Comparison of psychophysical and objective methods for the measurement of hearing protector devices attenuation

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ABSTRACT

This paper aims at presenting and examining the various factors relating attenuation values of hearing protection devices obtained using subjective and objective test methods. Experiments on several human subjects were carried out where the subjects were instrumented on both ears with miniature microphones outside and underneath the protector. They were then asked to go through a series of subjective hearing threshold measurements followed by objective microphone recordings using high level diffuse field broadband noises. Results are presented for various passive earmuffs, earplugs and their corresponding double protection.

INTRODUCTION

The noise attenuation is a primary characteristic of a hearing protection device (HPD) such as an earmuff or an earplug as it indicates the effectiveness of the device to block sound. There are several measurement methods to evaluate the attenuation and the most commonly used can be divided into psychophysical and objective (physical) methods. A thorough description and review of the different methods can be found in a paper from Berger (Berger, 1986). These methods lead to attenuation values, presented as a function of frequencies, which can be later used to produce various “performance” ratings for hearing protectors (ISO, 1994; ANSI, 2008). The “gold standard” in attenuation measurement is the real-ear attenuation at threshold, noted *REAT*. In this psychophysical method, human subjects go through hearing threshold tests at different frequencies, with and without the protector in place. Attenuation values are then obtained by taking the differences between the two auditory thresholds. On the other hand, with the increase popularity of individual fit testing and the advent of miniaturization of electronic components, the microphone-in-real-ear approach (*MIRE*) and its field counterpart Field-MIRE (*F-MIRE*) are becoming more appealing and well suited for estimating HPDs attenuation both in laboratory and in “real world” occupational conditions. In the *MIRE* approach (Berger, 2005), a miniature microphone is used to measure sound pressure levels in the ear canals. Measurements of sound pressure level (SPL) are then made with supra-threshold noise levels, with and without the HPD in place. Similar to *REAT*, the difference between the SPLs allow obtaining attenuation values in the form of an insertion loss (*IL*). If one uses an additional microphone to measure the sound field just outside the protector, it becomes possible to measure simultaneously the SPLs outside and inside the ear canal. The difference between these two quantities can be seen as attenuation in the form of a noise reduction (*NR*). This latter procedure, referred as *F-MIRE*, is well adapted to field measurements as the attenuation can be obtained with just one measurement as opposed to the *REAT* and *MIRE* which require the tests to be performed with and without the HPD in place, in two separate steps. *REAT*, *MIRE* and *F-MIRE* procedures all present advantages as well as weaknesses and lead to different attenuation readings. It is therefore important to understand the relationships that exist between these various attenuation estimates to better judge the applicability of the respective measurement methods. Casali et al (Casali et al., 1995) presented some comparisons and results on earmuffs showing that *NR* an *IL* yield comparable results as long the *NR* values are corrected by an average *TFOE* (as previously discussed by Berger (Berger, 1986)). Similar work on earmuffs with active noise reduction systems was recently presented by Perala and Casali (Perala and Casali, 2009). Also recently, work by Voix et al (Voix and Laville, 2009) showed in details how the *IL* and the *REAT* can be related using group average corrections for molded earplugs. Extension of this latter work was also presented for different types of earplugs (Berger et al., 2011). This paper aims at presenting and examining in more details the various factors relating the *REAT*, *IL* and *NR* attenuation values for various earmuffs and earplugs as well as their corresponding double protection use. Equations relating the psychophysical *REAT* values to the objectives attenuation data are first presented. Various comparisons obtained with the different attenuation values are then presented and discussed.

METHODS

Theoretical background

Figure 1 illustrates the external ear in the unoccluded (open) and occluded conditions (with an earmuff or an earplug). The subscripts to the sound pressure refer, respectively, to microphone locations just outside of the ear near the canal entrance (‘*ext*’), in the ear canal at some distance of the tympanic membrane (‘*c*’) and close to the tympanic membrane (‘*t*’). Sound pressures in the occluded conditions are noted with the symbol ‘prime’ in superscript. Given this notation, the Insertion Loss (*IL*) and the Noise Reduction (*NR*), expressed in dB, are defined as:

$$IL = 20\log_{10}\left(\frac{p_t}{p'_t}\right) \text{ and } NR = 20\log_{10}\left(\frac{p_0}{p'_t}\right) \tag{1}$$

where p_0 is the sound pressure in the absence of the subject.

