 subjects of the validation group β (no subject was discarded in this validation group). Using the compensation values $COMP_\alpha$ determined on the two trials of the first group α and the equivalent binaural $NR_{C(B)}$ computed with the second group β , the attenuation $REAT^i$ are predicted for each of the two test trials of group β .

These prediction values for group β are then compared to the REAT reported value for group β in order to evaluate the prediction error. The prediction error is presented in Sec. IV B, once the assumption of normality for compensation distribution is validated (Sec. IV A).

A. Validation of the assumption of normality for the distribution of the compensation values

The accuracy of fit of the compensation factor to a normal distribution was successfully validated at a significance level of 5% using the Jarque–Bera⁵⁴ tests of goodness-of-fit test of composite normality for both the first and second test trials of group α .

The normal probability plot for the compensation (from the first trial of group α) is presented in Fig. 4 together with the result of the statistical test ($H=0$ indicates that the null hypothesis “the data is normally distributed” cannot be rejected at the 5% significance level) and the p -value. The purpose of a normal probability plot of a physical quantity is to graphically assess whether this quantity could come from a normal distribution. If the data are normal the plot is linear. Other distribution types will introduce curvature in the plot. The plots in Fig. 4 provide a visual indication that the COMP function is a normal distribution although some outliers at high frequencies (2–8 kHz) can be observed. The normality hypothesis of Sec. III E is valid for the first trial of α data set at all octave-bands except 4 kHz at a significance level of 5%. A similar result is obtained by using the second trial of the α group.

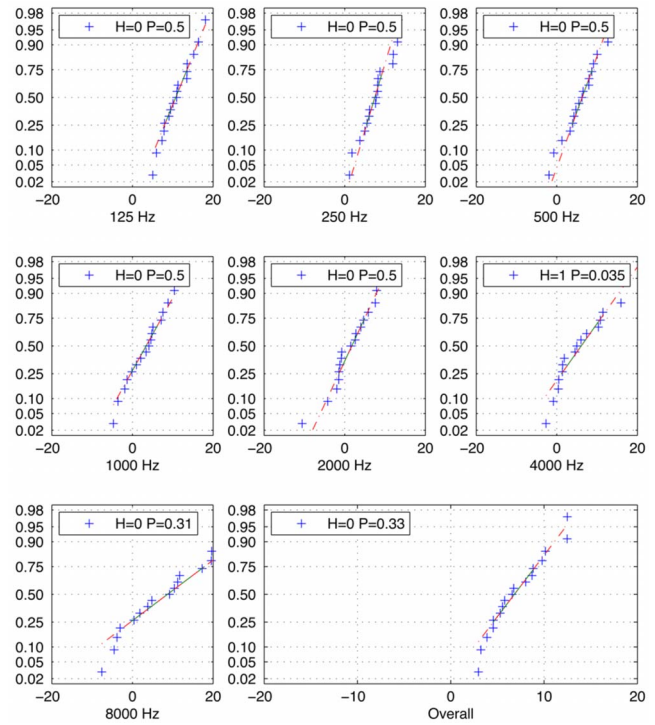


FIG. 4. (Color online) Normal probability plot of the Compensation for the first trial of α data set of experimental data ($n=17$). The abscissa coordinates are the unimodal Gaussian quantiles. The ordinate coordinates are the probability of the cumulative distribution.

B. Predicted vs observed attenuation

In Fig. 5, it can be seen that the average values predicted for the first trial of group β with the proposed field-MIRE approach are close to the REAT values in each octave-band and are less than 0.1 dB apart for the overall values. It can be seen that the standard deviation appears to be significantly lower in most octave-bands in the case of the field-MIRE than the one obtained from the REAT test. Given that the standard deviation primarily reflects the variability of the earplug attenuation in the group and does also include the

