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## Suitability of Commercially Available Systems for Individual Fit Tests of Hearing Protectors

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### ABSTRACT

Hearing protector attenuation is measured according to the REAT method given by ISO 4869-1. This method relies on optimum fitting under laboratory conditions and group statistics to predict an individual wearer's hearing protector performance. The consequence is that there has been an emergence of commercially available systems that offer the capability of individual fit testing of hearing protectors in the field to control how much attenuation each individual user will actually experience. The purpose of this paper is to appraise these methods. Four commercially available systems were used under laboratory conditions to assess the performance of two ear-muffs, 4 pre-formed or foam ear-plugs and 2 custom molded ear-plugs for at least 20 test subjects. Results were compared to REAT attenuations (obtained for the same group of subjects) and also to attenuations obtained from MIRE (ISO 11904-1). Three of the four systems provided mean attenuations close to the benchmark values. For these three systems, individual comparisons are acceptable in terms of personal attenuation rating, although discrepancies with REAT individual can be improved. Thus, these systems can be used to validate the hearing protection choice as long as a 10 dB safety margin is considered.

### 1. INTRODUCTION

HPD (Hearing Protection Devices) rated attenuation is measured according to the REAT method given by ISO 4869-1 [1]. This method assumes optimal fitting and calculates the HPD performance, called APV (Assumed Protection Value), statistically from a group of 16 subjects in laboratory conditions. Although the APV is the attenuation being reached or exceeded by 84% of the laboratory subjects (i.e. the average value calculated over a set of 16 subjects minus one standard deviation), the attenuation effectively provided by a HPD under conditions of actual use is generally lower than the APV. Numerous scientific studies demonstrate this point and a review of 22 of these studies can be found in [2]. Discrepancies between rated and field attenuation vary from one study to another and depend on HPD type, but are roughly estimated between 5 and 25 dB. Consequently some HPD manufacturers have recently introduced so-called fit-check systems allowing individual assessment of hearing protector attenuation in the field. Normally the aim of a fit check system is controlling the efficiency of a HPD for a user but some manufacturer products go as far as providing an assessment of the actual attenuation for a user. This paper is a result of a series of laboratory testing of these fit-check systems. As there is no standard or even recommendation for fit-check method validation, an original test protocol is followed. As a first step, a benchmark measurement of the attenuation is obtained by using the REAT method. To strengthen this benchmark, a complementary test is performed according to MIRE method described in ISO 11204-1 [3] to measure the insertion loss. To evaluate the benchmark validity, we consider the discrepancy between the two quantities. Then, we compare the data obtained with a fit-check system for the same group of subjects and for the same HPD to the

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previous benchmark measurements in order to assess the validity of the fit-check method. Comparisons are performed for average values calculated over the group of test subjects. Lastly, if the fit-check method validation proves to be successful, additional comparisons are then performed on each subject to evaluate the accuracy of the fit-check method for individual measurements.

## 2. Tested devices

We tested Four devices currently available on the market. Two of them, EARFIT and SVANTEK SV102, were developed from the MIRE technique. The third device, VERIPRO, uses loudness balance technique and the last one, CAPA, is derived from classical pure-tone audiometry.

The MIRE “Microphone In Real Ear” technique consists of placing a microphone in the ear canal to measure the sound pressure level at the eardrum. The sound attenuation of an ear plug can be determined from the difference of the sound levels in the ear canal with and without plug (insertion loss). Alternatively, sound pressure levels in the ear canal under the HPD, as well as those outside the HPD, can be simultaneously measured (dual microphone method). In this last case, the equivalent sound pressure level in the open ear canal can be obtained from the outside sound pressure level. The sound attenuation of the hearing protector is the difference between the two sound pressures in the open and in the occluded ear canal. The correction is accounted for by the so-called head-related transfer function (HRTF). A number HRTF are proposed in the ISO 11904-1, depending on both the measurement point location in the ear canal and on the sound field type. The main drawback of MIRE is that it cannot capture incoming sound transmitted through vibration of the eardrum or by direct excitation of the cochlea via sound that stimulates the bone (and tissue) conducting pathways. Thus, the insertion loss is not directly related to the plug attenuation and a correction of the occlusion effect as well as of the physiological noise must be applied to the insertion loss [4] in order to compare the two data. Alternatively, the dual microphone method can be calibrated with REAT data from an equivalent group of test subjects for the same products. The correction function can then be calculated by matching the data from the two measurement techniques. In that case, this correction function is similar to the HRTF but also includes bone transfer pathway corrections.