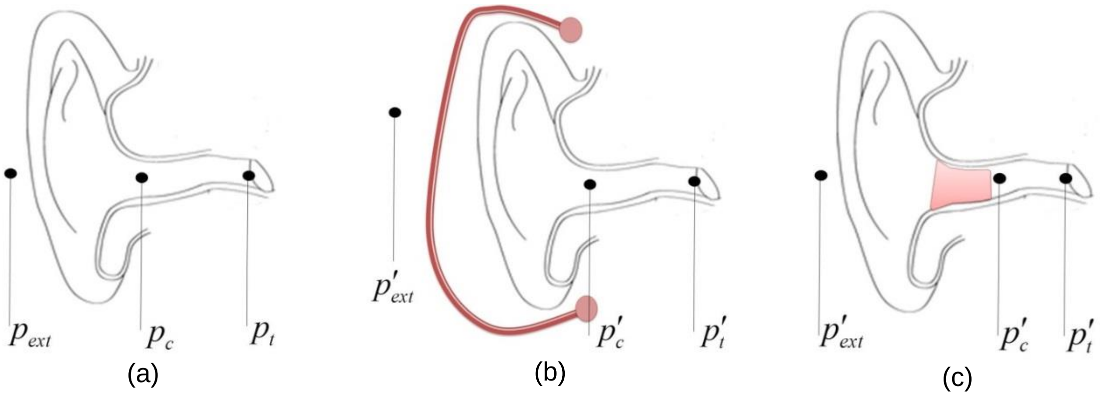


Figure 1: Illustration of the various microphone locations for the different ear conditions: a) open ear; b) occluded ear with an earmuff; c) occluded ear with an earplug

The *IL* is related to the *NR* through:

$$IL = 20\log_{10}\left(\frac{p_t}{p'_t}\times\frac{p_0}{p_0}\right) = 20\log_{10}\left(\frac{p_0}{p'_t}\times\frac{p_t}{p_0}\right) = NR + TFOE \tag{2}$$

where *TFOE* is the transfer-function-of-the-open-ear and is defined as:

$$TFOE = 20\log_{10}\left(\frac{p_t}{p_0}\right). \qquad (3)$$

If one makes the assumption that the bone conduction path is negligible for the HPD under test, it is accepted (Berger and Kerivan, 1983) that the *REAT* is related to the *IL* through:

$$REAT = IL + PN \qquad (4)$$

where *PN* is the physiological noise, an effect that was shown to be related to the device under test and to the occluded-ear canal volume. In practice, it is much more convenient and safer for the subjects to measure the sound pressure in the ear canal at some distance of the tympanic membrane (p_c *and* p'_c) rather than directly next to it (p_t *and* p'_t). It also more convenient to express the *NR* using the sound pressure measured just outside the HPD p'_{ext} instead of p_0. The relations between *REAT*, *IL* and *NR* can then be written as:

$$REAT = IL^* + TF'_{canal} - TF_{canal} + PN \, , \qquad (5)$$

$$REAT = NR^* + TF_{c-ext} + \left(TF'_{canal} - TF_{canal}\right) + \left(TF_{ext} - TF'_{ext}\right) + PN \, , \qquad (6)$$

$$IL^* = NR^* + TF_{c-ext} + \left(TF_{ext} - TF'_{ext}\right) \qquad (7)$$

where:

$$IL^* = 20\log_{10}\left(\frac{p_c}{p'_c}\right) \text{ and } NR^* = 20\log_{10}\left(\frac{p'_{ext}}{p'_c}\right) \qquad (8)$$

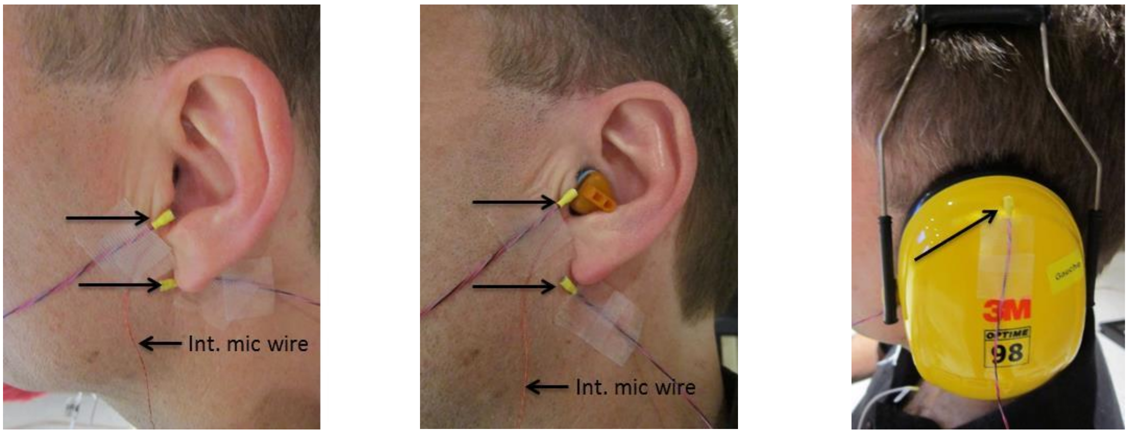
$$TF'_{canal} = 20\log_{10}\left(\frac{p'_c}{p'_t}\right) \text{ and } TF'_{ext} = 20\log_{10}\left(\frac{p'_{ext}}{p_0}\right), \qquad (9)$$