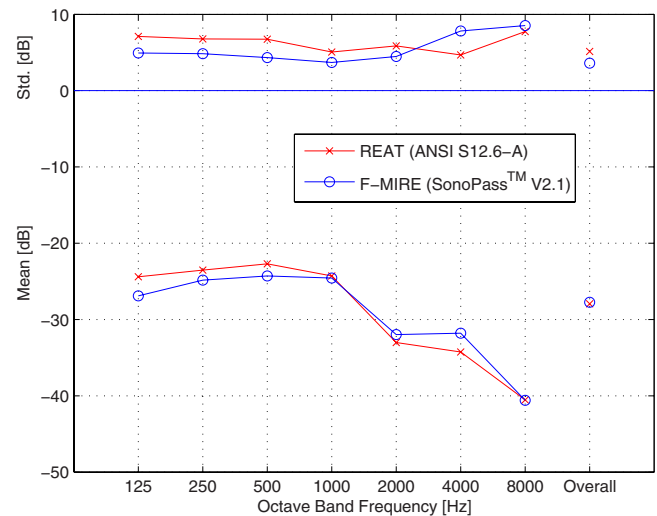


FIG. 5. (Color online) Mean and standard deviation of the attenuation measured, on the first trial test of group β , with the REAT and field-MIRE methods on the 20 subjects.

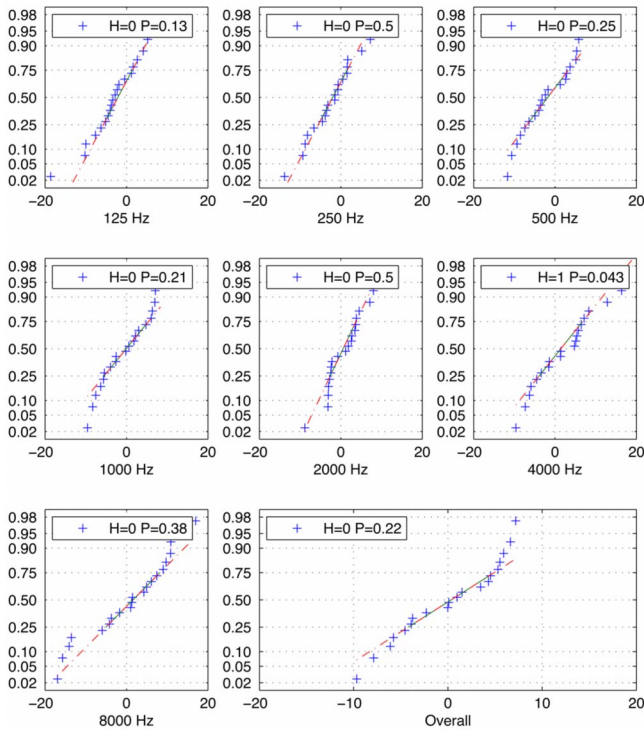


FIG. 6. (Color online) Normal probability plot of the observed prediction error ϵ^i per octave-bands and as an overall value for the first trial in the β data set ($n=20$).

variability associated with the measurement device itself, one could think that the proposed field-MIRE method is indeed introducing less variability (from 125 to 2000 Hz) than the REAT measurement approaches. Furthermore, the low-frequency octave-bands, where the field-MIRE shows less variability, are also the most critical for the assessment of the overall earplug attenuation, as it has already been demonstrated that the mere use of the 500 and 1000 Hz could be a good predictor of the overall attenuation.¹⁶

The observed prediction errors is defined as

$$\epsilon = \text{REAT} - \hat{\text{REAT}}, \quad (21)$$

where the measured REAT is considered the “true” attenuation value and $\hat{\text{REAT}}$ is the predicted one. If the observed prediction errors appear to behave randomly, this suggests that the model fits the data well. On the other hand, if a non-random structure is evident in the observed prediction errors, this is a clear sign that the model fits the data poorly. It can be observed by the normal probability plot of the observed prediction errors in Fig. 6 that the distribution of the observed prediction errors for the “first” trials is very close to a normal distribution for the whole frequency range.

The Jarque–Bera hypothesis test of composite normality for the first trials indicates that for all octave-bands (at the exception of 4 kHz), the null hypothesis (“the data are normally distributed”) cannot be rejected at the 5% significance level. The normality test is passed for 4 kHz by lowering the significance level to 4%. For the “second” trial, the normality test is passed at all frequencies at a significance level of 5%.

