Systematic evaluation of the relationship between subjective and objective measurement methods of hearing protector devices attenuation

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Summary

This paper aims at presenting a systematic evaluation of the various factors relating the subjective and objective attenuation values of hearing protectors. 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. Passive earmuffs, earplugs and double-protection were tested for each subject and attenuation values were compared. The various factors relating the subjective REAT values to the objective attenuation data are presented and their importance is discussed.

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1 Introduction

A primary characteristic of a hearing protection device (HPD) is the noise attenuation it provides as it is one indication of the effectiveness of the devices to block sound. Several measurement methods have been employed in the past to evaluate the attenuation and the most commonly used can be divided into two categories: subjective and objective methods. Descriptions and reviews of these methods can be found in the literature[1–3]. These methods lead to attenuation values, presented as a function of frequencies, which can be used to produce various "performance" ratings for hearing protectors or to estimate worker's noise exposure under the protector[4,5].

The "gold standard" in attenuation measurement is the real-ear attenuation at threshold, noted REAT. In this method, subjects are asked to go through hearing threshold tests at different frequencies, with and without the protector in place. Attenuation values are obtained by taking the differences between the open and occluded ear auditory thresholds. Such method offers the advantage that all significant sound paths to the inner ear are taken into account. However, it is generally time-consuming and very sensitive to the ambient background noise. REAT is also known to be limited by masking effects due to physiological noise at low frequency and it demonstrates a high variability due to the inherent subjective nature of the testing.

To palliate these limitations and with the increase popularity of individual "fit testing" and the advent of miniaturization of electronic components, the microphone-in-real-ear approach (MIRE) is gaining in popularity. In MIRE, a miniature microphone is used to measure the sound pressure level (SPL) in the ear canal near the tympanic membrane. SPL measurements are 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 an additional microphone is used to measure the sound field just outside the protector, it becomes possible to obtain simultaneously the SPLs outside and inside the ear canal. The difference between these two quantities is seen as attenuation in the form of a noise reduction (NR). This latter procedure is well adapted to field measurements since the attenuation can be obtained with just one measurement as opposed to

IL-based procedures which require tests performed in two separate measurements. REAT and MIRE procedures all present advantages as well as weaknesses and lead to different attenuation values. It is then deemed important to understand the relationships that exist between these various attenuation estimates to better judge the applicability of the respective methods. In this context, comparative studies have been published in the past by several authors[1,3,6–9]. Overall, these studies have shown good correlations between the REAT and MIRE measurements methods and that MIRE/NR-based method is relatively quick to perform and is particularly well adapted for field measurements. However, for comparisons with REAT data, the MIRE results have to be corrected with various factors that are generally approximations derived from ensemble averages taken over a group of subjects. There are generally little details on how these corrections factors are affected by different parameters such as the positioning of the microphones, the physical characteristics of the individuals, the sound field, etc. Moreover, due to the specifics of the test procedures, data obtained with REAT and MIRE techniques have been almost exclusively obtained through separate measurement sessions, with generally different subjects. This paper presents some results of a detailed evaluation of the various factors relating the REAT, IL and NR attenuation values. Sequential measurements of the various attenuations on the same subjects in similar conditions were performed for three HPD categories: earmuffs, earplugs and dual protection. More specifically, the goal is to examine if individual corrections factors are needed instead of "average" ones and to investigate the effects of these factors on the attenuation. A quick recap of the equations relating the REAT values to the MIRE-based attenuation is first presented. Secondly, the test procedures are explained and detailed. Finally, various comparison results obtained with the different attenuation values are presented and discussed.