$$TF_{c-ext} = 20\log_{10}\left(\frac{p_c}{p_{ext}}\right) \qquad (10)$$

The quantities TF_{canal} and TF_{ext} are similar to those defined in equation (9) but for the unoccluded condition. Equations (5), (6) and (7) form the basis for attenuation value comparisons between the objective measurements *IL* and *NR* and the psychophysical *REAT*. One particular interest of these equations lies in the fact that most terms, with the exception of $\mathrm{TF}_{\mathrm{canal}}$, TF'_{canal} and *PN*, can be obtained and examined using the test setup proposed in the next section.

Test procedures with human subjects

The subjects were first instrumented with three miniature microphones (Knowles Electronics, Itasca, IL) per ear. One microphone was positioned in the ear canal approximately halfway between the entrance and the eardrum (open ear and occluded ear with earmuffs) or few millimeters from the plug (occluded ear with earplugs) to measure p_c and p'_c. A second microphone was positioned at the ear canal entrance (open ear and occluded ear with earmuffs) or right in front of the plug (occluded ear with earplugs). Finally, a third microphone was used to measure the exterior sound field (p_{ext} and p'_{ext}). It was placed near the ear lobe (open ear & occluded ear with earplugs) or on the upper part of the cup (occluded ear with earmuffs). Locations of the microphones are shown in Figure 2.



(a) (b) (c)

Figure 2: Locations of the microphones for the different conditions: a) unoccluded; b) earplugs; c) earmuffs. For the microphone located in the ear canal, only the connecting wire can be seen.

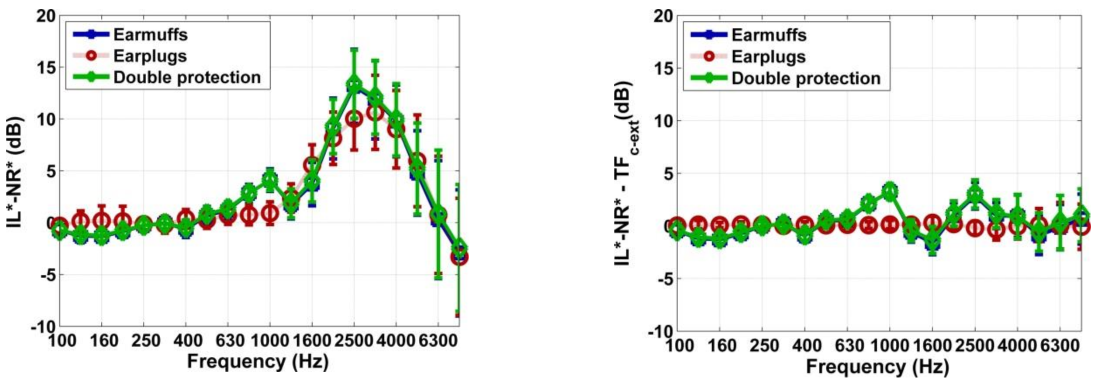
The tests were conducted in a semi-anechoic room equipped with four uncorrelated sources generating a broadband signal played by 4 loudspeakers in order to create a diffuse sound field meeting the requirements of the ISO 8253-2 and ANSI S12.6 standards for *REAT* audiometric testing. Each subject was asked to sit still in the test room and was tested under four conditions of ear protection: i) open ear; ii) earmuffs; iii) earplugs; iv) double protection. For each condition, the following test sequence was conducted: 1) threshold measurements using a commercial automated *REAT* measurement software, REATMaster (ViAcoustics, Austin, TX); 2) 90 dB constant pink noise with 20sec time recordings for each microphone; 3). Band limited noises (7 octave bands ranging from 125 to 8000 Hz, 85 dB/band) and 20 sec time recordings for each microphone and each frequency band.