With the EARFIT system, the excitation is generated by a loudspeaker in a quiet room. The sound pressure level in the ear canal under the HPD, as well as that outside the HPD, are simultaneously measured. The system uses surrogate plugs crossed by an axial tube that linked a microphone to the ear canal for the measurement of the inside pressure level. A second microphone measures the outside pressure level. The transfer function has been obtained as explained in the previous§ by calibration with REAT tests for a group of 20 subjects. The advantage of this system is that an actual measurement takes about 10 seconds for any one fit in one ear to obtain data at the standard 7 test frequencies from 125 Hz to 8 kHz, as well as an overall noise reduction rating called the Personal Attenuation Rating (PAR) that can be compared to the SNR of the HPD. The main drawback of this method is the accuracy of the transfer function, as it has to account for the effects of the tube, the ear canal, the head, the sound field and the bone conduction path. Secondly, it is only be limited to earplugs provided by the manufacturer (3M), since correction factors are established and are only valid for a particular earplug. Lastly, tests are done with a surrogate plug (with a tube inserted) that fit differently compare to common ones.

The SVANTEK SV102 is designed for field measurement underneath an earmuff. It is a two-channel device with a probe connected to the first channel and a microphone connected to the second channel. The probe has to be placed at the entrance of the ear canal so that the ear canal entrance sound pressure can be measured and the microphone has to be located on the subject’s shoulder for the outside sound pressure measurement. The probe length is chosen according to the size of the subject ear canal. Three lengths are available – 16, 20 and 25 mm. The effect of the probe tube on the inside pressure measurement is corrected. The HRTF used to correct the external pressure is the mean open ear theoretical transfer function given in [3] (open entrance transfer function). So this SV102 system only provides the insertion loss of the HPD at the standard 7 test frequencies from 125 Hz to 8 kHz. It is therefore not directly comparable to REAT.

Loudness balance is a subjective method which consists in asking the subject to establish the balance in the loudness of pure-tones presented alternately at each ear. Balance is measured first with unoccluded ears, then with only the right ear occluded and lastly with both ears occluded. The HPD attenuation is deduced from the sound intensity difference. The sound is presented through circumaural headphones. It takes about 15 minutes to obtained attenuation data at test frequencies from 250 Hz to 4 kHz, as well as the PAR. This method needs a quiet environment since loudness

matching is a rather challenging task. It can be used for all types of earplugs that can be worn under a headphone.

The last method tested, CAPA, is derived from audiometry. Earplug attenuation can effectively be evaluated through an audiogram with and without the plug. This is similar to REAT testing. This method determines the hearing threshold of the test subjects with and without hearing protectors and then calculates the difference. The main drawback of such method is that determining the hearing threshold takes time. In addition, it has to be repeated for each ear. So, rather than determining the hearing threshold by oscillation, CAPA only works with rising sounds. At each frequency, the sound is presented three times with a decrease of the sound slope and an increase of the starting level. Each step increases the accuracy of the determination of sound detection threshold. The resulting threshold is higher than the hearing threshold but this method speeds the test up. The sound is presented through a headphone. Test sounds are pure tones. The threshold is measured first with unoccluded ears, then with both ears occluded. The HPD attenuation is deduced from the threshold difference. Actual measurement takes about 7 minutes to obtain attenuation data at the standard 7 test frequencies from 125 Hz to 8 kHz for both ears, as well as the PAR. A quiet environment is needed for such test since it works just above the hearing threshold. The method can be used for all types of plugs that can be worn under headphones.

### **3. Test Protocol**

For each system, two to four HPD were used. The SV102 was tested on two earmuffs. The EARFIT and the VERIPRO were tested on four pre-molded or foam earplugs. CAPA was tested on two custom molded earplugs, one pre-molded earplug and one foam earplug. All test subjects were trained to use HPD and the fitting of the earplug was systematically checked by the investigator.

A benchmark was initially established for each HPD. All the manufacturers use REAT [1] to assess the attenuation of their HPD. This has been considered as the best method for years – i.e. the “gold” method [5]. This is also the harmonized method for HPD European certification. Therefore, we considered this method as the benchmark for the study. Results obtained by using REAT have been confirmed by MIRE measurements. MIRE was applied according to ISO 11904-1 [3]. Tests were performed in a large reverberant chamber (205 m<sup>3</sup>) to obtain an acoustic diffuse field. The HRTF was measured individually for each ear and subject according to ISO 11904-2 §10.2. For each HPD, MIRE and REAT tests were done for the same group of subjects.