2 Methods

2.1 Relationship between REAT and MIRE-based attenuations

The relationship between the REAT and MIRE-based attenuation values is presented in details in a paper recently submitted by the present authors[10] and is only briefly summarized here. One defines the sound pressure p at three different locations: the exterior microphone just outside protector ('ext'), in the ear canal at some distance of the tympanic membrane ('c') and close to the tympanic membrane ('t'). One also defines the sound pressure in the occluded conditions with the symbol 'prime' in superscript. It can be shown relatively easily that IL and NR-based attenuations are related to REAT through the following relations:

$$REAT = IL^{*} + (TF'_{canal} - TF_{canal}) + PN \quad (1)$$

$$REAT = NR^{*} + TF_{c-ext} + (TF'_{canal} - TF_{canal}) + (TF_{ext} - TF'_{ext}) + PN \quad (2)$$

$$IL^{*} = NR^{*} + TF_{c-ext} + (TF_{ext} - TF'_{ext}) \quad (3)$$

The 'star' symbol refers to the fact that the SPL in the ear canal is not measured directly at the tympanic membrane but rather at some distance of it as it was the case in the series of tests performed on human subjects. By doing so, one also gets:

$$IL = IL^{*} + (TF'_{canal} - TF_{canal}) \quad (4)$$

$$NR = NR^{*} + TF'_{canal} - TF'_{ext} \quad (5)$$

where IL and NR are obtained using the SPL directly next to the tympanic membrane. The terms TF'_{canal} and TF_{canal} are the transfer functions between the tympanic membrane ('t') and the ear canal location (noted 'c') while the terms TF'_{ext} and TF_{ext} are the transfer function between the microphone placed just outside the protector and one at the center of the head without the subject. PN is the physiological noise effect, which is known to be related to the device under test and to the occluded-ear canal volume. Finally, the term TF_{c-ext} relates the ear canal location to the exterior microphone and is directly proportional to the transfer function of the open ear (TFOE) through:

$$TF_{c-ext} = TFOE + TF_{canal} - TF_{ext} \quad (6)$$

The particular interest of equations (1)-(6) lies in the fact that most terms, with the exception of TF_{canal}, TF'_{canal} and PN, can be obtained and examined using the test setup described in the next section.

2.2 Test procedures

To test the subjects under similar noise environments and HPD fitting conditions for REAT and MIRE evaluations, a three-step procedure was developed. The subjects were first instrumented with three Knowles miniature microphones per ear. One microphone was positioned in the ear canal, at the same position for the open and occluded ear conditions, approximately halfway between the entrance and the eardrum and a few millimetres from the plug. Another microphone was used to measure the external sound field. It was placed near the ear lobe (open ear and occluded ear with earplugs) or on the upper part of the cup (occluded ear with earmuffs). Additionally, a 1-in B&K microphone was placed approximately 30 cm above the head of the subject and was used as a control microphone. The tests were conducted in a semi-anechoic room equipped with four uncorrelated speakers/sources generating a local diffuse field meeting the requirements of uniformity and directionality 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) corresponding dual protection. The HPD was positioned by the experimenter unless it was asked by the subject to place it himself.

For each subject, the following steps were performed. Steps 1 and 2 were repeated for each ear protection condition.

Step 0. Measurement of P_0: Without the subject, all microphones were placed at the center of the head location.
a. Seven band-limited noises were generated successively (125 to 8000 Hz, 85 dB(A) SPL/band), 10 sec time recordings for each microphone per frequency band.
b. Pink noise (90 dB(A) SPL) was generated and 10 sec time recordings were made simultaneously for each microphone.
Step 1. REAT using Bekesy hearing threshold measurements. Threshold levels as a function of frequency were recorded.
Step 2. Measurement of P_{ext} and P_c:
a. Using the same seven band-limited noises as in step 0.a, 10 sec time recordings were made simultaneously for each microphone.
b. Using the same pink noise as in step 0.b, 10 sec time recordings were made simultaneously for each microphone.
After each HPD installation i.e. before step 1, a 1-5 min resting pause was observed by the subject. Time recordings were analysed and post-processed using in-house Matlab scripts. Various spectra were obtained in narrow, third-octave or octave bands for all microphones, ear protection conditions and tests combinations. It enabled the calculation of all the REAT, IL* and NR* attenuation values needed for comparison purposes as well as the computations of the correction factors presented in equations (1)-(3).