A total of 29 subjects were tested, each of them with one pair of earmuffs, one pair of earplugs and their corresponding double protection. Some subjects were tested more than once with a different combination of earmuffs/earplugs. Additionally, some data had to be rejected due to some technical problems. As a result, a total of 57 test sequences were performed. Three types of earmuffs and three types of earplugs were selected. The selected earmuffs were different in construction (dual-cup vs single shell), sizes and labeled noise reduction ratings of 20, 23 and 30 dB respectively. As for earplugs, classic foam, push-ins no-roll foam and custom molded earplugs were selected.

RESULTS

IL* vs NR*

Emphasize is first put on equation (7) in order to examine the importance of the exterior microphone location as well as the effect of the ear canal through the term $TF_{c\text{-}ext}$. Since they are directly obtained from the test procedure and from the choice of microphone locations, *IL** and *NR** values are used rather than *IL* and *NR*. Results for the differences *IL*-NR** and $IL^*\text{-}NR^*\text{-}TF_{c\text{-}ext}$, averaged across all subjects and protectors (left and right ears results combined), are shown in Figure 3 for the three protection conditions. Important values for the standard deviation are observed in the first plot (a) above 1 kHz due to the variations in the $TF_{c\text{-}ext}$ terms. This is not a surprise as this term is, in a way, an approximation of the *TFOE*, a quantity that is known to vary largely from an individual to another. However, when corrected for this term, the differences between *IL** and *NR** are found to be significantly lower regardless of the type of protection, with a small standard deviation (in accordance with previous findings (Casali et al., 1995)). This suggests that SPL measured by the exterior microphone is not much affected by the presence of the protector, in particular for earplugs. As expected, this effect is more important for earmuffs. Additional analysis of the results (not presented here) allowed us to propose a set of $TF_{c\text{-}ext}$ curves to correct the *NR** values. Based on ear canal length estimation for each subject, this set of curves helped to produce equivalent *IL* and *NR*-based attenuation values.



(a) (b)

Figure 3: Differences between IL*-NR* for the three hearing protection condition tested: earmuffs (N=106), earplugs (N=106) and double protection (N=101)

REAT vs NR*

Importance of the ear canal and of the exterior microphone can also be examined through equation (6) by comparing *REAT*- and $NR^*+TF_{c\text{-}ext}$-based attenuation values. Results for each earmuffs and earplugs are presented in Figure 4. Due to space consideration, results for double protection are not presented here. Mean and standard deviation values (average across subjects) are presented. For the NR-based results, left and right ear data for a given subject were combined to obtain a binaural estimate using an approach proposed by Voix and Laville (Voix and Laville, 2009). Results show a fair agreement between *REAT* and *NR*-based values considering the observed variability. However, for earmuffs, the NR-based attenuation values tend to be generally higher than the REAT ones, a result already observed in the past (Casali et al., 1995). Although fairly good agreement is obtained for earplugs, higher standard deviations are observed. This is most probably due to the variations in fitting compared to earmuffs. Interestingly, *REAT* and *NR*-based standard deviation values are very similar with the exception of the classic foam earplugs (Erp1) above 2 kHz for which the NR-based variability is higher. The variation in fittings for earplugs has probably an effect on the $(TF'_{canal}-TF_{canal})$ term in Eq. (6). Investigations are currently undergoing using Finite Element Models (FEM) to quantify this effect but early examinations suggest that the absolute values of TF'_{canal} and TF_{canal} do not exceed 1dB below 5 kHz.