After completion of the benchmark test, each fit-check system was also tested for the same group of test subjects. At least one measurement was done with VERIPRO and at least three measurements were done for the three other systems for each subject and each HPD. The reason is that VERIPRO takes more time and requires more concentration than the other fit check systems and it was therefore not possible to undertake more tests in the study.

Comparisons were initially performed for the calculated mean attenuation in octave band for the group of subjects. Then, and only if mean values correlated closely, individual results were compared. When existing, the PAR given by the fit-check system was compared to an “individual SNR”. This “individual SNR” was calculated by using the subject individual octave band attenuations obtained with REAT as inputs and neglecting the standard deviation (i.e. null standard deviation). For the SV102 system, individual insertion loss values obtained by MIRE and by SV102 were averaged over octave bands and compared.

## **4. Results**

### **4.1 Benchmark measurements**

Mean attenuation correlations between REAT and MIRE were very good in the 500 Hz – 4 kHz bandwidth for all HPD except 3M Classic earplug (see figures 1 and 2 – two figures for clarity). Below 500 Hz, MIRE gives lower results. This result was expected. Two main reasons explain discrepancies between MIRE and REAT at low frequencies. Firstly, HPD attenuation is underestimated by MIRE because HPD effects on bone conduction paths are not measured. Secondly, HPD attenuation is overestimated by the subjects during REAT tests because of physiological noise masking [5]. At 8 kHz, MIRE measurements are also invalid because the signal-to-noise ratio of the probe inside the ear canal is too low. References obtained with REAT can therefore be considered as reliable and precise although the attenuation is probably overestimated at 125 Hz and 250 Hz.

