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Assessing Differences in Methodologies for Effective Noise Exposure Calculation

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The aim of the present study was to analyse the adequacy of hearing protection devices (HPDs) by applying and comparing different methods for the estimation of effective exposure levels. This comparison involved the attenuation data of 50 HPDs (ear muffs and ear plugs), as well as 11 types of noise spectra and 4 methods. The application of the several methods considered and the comparison of the obtained estimations seem to demonstrate that there are significant differences between effective exposure levels estimated with the different methods analysed.

hearing protection devices   attenuation   methods

1. INTRODUCTION

Hearing protection devices (HPDs), as cited frequently in literature, are widely used in noisy workplaces, most likely due to the complexity and costs associated with the implementation of technical and organisational noise reduction measures [1]. When HPDs are adopted, the selection process is quite often based exclusively on the attenuation characteristics of the devices [2]. These characteristics are reported by manufacturers as part of the process of homologation and certification of personal protective equipment, with corresponding CE (Conformité Européenne) marking [3].

Attenuation data reported by manufacturers are typically highly optimistic when compared to the field, or terrain, attenuation characteristics obtained with the devices. These differences arise on account of varying contexts, such as those attenuation values having been obtained in controlled laboratory tests carried out by well-trained users, and thus not reflecting, at least entirely, the field performance of those devices. Moreover, there are several additional aspects to be considered in the estimation of protection obtained by users while wearing HPDs. These include obtaining valid estimates of the attenuation of HPDs as influenced by user training and motivation, as well as the proportion of exposure time during which users actually wear the devices, the individual variability in fitting the devices, and accurate measurements of specific noise exposure [1].

As a result of these discrepancies, HPD users are advised to use manufacturers' attenuation data with caution [4]. Therefore, whether these values can be used to obtain more realistic attenuation values has been a source of constant debate [5]. As a consequence, several attenuation labels, or rates, have been developed and proposed, as well as corresponding methods of estimating the effective sound pressure level (SPL) for HPD users.

In Europe, as a consequence of the application of a specific standard regarding attenuation methods for HPDs [6, 7], these have been commercialised with a compulsory cataloguing with three types of attenuation indexes: (a) *M* and *SD* of each octave-band (OB) frequency attenuation value, or alternatively the assumed protection value by OB, (b) HML (high, medium,

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low), and (c) single number rating (SNR) values. Therefore, the verification of the adequacy of HPDs for a specific noise environment relies on the calculation of the effective attenuation afforded by the devices and, consequently, on the estimation of the effective daily exposure levels based on laboratory data.

In Portugal, occupational exposure is regulated with legislation transposed from the relevant European directive [8]. According to this legislation, workers' effective daily exposure levels should not exceed the threshold limit value for an exposure period of 8 h per day, that limit being 87 dB(*A*) [9]. Ideally, this value should be lower than the lowest action value, i.e., 80 dB(*A*).

For computation of effective levels, Portuguese legislation refers to the use of three possible methods: octave band (OBM), HML, and SNR. For the application of the so-called long method, i.e., OBM, legislation considers the use of a 2 *SD* correction, which implies that the level obtained is equal or lower than the predicted level in nearly 98% of situations.

Rating methods and rating labels have been extensively discussed in recent years. The selection of the best rating and effective estimation methods is a complex task, which should include an analysis of the simplicity, consistency, and accuracy of each rating [5]. Murphy, Franks and Shaw [10] and Gauger and Berger [5] focused on accuracy analysis. However, the present study focuses on an analysis of the consistency between different methods using a specific sample of HPDs and noise sources.

The aim of this paper was to compare different methods for effective estimation of exposure levels. This comparison involved 30 conventional ear muffs and 20 ear plugs, as well as different noise environments.

2. METHODOLOGY

2.1. HPDs Sample and Noise Spectra

Attenuation data provided by HPD manufacturers and various methods were used to estimate attenuation of 50 passive HPDs, 20 ear plugs and 30 ear muffs. The HPDs were selected according to their typical spectra attenuation and their usage rate in Portuguese industrial settings. The selection included some devices that had been identified as the most frequently used in Portuguese industry [11]; other ones were commercially available at the time of the study.