Overall, the assumption of a normally distributed observed prediction error is verified, which validates the model.

In addition, it becomes possible to evaluate the uncertainty which is associated with the proposed measurement approach, as described in the first author doctorate thesis.⁴⁹

V. CONCLUSIONS

To meet the need to improve earplug field performance prediction accuracy, average group performance prediction was replaced by individual performance prediction on a recently designed instrumented expandable custom earplug. The individual earplug field performance was objectively obtained using a field-MIRE method based on the field measurement of the NR through the earplug. Individual attenuation first resulted in a set of values for each octave-band center frequency and these values were then combined into a single value, the PPAR, which takes into account the measurement uncertainty. This PPAR is the equivalent of the “individual” NRR obtained from the traditional REAT attenuation testing. The method was validated experimentally on an ATF and using third party REAT testings on two groups of 20 subjects.

For effective hearing protection practices, the benefits of the proposed approach are threefold: (a) Fast and reliable measurement: the effective performance of the earplug can be measured quickly using a field-ready, durable, and robust measurement device. (b) The adaptation of earplug attenuation is now possible. If the earplug attenuation is known, it becomes possible to use acoustical filters to match the wearer’s hearing protection needs. This will allow the wearer to more easily discriminate between noise and speech or warning signals and will maximize speech and warning signals perception. (c) Quick field tests are possible by adopting portions of the testing protocol described herein that could be performed in little time. A quick field test device could potentially be used to greatly facilitate user motivation and training: such a measurement device could be installed at the entrance of a noisy plant so that exposed wearers could check the fit and efficiency of their HPD prior to sound exposure.

An immediate improvement in HPD rating and labeling would come from updating standards and regulations with this new approach. Easy access to personal measurement of earplug performance on the wearer could completely supersede the current use of a single number rating (like the NRR) as the individual PPAR values are inherently superior to the population-based, statistically-derived, laboratory-driven NRR estimation. A proposal has been written and submitted to the ANSI S12 Working Group WG11: the HPD product would be rated with average and standard deviation on a laboratory panel, as currently done in ANSI S12.6—Method B, and the field measurement device would be rated in terms of the uncertainty that is associated with the individual measurement. A new rating and labeling paradigm would therefore contain the typical attenuation value that users can achieve (using a “subject-fit” REAT attenuation measurement), the variability observed on a panel group and the uncertainty associated with the field measurement device.⁵⁵

A more long term improvement in HPD rating and labeling could come from the fact that the proposed field-

MIRE approach shows an equivalent or better uncertainty as compared to the current “gold standard” REAT and may be considered as a possible alternative for HPD attenuation measurement in the laboratory. In such cases, the IL could be used as an objective attenuation metric, rather than trying to predict a subjective REAT value that is also biased in several ways. Such an approach would bring the benefits of an objective measurement (lower measurement uncertainty) while keeping the human factor effect (variation in HPD fit with individuals). It could be integrated into current MIRE or ATF related standards [i.e., ANSI S12.42 (Ref. 28)] or could even be—when the remaining challenges associated with the instrumentation of all HPD will have been overcome—used instead of the current REAT method in a standard to measure the real-ear attenuation of hearing protectors [such as the current ANSI S12.6 (Ref. 7)].

Future research should address the need for an engineering design of a less intrusive dual microphone probe for reduced probe insertion variability and the need for computing compensation on an individual basis from an identification scheme rather than on a group basis from a statistical model. Individual compensation could be derived from the NR measurement in the occluded-ear using the identification of some individualized dimensions and characteristics from which it would be possible to reconstruct the required corrections (TF) that are part of COMP. For example, the computational process could identify the exact frequency of the occluded-ear canal resonance, then determine the length and area of the occluded residual ear canal, from which it would be possible to model the TF of the occluded-ear canal, as an acoustical duct. Such refinement could be beneficial for the precise and accurate prediction of an individual REAT-like attenuation but could also benefit the future measurement approaches presented in the previous paragraph, the prediction of the individual ILs.

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