A total of 29 subjects with normal hearing participated. Hearing threshold levels were measured independently for each ear. Each subject took part to the test sessions with one pair of earmuffs, one pair of earplugs and their corresponding dual protection. Some subjects were tested more than once with a different combination of earmuffs/earplugs. The experimental protocol and the selection process were approved by the Ethics Committee of research of the École de technologie supérieure. Three different models of earmuffs and earplugs were tested. The selected earmuffs were the Ear1000, Optime 98 and Optime 105 from 3M (3M©) and the earplugs were the custom molded earplugs (Self-Fit^{TM} Hearing Protection HPD-V5) from Sonomax (Sonomax Technologies Inc.$^{©}$) and push-ins no-roll foam and classic roll-down foam earplugs, also from 3M. Subjects selection was made such that each HPD was tested 18 or 19 times. A total of 55 test sessions were performed.

2.3 Equivalent binaural estimates

MIRE-based attenuation values are monaural estimations (left and right) while REAT-based are binaural ones. In order to compare results, it is then convenient to transform the left and right MIRE-based monaural values to an equivalent binaural estimate. The approach proposed by Voix and Laville[8] was used. An assumption is made that during hearing threshold determination, a subject is able to perceive the audio stimulus through the ear that is presenting a combination of the lowest HPD attenuation and the best hearing sensitivity. An equivalent binaural estimate can then be obtained using a simple calculation algorithm if one uses the subjects' hearing thresholds of each ear. Unless mentioned otherwise, MIRE-based results presented in the rest of this paper are equivalent binaural estimates.

3 Results and discussion

3.1 Frequency dependant attenuations

Attenuation results for REAT and IL* are shown in figure 1. It is particularly interesting to note that good correlation was not only obtained for various types of protectors but also for a wide range of attenuation. It is also worth noting that standard deviation values obtained with REAT and IL* are very close to each other for all protection conditions. These results are somewhat in contradiction with the literature where one typically reports higher standard deviations for REAT-based values than for MIRE-based. It is important to mention that no specific control was made on the fit of the HPDs in the present study. Therefore, higher standard deviations are obtained, more typical of subject-fit data or even real-world data reported in the literature as opposed to experimenter-fit data. It may suggest that the similar standard deviations obtained here are more representative of the variability in fit of the HPDs rather than to threshold variability usually attributed to REAT.

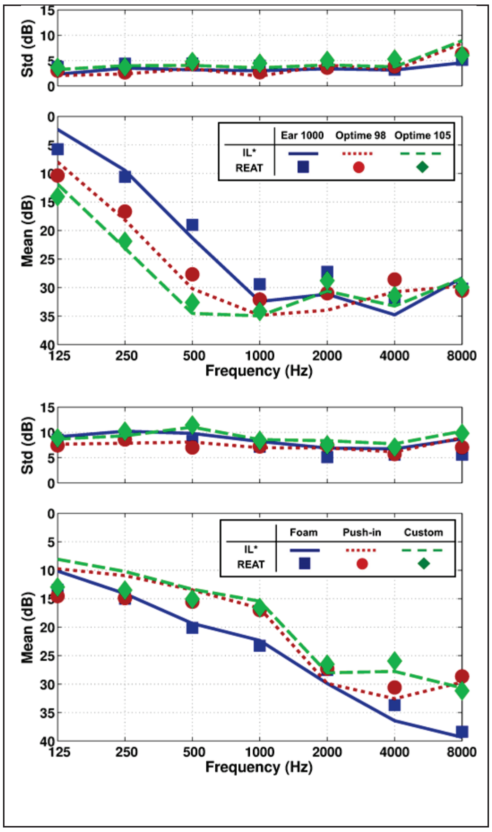

Figure 1: REAT and IL* attenuation values (mean and standard deviation) for the earmuffs (upper) and the earplugs (lower) tested

Equation 1 shows that *REAT* and *IL** differ by the factor (TF'$_{canal}$ -TF$_{canal}$) + PN. A recent study[11] shows, using FE models of the ear-canal/earplug assembly, that TF'$_{canal}$ and TF$_{canal}$ are well below 1 dB for frequencies below 1000 Hz and don't exceed 3 dB at the highest frequency band (5 kHz band) for typical microphone insertion in the ear canal. Moreover, the difference (TF'$_{canal}$ -TF$_{canal}$) remains below 1 dB for the entire frequency range. Deviations in attenuations observed in the 125 and 250 Hz bands are attributed to the physiological noise PN and are greater for earplugs, in accordance with literature results.