Table 1 shows general statistics about manufacturers' attenuation characteristics of the selected devices with respect to the simplest rating methods, the HML and SNR. According to this table, the selected ear muffs and ear plugs had similar attenuation values. Some typical differences were observed, such as the higher mean value of *L* in ear plugs [1].

TABLE 1. Hearing Protection Devices Sample Characterisation According to Manufacturers' Attenuation Data

Index		Ear Plugs ($N = 20$)	Ear Muffs ($N = 30$)
High	*M*	34.4	32.5
	range	24.0–36.0	24.0–37.0
Medium	*M*	25.8	26.2
	range	19.0–35.0	20.0–34.0
Low	*M*	24.0	21.5
	range	15.0–32.0	13.0–29.0
SNR	*M*	29.1	29.4
	range	22.0–37.0	23.0–36.0

Notes. SNR—single number rating.

An analysis of the differences between methods of estimating effective attenuation levels recommended in European and in international standards was one of the goals of this study. As the noise source type might play a role in the final results, this analysis was carried out considering the use of HPDs in three types of noise sources. Eleven noise sources typical for industrial workplaces were considered in estimating effective exposure levels. Those noise sources were classified according to their main spectral characteristics, using $L_C - L_A$ as an indicator. Accordingly, noise sources were classified as low-, medium-, and high-frequency [12] (Table 2).

TABLE 2. Noise Spectra, in dB(*A*), From the Noise Sources Considered

	Octave Band (Hz)									
Noise Source Type	63	125	250	500	1 000	2 000	4 000	8 000	L_{eq}	$L_C - L_A$
Low-frequency	79.2	88.4	91.5	95.9	95.4	90.6	82.1	79.6	100.4	8.6
	77.6	87.9	93.3	93.8	94.2	91.4	87.9	79.9	100.0	8.4
	75.6	84.1	90.0	93.6	96.2	91.3	87.9	81.9	99.9	6.1
	70.7	81.9	89.2	93.3	95.6	93.0	90.1	83.0	100.0	4.3
	65.4	77.3	86.4	92.5	96.4	93.0	90.4	83.7	100.0	2.3
Medium-frequency	65.4	77.1	84.4	89.8	95.5	94.3	92.5	88.8	100.0	1.6
	64.6	70.9	77.9	93.9	98.7	85.8	84.3	82.3	100.3	1.5
	59.8	71.0	80.7	88.0	95.0	94.4	94.1	89.0	100.0	0.1
High-frequency	59.5	68.8	78.2	84.3	92.8	96.6	94.0	90.0	100.1	–0.5
	51.4	62.5	70.7	81.0	90.4	96.2	94.7	92.3	100.0	–1.2
	48.0	57.7	66.6	75.4	89.5	94.1	97.8	97.3	101.7	–1.6

Notes. L_{eq}—equivalent continuous noise level, $L_C - L_A$—difference between *C*- and *A*-weighted noise levels.

2.2. Methods of Effective Level Estimation

All the methods in this study were used to estimate the effective level of *A*-weighted sound pressure when a hearing protector was worn in the 11 aforementioned noise environments. Consequently, the estimation of the effective level results was an individual value for each HPD/noise spectrum/method combination. For comparison purposes, the estimated attenuation was obtained by finding the difference between the exposure levels and the estimated effective exposure levels.

The methods for estimating the effective level were selected according to the recommendations made in Portuguese legislation [9]. The methods considered were OBM, using a 2 *SD* correction, as defined by current Portuguese legislation, OBM with a safety margin of 2 dB (OBsm), as established by former Portuguese legislation, HML, and SNR.

The first two methods involve the use of the frequency spectrum data of the noise source, as well as the attenuation characteristics (*M* and *SD*) of the device. These methods are typically called long methods. The two latter methods are called short because their computation is based on simplified data, i.e., the difference between the *A*- and *C*-weighted SPLs. Even amongst the long and short methods there are some differences in simplicity. The classification of simplicity, or complexity, of the tested methods was based on the computation and noise exposure data requirements. Accordingly, the simplest tested method was the SNR, followed by the HML, and, with equal data and computation requirements, the OBM and OBsm.