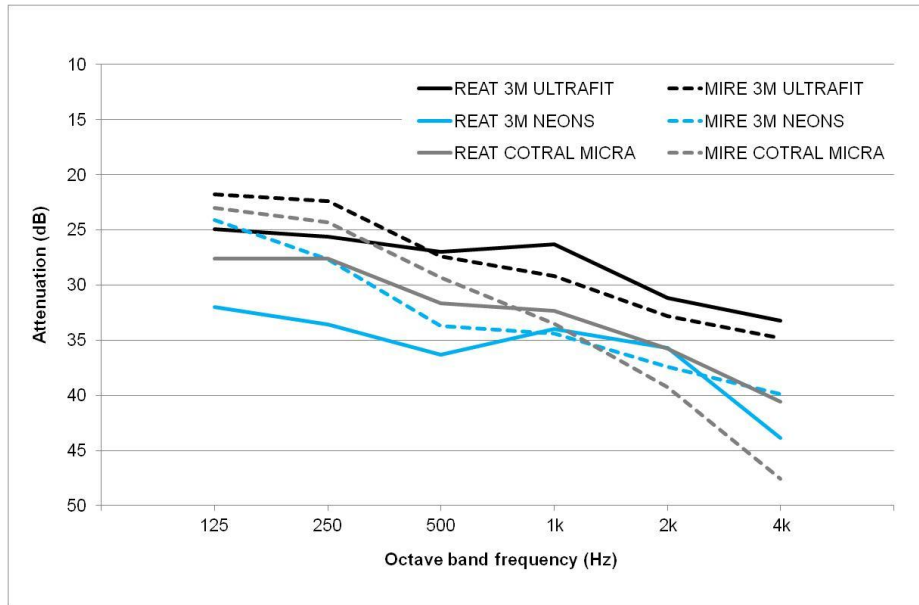


Figure 1: benchmark results and comparison with MIRE

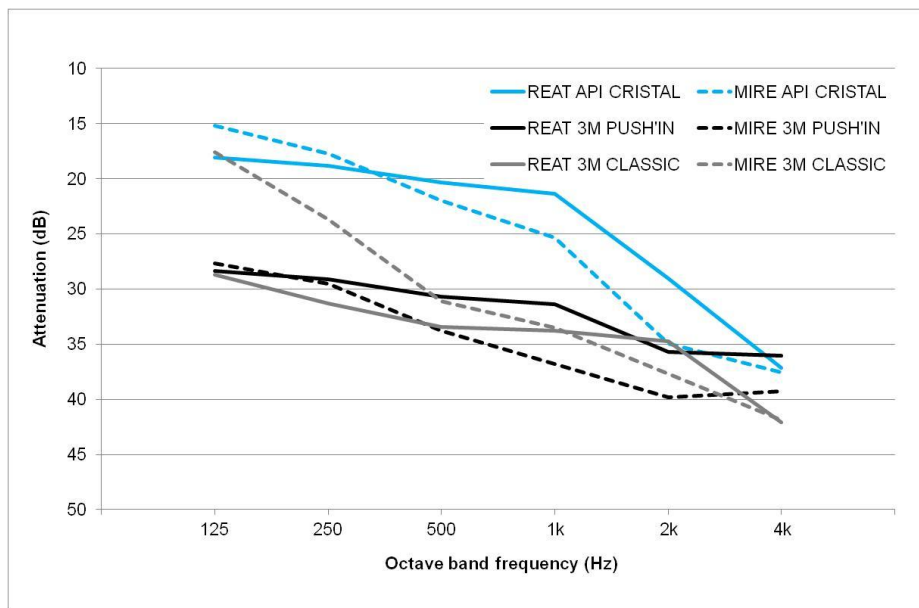


Figure 2: benchmark results and comparison with MIRE

## 4.2 Svantek SV102

This fit-check system only gives the insertion loss, so comparisons were performed using the MIRE results. Mean attenuations correlated perfectly up to 2 kHz. Above, discrepancies increased with frequency and reached 5 dB at 8 kHz (Figure 3). These discrepancies are due to the position of the probe tip and also arise from the HRTF applied by the SV102. The probe internal tip should be positioned exactly at the ear canal entrance. This was not always easy to do. In addition, the probe is supported by an over-ear hook, which also did not always fit well with the helix. According to the ISO 11904-1, an improper location of the probe may result in a large error (up to 12 dB at 4 kHz for a 3mm variation). The differences observed are far less lower.

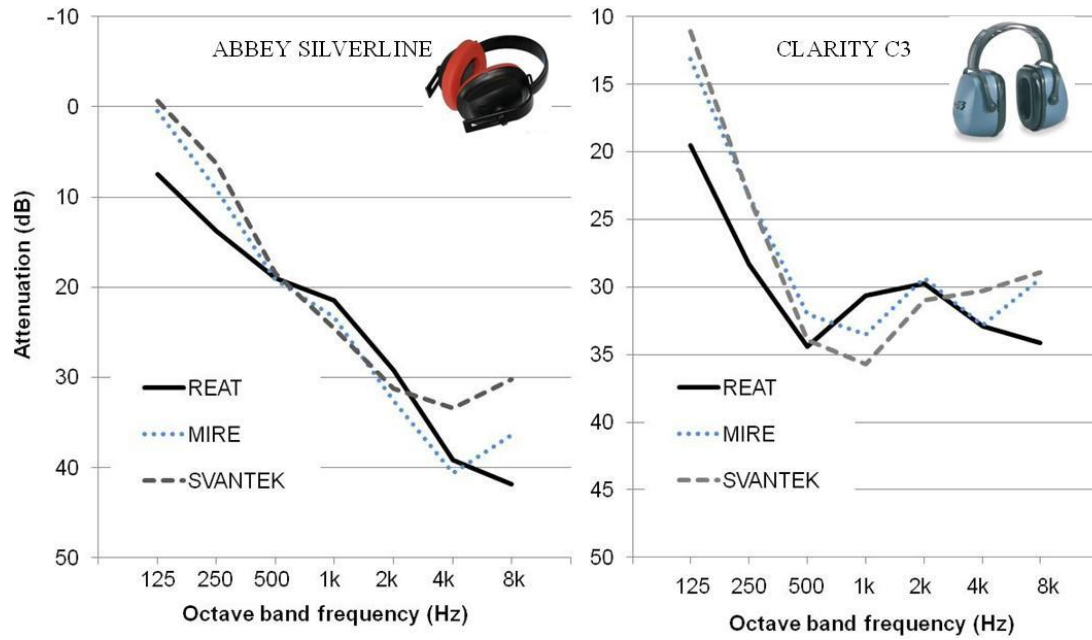


Figure 3: Svantek SV102 compared to benchmark

Individual comparisons show the same trends (Figure 4). Differences with MIRE measurements are largely constant. Points are more or less collinear and the scatter of points is centered on the middle line and a minor underestimation of the attenuation.