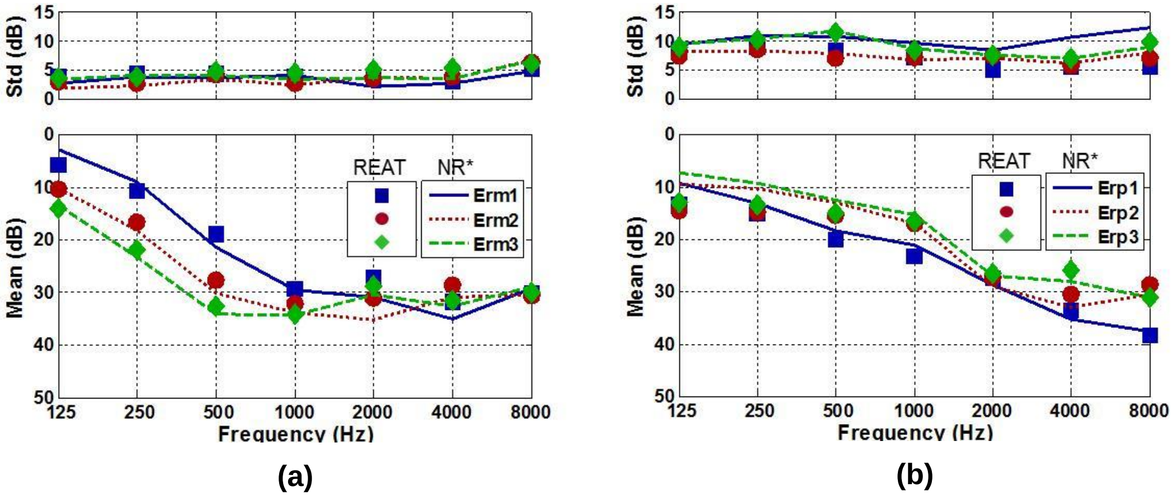


Figure 4: Comparisons of *REAT* (symbols) and *NR** (lines) values for: a) the three earmuffs tested; b) the three earplugs tested. Mean and standard deviation values are shown (average over subjects)

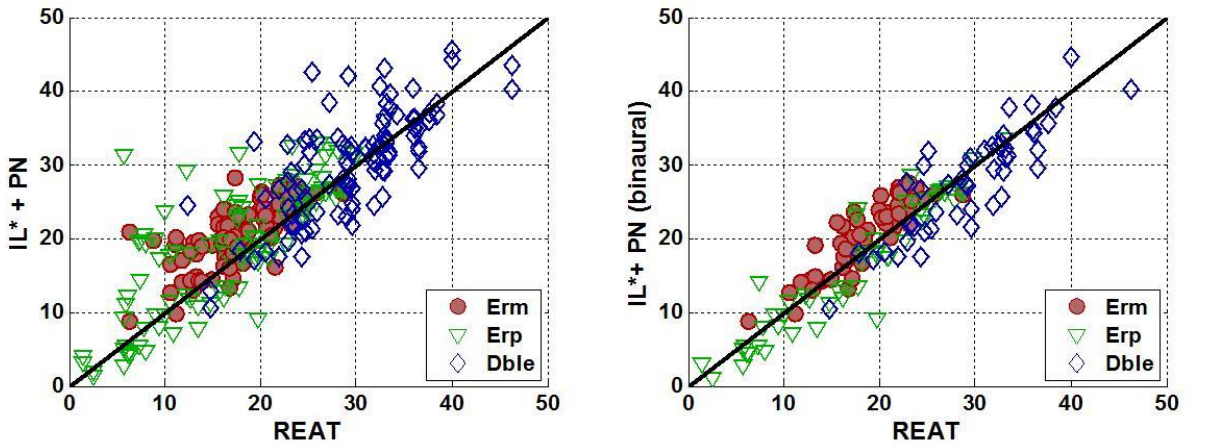
Attenuation rating

Attenuation values are often used to compute single-number attenuation rating. For the sake of comparisons between *REAT* and *IL*-based values, a personal attenuation rating (*PAR*) was computed using the measured data. The *PAR* is herein defined as:

$$PAR_{AV} = \frac{1}{N_{noise}} \sum_{i=1}^{N_{noise}} \left(10\log_{10} \sum_{k=1}^{7} 10^{0.1 L_k^i} - 10\log_{10} \sum_{k=1}^{7} 10^{0.1\left[L_k^i - AV_k \right]} \right) \qquad (11)$$

where the index *i* refers to individual noise spectra taken from the NIOSH 100 database of industrial noise (see (ANSI, 2007)) and the index *k* to the seven octave bands in the 125 to8000 Hz range [. The quantities AV_k are the spectral attenuation values obtained in this study through *REAT*, *IL* or *NR* procedures. Comparisons between PAR_{IL*+PN} and PAR_{REAT} values computed using Eq. (11) are shown in Figure 5. Individual left and right ear *IL**-based results are shown in Figure 5(a) while they were combined (binaural estimate; see the discussion in the preceding section) to produce the *PAR* values in Figure 5(b). Additionally, approximate values for *PN* were used to correct the *IL** results (Schroeter and Poesselt, 1986) in an attempt to match the *REAT*-based as much as possible. The results show how binaural estimates help obtaining *IL*-based rating values in much closer agreement with *REAT*-based values.