According to Portuguese legislation, the effective daily exposure level is calculated according to Equation 1, where t_e represents exposure duration and t_0 the reference duration for daily exposure, in this case 8 h [9]. In the analysis that was carried out it was assumed that daily exposure (t_e) was, for simplification, 8 h. Therefore, the effective daily exposure level was the same as the effective equivalent level:

$$L_{\text{EX,8h, effective}} = L_{\text{Aeq, effective}} + 10 \times \log\left(\frac{t_e}{t_0}\right). \quad (1)$$

Both of the long methods, i.e., OBM and OBsm, consisted of a straightforward noise reduction calculation involving the workplace OB noise levels and the OB attenuation data for the hearing protector being assessed, according to Equations 2 and 3, respectively, where m_f represented the mean attenuation and s_f the corresponding *SD*:

$$L_{\text{Aeq, effective}} = 10 \times \log\left[\sum_{f=63}^{8000} 10^{0.1\times\left(L_{A,f} - m_f + 2\times s_f\right)}\right], \quad (2)$$

$$L_{\text{Aeq, effective}} = 10 \times \log\left[\sum_{f=63}^{8000} 10^{0.1\times\left(L_{A,f} - m_f + s_f + 2\right)}\right]. \quad (3)$$

The HML method specifies three attenuation values (*H*, *M* and *L*) determined from the OB attenuation data of a hearing protector. When combined with a measurement of the *A*- and *C*-weighted SPLs of noise, these values are used to calculate the predicted noise level reduction (PNR). This calculation is made according to the specific type of noise, i.e., the PNR calculation equation differs according to the difference between the *C*- and *A*-weighted SPLs, as illustrated in Equations 4 and 5, when $L_C - L_A \leq 2$ dB and $L_C - L_A > 2$ dB, respectively:

$$PNR = M - \frac{H - M}{4} \times (L_C - L_A - 2), \quad (4)$$

$$PNR = M - \frac{M - L}{8} \times (L_C - L_A - 2). \quad (5)$$

The *PNR* was then subtracted from the observed *A*-weighted SPL to calculate the *A*-weighted sound pressure effective to the ear when the hearing protection was worn:

$$L_{A\text{eq, effective}} = L_A - PNR. \quad (6)$$

The SNR method specifies a single attenuation value, the *SNR*. In the same manner as with the *PNR*, the *SNR* was subtracted from an overall sound level value, in this case the *C*-weighted SPL, to calculate the effective *A*-weighted sound pressure to the ear (Equation 7) when the hearing protector was worn:

$$L_{A\text{eq, effective}} = L_C - SNR. \quad (7)$$

3. RESULTS AND DISCUSSION

The methods were compared with the estimated attenuation afforded by all the considered devices in all the considered spectra. For this purpose, attenuation was estimated and expressed as the difference, in dB(*A*), between the noise workplace exposure level (Table 2) and the effective noise workplace level, computed using a specific device and method. For the purpose of clarity, this comparison was firstly made considering the type of HPD and then the type of noise source.

3.1. Type of HPD

The mean estimated attenuation values for all the methods were computed considering the two types of HPDs under study (Figure 1). As expected, when estimates were based on the OBM [2, 13], i.e., a 97.7 percentile, attenuation values were lower than in the other methods. On the other hand, the use of the OBsm, implied a protection percentile of 84 with an additional safety margin of 2 dB in each frequency, which increased the predicted percentage to a nondefined value.