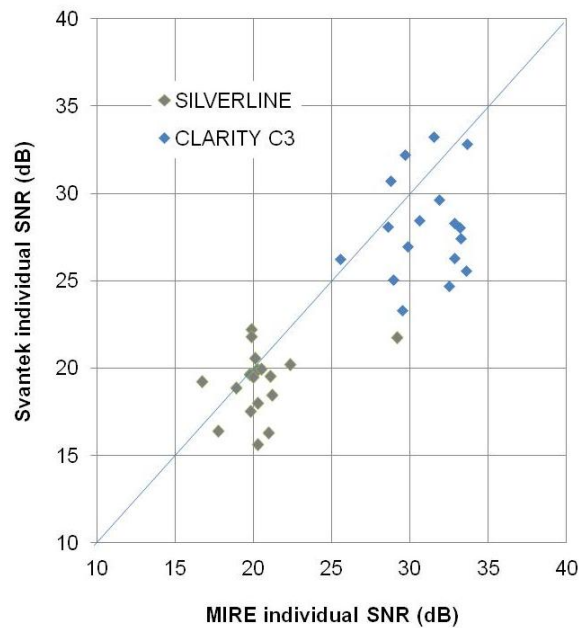


Figure 4: Svantek individual comparisons

So this system ensured reliable individual measurements, provided the probe support was fixed with adhesive tape. At high frequencies (At 4 and 8kHz), the measurement itself was reliable but discrepancies increase because of correction factors, particularly with respect to the probe positioning.

### 4.3 3M EARFIT

The EARFIT fit-check system gives an estimate of the octave band attenuation level and of the PAR. The mean octave band attenuation was thus compared to that obtained with REAT for 4 earplugs: 3M UltraFit, 3M Push-in's, 3M Neons and 3M Classic. The two sets of data are correlated closely for the

3 first earplugs (Figure 5). For the 3M Classic plug, the correlation was acceptable but EARFIT overestimated the attenuation below 2 kHz by approximately 4 dB. In the system's current version, the compensation factors have been adjusted by -2 dB on the 3M Classic, thereby reducing this difference to 2 dB.