As observed previously with spectral attenuation values (Figure 4), higher *PAR* values are obtained for earmuffs when using *IL** values compared to *REAT*, even if correction terms were introduced for the physiological noise *PN*. Linear regressions were made using the *IL* binaural- and *REAT*- based *PAR* data from Figure 5(b). Assuming a linear relation of the form $y = m\,x + b$, the three sets of data were fitted (earmuffs, earplugs and double protection). Parameters of the three fits are presented in Table 1. Additionally, normal probability plots of the residuals are presented in Figure 6 to verify the accuracy of fit. While good accuracy was obtained for the three types of protection, fit results showed clearly that *IL*-based ratings were, in average, 2.2 dB higher than the *REAT* based for earmuffs. For earplugs and double protection, differences between *IL*- and *REAT*- based ratings were, in average, less than 1 dB although the standard deviations of the residuals were around 3 dB and few outliers were obtained.

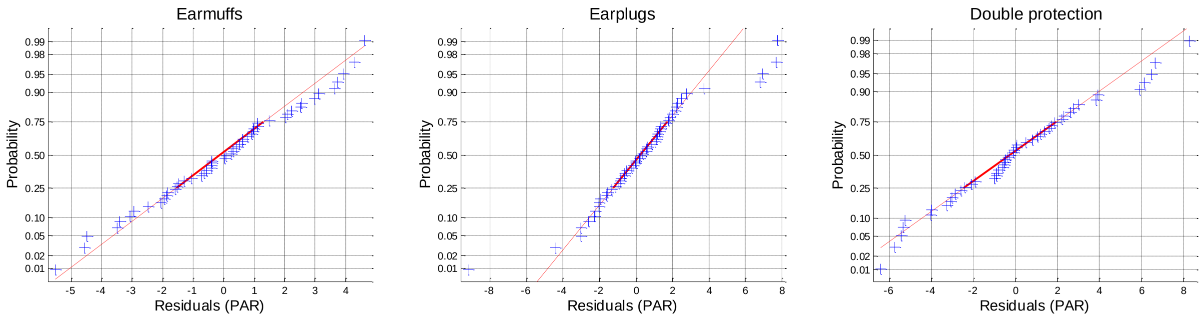


(a) (b)

Figure 5: Comparisons of *PAR* values computed using *AV=IL*+PN* and *AV=REAT* in equation (11): a) left and right ear results for *IL** results; b) left and right ear combined for *IL** results (binaural estimate). Results are presented in three groups: earmuffs (Erm), earplugs (Erp) and double protection (Dble).

Table 1: Parameters of the linear fit of *PAR* values (linear fit of the form $y = m\,x + b$)

	M	b (dB)	Standard deviation of residuals (dB)	Correlation coefficient
Earmuffs	0.98	2.2	2.4	0.88
Earplugs	1.00	-0.9	2.9	0.94
Double protection	0.97	-0.7	3.5	0.87



(a) (b) (c)

Figure 6: Normal probability plots of the *PAR* residuals for the three linear fits: a) earmuffs; b) earplugs; c) double protection

CONCLUSIONS

Comparisons of different types of hearing protector attenuation measurement procedures were presented and discussed. Equations relating the psychophysical (*REAT*) values to the objectives attenuation data (*IL* and *NR*) were first presented. This set of equations served to highlight the various factors linking the objective and psychophysical attenuation values. A multi-step test procedure was proposed and applied to human subjects wearing earmuffs, earplugs and double protection. The few preliminary results presented here showed how the proposed procedure can be used to explain some of the differences observed between *REAT*, *IL* and *NR*-based attenuation values. For example, it was shown that *IL* and *NR*-based data lead to similar attenuation values as long as the NR values are correctly corrected for the *TFOE*, Additionally, the results suggest, although indirectly and partially presented here, that this *TFOE* can be approximated by the transfer function between a microphone placed just outside the ear and another one inside the ear canal. It opens the door to practical field implementation where the miniature microphones could not only be used to measure attenuation but also to estimate the necessary transfer functions or to identify the frequency of the occluded-ear canal resonance. The results also suggested that *IL*- and *NR*- based data lead to attenuation values and ratings that are comparable to the ones obtained with *REAT*, in particular if a *binaural estimate procedure* is performed on the objective values. The *NR*-based method is then a viable option to measure attenuation, in particular if one interested to measure HPDs' performance in the field. Detailed analysis of the entire set of results is currently undergoing to investigate in more details the importance of each factor in the equations relating *REAT* to *IL* and *NR*.

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