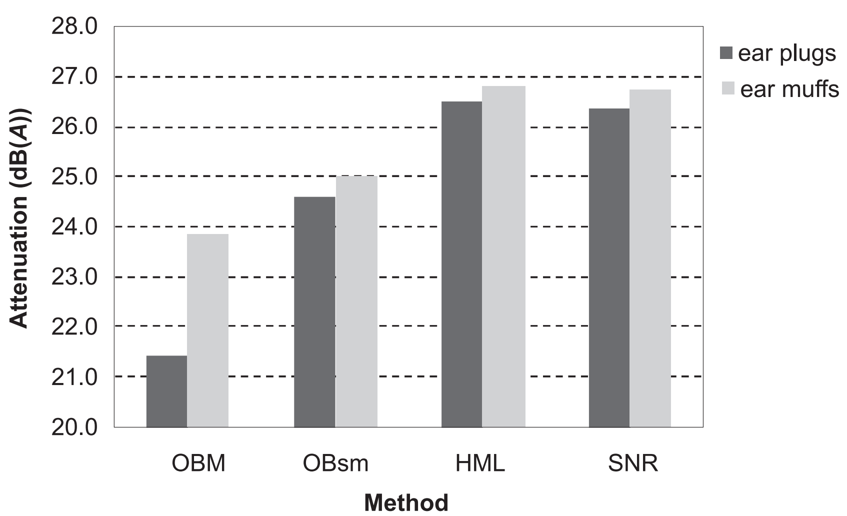

Figure 1. Mean attenuation values obtained from each method. *Notes.* OBM—octave-band method; OBsm—octave-band with a safety margin; HML—high, medium, low; SNR—single number rating.

From Figure 1 it is also possible to verify that, in all the used methods, ear muffs performed better than ear plugs. However, this difference was more evident in the OBM. This was essentially because this method relied greatly on attenuation variability, which was typically greater in ear plugs [1].

This result seemed to demonstrate that the option for OBM in recent Portuguese legislation [9] was a good choice as far as workers' protection is concerned. This method was also a better indicator of the attenuation data variability of the devices for each OB frequency.

An analysis of the OBsm verified that the difference between ear plugs and ear muffs was very small, thus not reflecting the variability associated with the type of HPD. As expected, this method did not rely in the same way as the other long method on the HPD attenuation data variability.

A common aspect across all methods was the greater attenuation of ear muffs, even if the attenuation characteristics of the ear muffs and ear plugs considered were somewhat similar (Table 1). In almost all methods the differences were not particularly high. Only in OBM was the difference higher, 2.4 dB(*A*). The greatest difference corresponded to the attenuation of ear plugs with respect to OBM and HML, 5.1 dB(*A*).

A correlation analysis was carried out to better analyse the comparison between the four methods (Table 3). As expected, because all methods were calculated on the basis of the same attenuation characteristics of the devices, all the correlation factors were statistically significant at $p < .001$.

TABLE 3. Correlation Matrix Between the Methods Under Analysis

		OBsm	HML	SNR
OBM	ear plugs	0.974	0.931	0.870
	ear muffs	0.993	0.977	0.938
OBsm	ear plugs	—	0.966	0.888
	ear muffs	—	0.984	0.943
HML	ear plugs		—	0.912
	ear muffs		—	0.944

Notes. OBM—octave-band method; OBsm—octave-band with a safety margin; HML—high, medium, low; SNR—single number rating.

A lower correlation index was found between the long methods (OBM and OBsm) and the most simplified method, SNR. This was in part expected due to the contribution of variability and it demonstrated the need to apply the simplified methods differently for the two types of devices. Indeed, some previous studies suggested a different derating factor for different types of devices. For example, the National Institute for Occupational Safety and Health suggested a subtraction of 25, 50 and 70% in noise reduction rating values for ear muffs, formable ear plugs, and other types of ear plugs, respectively [4].

3.2. Type of Noise Source

As the estimated value for the attenuation of devices depends, either totally or partially, on the type of noise source considered, results were analysed in terms of the noise source type used for attenuation estimation. Table 4 shows that the estimated attenuation was significantly lower when a low-noise source was considered. In the same way, the variability was lower in a high-noise source.

TABLE 4. Estimated Attenuation Values, in dB(*A*), for Each Noise Source Type

Noise Source Type		OBM	OBsm	HML	SNR
Low-frequency	*M*	20.5	22.6	24.6	23.3
	SD	4.4	4.3	4.4	4.3
Medium-frequency	*M*	23.5	25.3	27.5	28.2
	SD	4.2	4.0	3.7	3.6
High-frequency	*M*	26.2	28.1	29.4	30.4
	SD	3.3	3.2	3.1	3.6

Notes. OBM—octave-band method; OBsm—octave-band with a safety margin; HML—high, medium, low; SNR—single number rating.