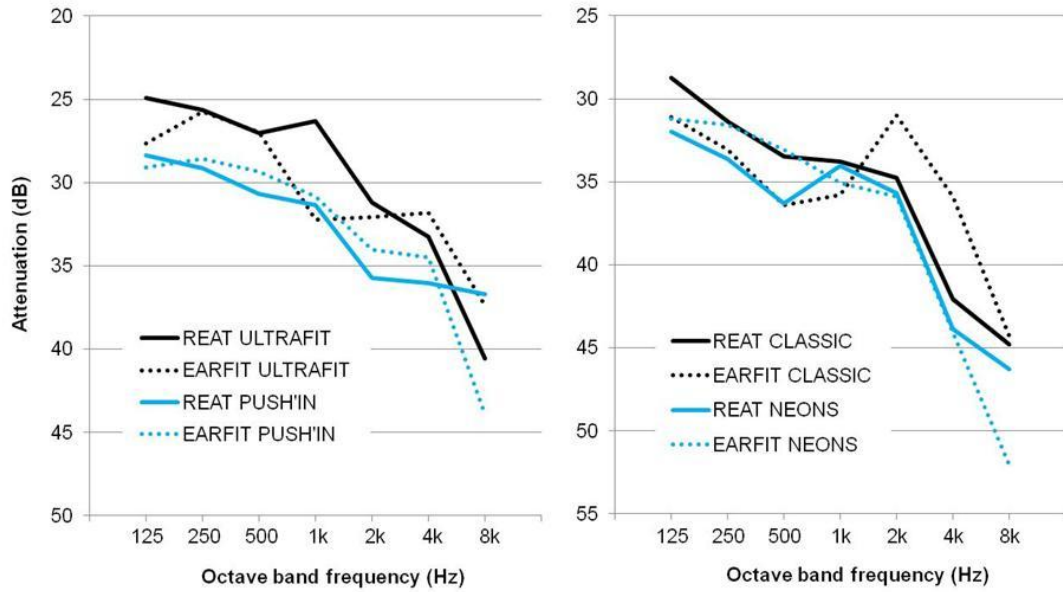


Figure 5: 3M EARFIT compared to benchmark

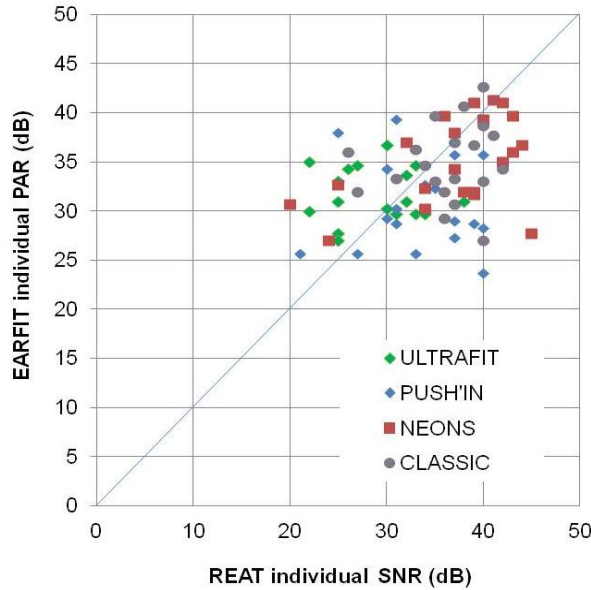


Figure 6: 3M EARFIT individual comparisons

Our results demonstrate that this system provides a correct estimate of earplug attenuation, although the tested earplugs were not the same (surrogate plugs were used for EARFIT measurements and common commercial plugs were used for REAT measurements). In particular, the compensation factors were valid. These results reach those reported by J.VOIX et al. [6], when the method was validated. Individual comparisons were performed by comparing the PAR and the pseudo SNR (so-called "individual SNR"). The results were less effective than what could be expected with regard to previous comparisons (Figure 6). Although the scatter of points is centered on the middle line, they are not collinear and the PAR can sometimes overestimate the SNR by up to 10 dB. The EARFIT system reports an uncertainty of 7 dB. This uncertainty is verified for the majority of the comparisons

except few points – i.e. except for few subjects. To conclude, average values predicted for the group with EARFIT are close to REAT values. Subject-related comparisons exhibited larger differences. However, with the exception of a few individuals, these differences are acceptable regarding the uncertainty reported by EARFIT, the fact that refitting was performed between measurements and the variability inherent to the REAT benchmark method.

#### 4.4 Howard Leight VERIPRO

The VERIPRO fit-check system provides an estimate of the octave band attenuation level from 250 Hz to 4 kHz and of the PAR. The mean octave band attenuation was compared to that obtained with REAT for the same 4 earplugs than used with EARFIT. VERIPRO results do not compare well with REAT (Figure 7). This finding is similar to that of E. KOTARBINSKA in a previous study [7] comparing rated SNR and PAR provided by VERIPRO for 16 subjects and 10 different earplugs. The VERIPRO-based data underestimates attenuation and differences vary with the earplug used.