Similar results were obtained using NR*. However, as seen in equation (2), more correction factors appear in the relation between REAT and NR*. Various results on these factors (not shown here) could be obtained in the present study. For example, the factors TF'$_{ext}$ and TF$_{ext}$ were mostly below 2 dB for the entire frequency range and, most importantly, essentially independent of the earmuff or earplug under test. It indicates that locating the external microphone just outside the protector has a small impact on the results but offers a clear advantage for field testing in the NR-based context. Another important factor is the TF$_{c\text{-}ext}$ factor (see equation (6)). Measured in open ear conditions, it is directly related to the TFOE and, as such, is the most important factor relating the NR-based attenuation to the objective REAT and subjective IL-based one. Given the relatively low values obtained for TF$_{ext}$ and TF$_{canal}$, it seems reasonable to assume that TF$_{c\text{-}ext}$ could serve as a surrogate for the TFOE without losing too much accuracy. Additionally, our results suggest that individual curves for TF$_{c\text{-}ext}$ could be replaced by an average curve if one accepts an increase in the variability. One advantage is that measuring the function TF$_{c\text{-}ext}$ is easier than measuring the TFOE and it could be performed relatively easily in laboratory of field conditions on a subject instrumented with miniature microphones, before the positioning of a HPD.

3.2 Personal attenuation rating (PAR)

Frequency dependant attenuation values such as those presented in the previous section are often used to calculate various ratings used to label HPDs, classify and compare them between each other and estimate a worker's noise exposure. For the sake of comparisons between REAT and MIRE-based values, a personal attenuation rating (PAR) was computed using the measured data. The PAR is defined as:

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

where the index i refers to individual noise spectra taken from the NIOSH 100 database of industrial noise and the index k to the seven octave bands in the 125 to 8000 Hz frequency range. The quantities AV_k are the frequency dependant attenuation values obtained with REAT, IL or NR. The quantity L_{ik} is the SPL value of the i^{th} noise in the k^{th} frequency band. The PAR defined here is very similar to the A-weighted noise level reduction defined in the ANSI S12.68 standard, averaged across the noises from the database.

Examples of PAR results are shown in figure 2. Comparisons of PAR calculated with IL* and REAT are presented. The upper graph shows PAR calculated with IL* for both ears separately (left and right) and the lower graph shows PAR calculated with equivalent binaural estimates for IL*. Consequently, the upper graph contains twice more data points than the lower graph.

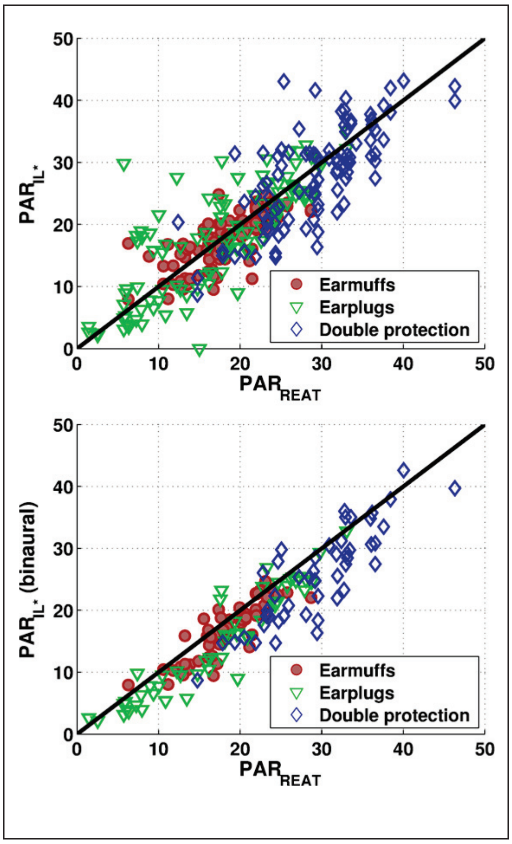

Figure 2: PAR values computed with IL* compared to PAR computed with REAT for earmuffs, earplugs and double protection. PAR values calculated for left and right ear separately (upper) and PAR values calculated with equivalent binaural estimates (lower) are shown.