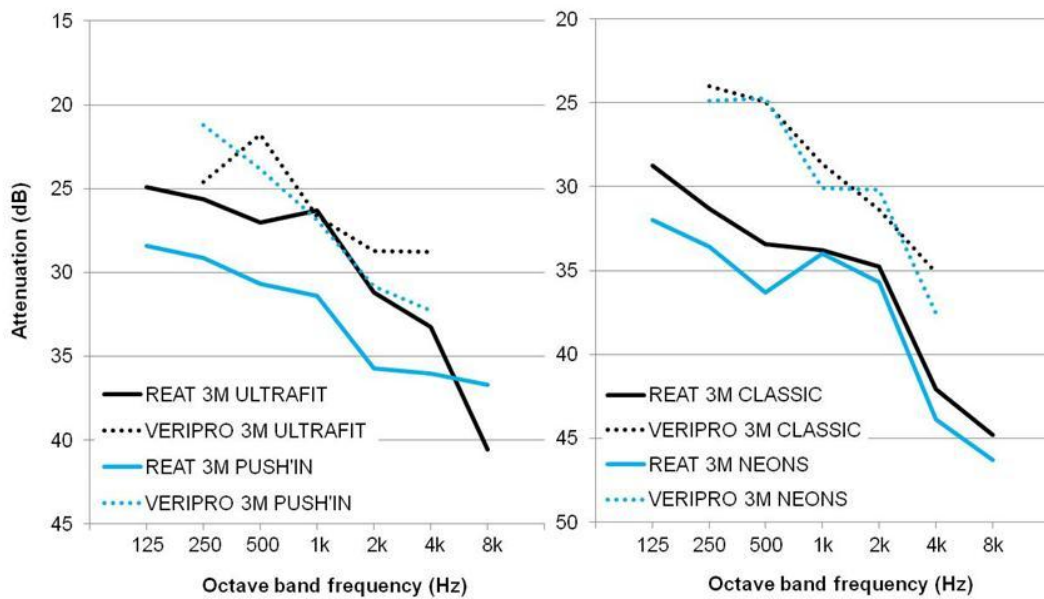


Figure 7: Howard Leight VeriPro compared to benchmark

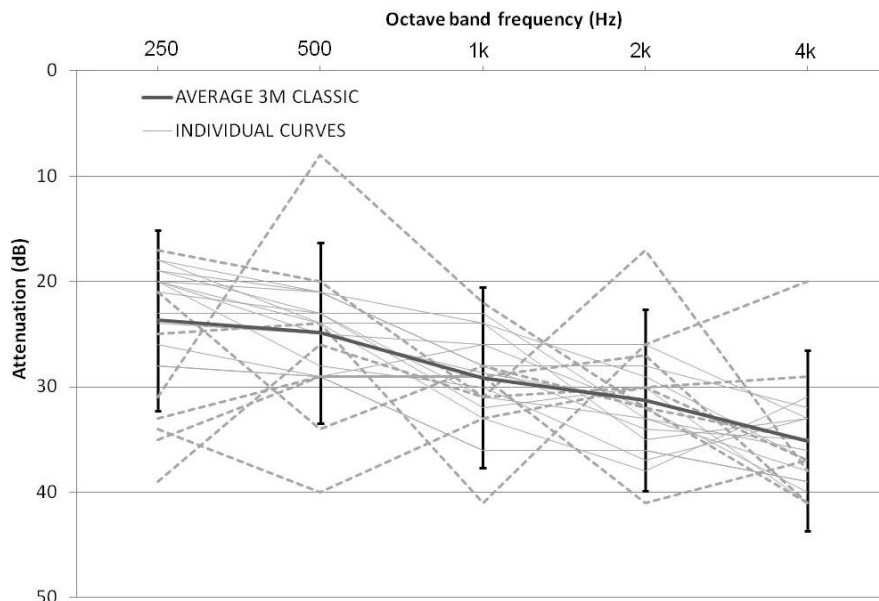


Figure 8: Howard Leight VeriPro individual results compared to mean value

Another problem was the distribution of the octave band results as illustrated by Figure 8:

approximately half the individual results exhibit irregular shapes (heavy dotted lines) with large variations between consecutive octave band frequencies. This is particularly true for two earplugs: 3M UltraFit and 3M Neons. We conclude that the VERIPRO system does not allow recovery of the REAT benchmarks. No individual comparisons were performed, mainly because of the many erratic octave band shapes of attenuation individual curves but also because of major discrepancies between REAT and VERIPRO, calling into question the system validity.

#### 4.5 COTRAL CAPA

Results obtained with CAPA also reflect octave band level attenuation for the 7 standard frequencies and the PAR. These data were compared to REAT measurements for one pre-molded ear plug (3M UltraFit), one foam plug (3M Neons) and two custom molded plugs (COTRAL Micra and API Classic). These two custom molded earplugs were not fitted with filters. The filter housing tube was used to pass an Etymotic probe through the plugs for MIRE measurements and was then blocked. Comparisons of mean attenuation values obtained with CAPA are compared to REAT references on figure 9. These two data sets are closely correlated. CAPA slightly under-estimates the attenuation at low frequencies compare to REAT.

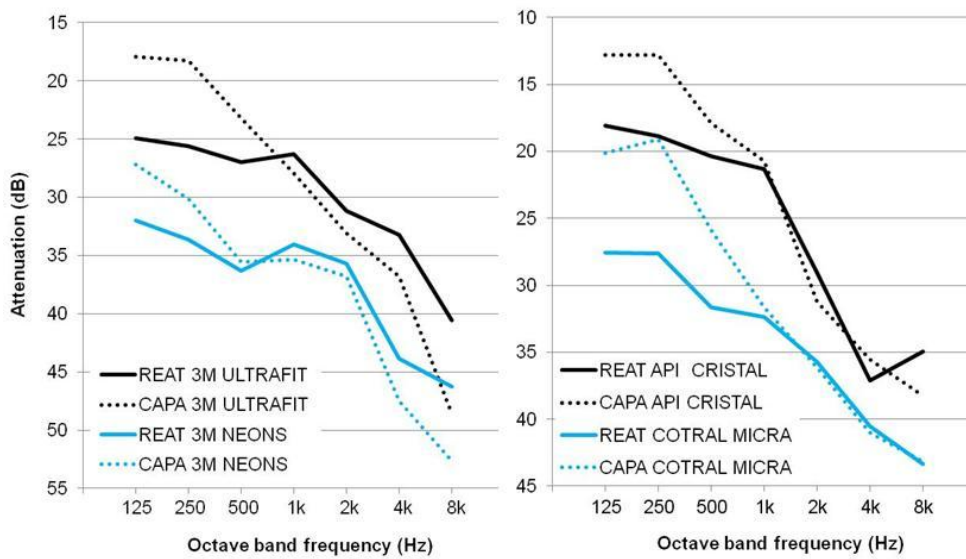


Figure 9: COTRAL CAPA compared to benchmark

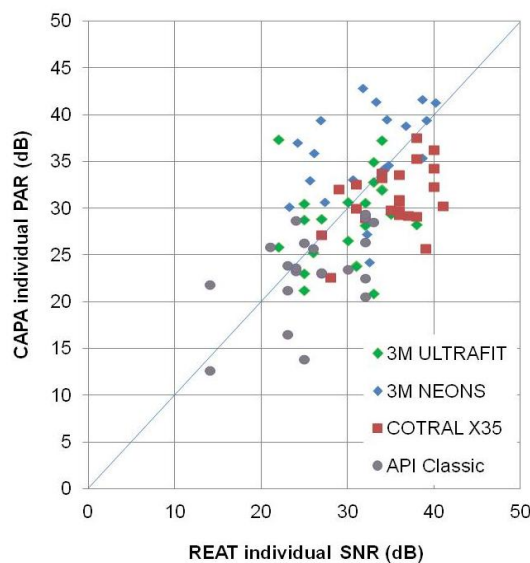


Figure 10: COTRAL CAPA individual comparisons

Results of individual comparisons (Figure 10) are similar to what was found with EARFIT: the



scatter of points is centered on the null line, in accordance with the close correlations of average attenuations, but the points are not collinear and the PAR can overestimate the pseudo SNR by up to 10 dB. Curiously, CAPA reported the same uncertainty as EARFIT (7 dB). This uncertainty is verified for the majority of the comparisons, except for six test subjects.

The same conclusions apply: average values predicted for the group with CAPA are in accordance with REAT. Comparisons per subject exhibit larger but acceptable differences with regard to the system reported uncertainty, the refit between measurements and REAT benchmark method inherent variability.

## 5. Conclusion

The aim of this research was to test four so-called fit-check methods for individual in-situ measurement of hearing protector attenuations. One of these methods is dedicated to earmuffs, the other three to earplugs. The measurement protocol involved establishing a benchmark on a set of two to four HPD, validating each fit-check system by comparison with benchmark and evaluating system accuracy by individual comparisons.

The benchmark was established on a group of at least 20 subjects based on the harmonized Standard ISO 4869-1 (REAT method), which is mandatory for attenuation labeling of the hearing protector. Benchmark results were confirmed using a second standard ISO 11904-1 (MIRE method) dedicated to measuring the exposure underneath the hearing protector. A strong benchmark was therefore established.

Two of the four systems of measuring individual in-situ attenuations of hearing protectors, EARFIT and CAPA, provide mean attenuations close to benchmark values. For these two systems, individual comparisons are acceptable in terms of SNR values, although deviations from these benchmark values may be fairly important. But these deviations can be explained by the refit of the HPD between tests, the variability of the benchmark method and the variability of the fit-check method. Thus the two systems can actually be used to validate hearing protection choice as long as a safety margin is considered (approximately 10 dB). The EARFIT system has the advantage of being very quick. It can therefore also be used to train users – this is of crucial importance in hearing conservation programs. It is passive and does not require effort from the subject. On the other hand, correction factors are applied to the measurements by the system. These factors are obtained experimentally on a group of 20 subjects and can be questioned. In addition, they increase uncertainty and are only valid for a given earplug. EARFIT system also requires the use of specific earplugs for testing. Thus, it is limited to the 3M manufacturer products. CAPA system can be used for any earplug. No corrections are applied nor necessary. On the other hand, it is slower than EARFIT and its accuracy is roughly the same because the method is subjective and requires concentration.

Earmuff-dedicated SV102 allows the MIRE method to be applied in situ. The hardware is promising, well designed and provides accurate measurements; but the probe hook support could be improved. The current probe is rather difficult to install and a bit rigid. However, this system is suitable for on-site measurement of exposure underneath an earmuff and for checking earmuff efficiency.

Lastly, the VERIPRO system failed to make the benchmark values. In addition, for a relatively large number of subjects, attenuation per octave band curves exhibit abnormal discrepancies between adjacent octave bands and inverted slopes (attenuation decrease with frequency increase). However, this method is widely used and has been validated in a previous study [8]. Discussions are underway with the manufacturer to try to understand the obtained results.

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