The PAR results show a good agreement between REAT- and IL*-based values even when analysed from a broader view. Similar results were also obtained using NR* (corrected with $TF_{c\text{-}ext}$) to calculate the PAR (see equation (2)). However, one generally observes higher PAR values with REAT than with IL*/NR*. Some of these differences are expected to come from the physiological noise PN. Approximate PN correction terms found in the literature were applied to the results to improve the correlation (not shown here) but caution should be taken when doing so since they depend on the device under test and on the occluded-ear canal volume. Another portion of the differences observed between REAT and MIRE-based ratings may also come from the bone conduction (BC) limit. This is particularly important for dual protection where attenuation values in the order of the BC limit defined by Berger and Kerivan[12] were observed in our results.

The wide extent of attenuation obtained in the present study is clearly put into evidence as PAR values ranging from 0 to 45 dB are obtained. The results also show that using an equivalent binaural transformation is beneficial when comparing physical monaural estimates to binaural values. On the other hand, the monaural physical results show left/right differences for many subjects, especially for conditions involving earplugs where fitting issues are more frequent. It is one of the benefits of using the IL or NR-based method as it provides a tool that can be used not only to easily measure the performance of a HPD for both ears individually and simultaneously in laboratory or field conditions but also that can serve for training and motivation for workers as discussed by Berger et al[13].

As a final example, figure 3 shows the repercussion of using average $TF_{c\text{-}ext}$ values (our surrogate for TFOE) instead of individual values on PAR values.

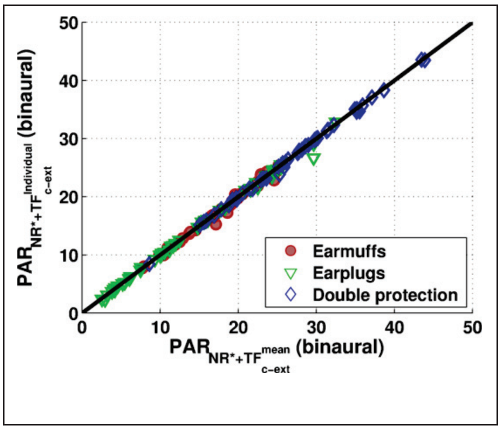

Figure 3: PAR results computed with NR* corrected with individual TFc-ext (ordinate) vs mean TFc-ext values (abscissa).

With the exception of few cases, one clearly sees little differences in PAR values when using ensemble-average values compared to the use of individual functions and that, for the wide range of attenuation and independently of the type of protection. These results are not surprising since the rating values are mostly dominated by the lower attenuation values found below 1000 Hz, a frequency range where individual values do not differ significantly from the mean values. It thus eliminates the need for individual measurements of this function, a feature that is of particular interest if one needs to use NR-based procedures in workplace environments where complex measurement logistic is generally problematic and limited.

4 Conclusion

This paper presented a unique systematic procedure which allows comparing subjective REAT to the objective IL and NR-based testing procedures. It permitted analysing various factors relating both approaches precisely at the individual level for single and dual protection conditions. While specific details of the procedures and most extracted results are presented in a separate paper recently submitted, some examples of results were presented in the present paper. The main outcomes of this study were: (i) the MIRE-based technique is a viable option for measuring attenuation in laboratory or field environments. Effect of microphone positioning under and outside the protector could be assessed using the proposed procedure; (ii) NR-based values can be corrected by an average canal transfer function, a surrogate for individual TFOE values, without losing too much accuracy; (iii) equivalent binaural estimates can be obtained from monaural objective attenuation values in order to improve comparisons with binaural REAT values.

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