Major differences were found in the SNR method when extreme values were considered, whereas the differences were minor in the HML. It is also important to emphasise that, in the case of SNR, the difference of the estimated attenuation for the considered noise sources was >7 dB(*A*). Figure 2 presents a more precise analysis of these results: a comparison of different types of noise sources and the values obtained for ear plugs and ear muffs.

Typically, HPDs presented minor estimated attenuation values when the low-noise sources

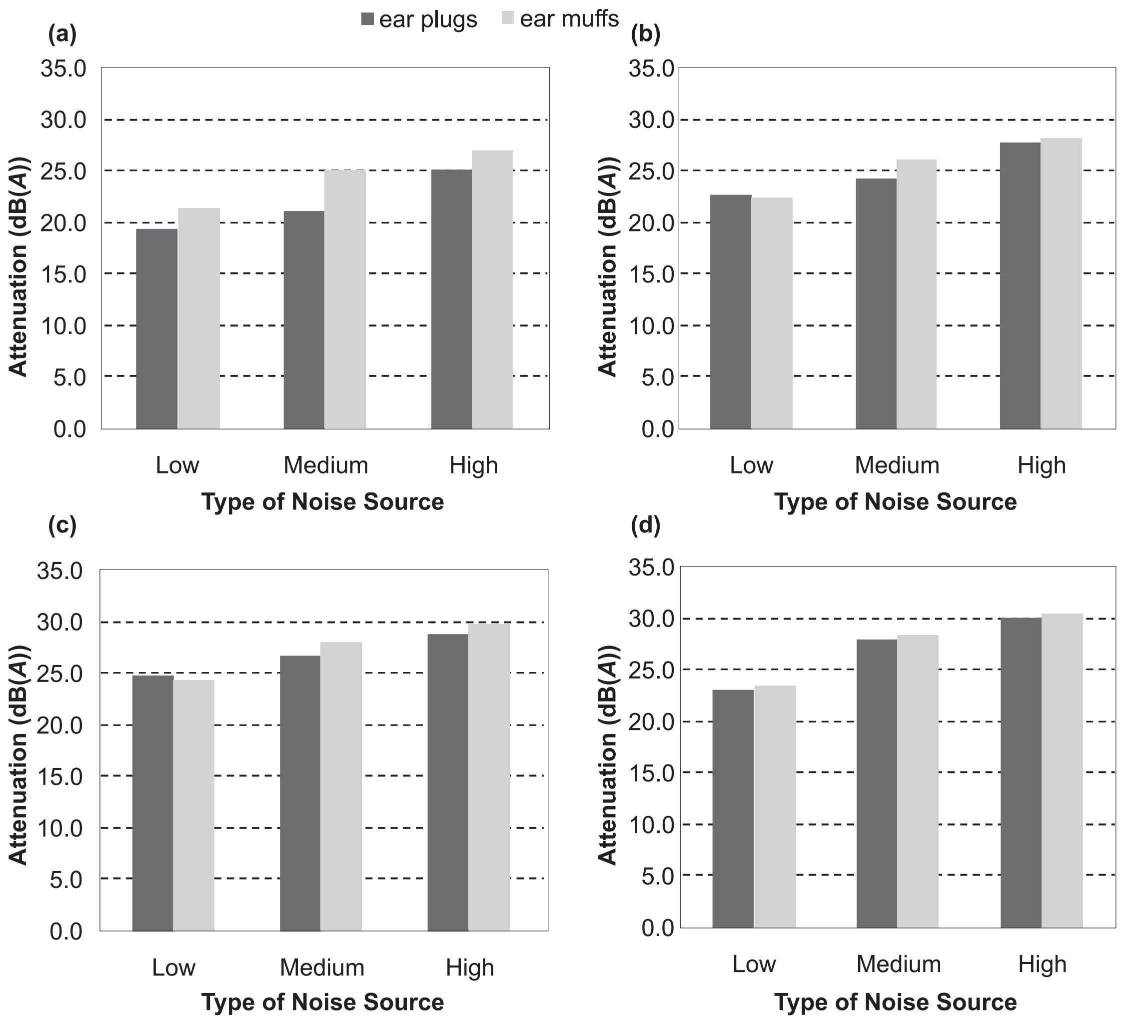

Figure 2. Estimated attenuation for hearing protection device (HPD) type; (a) OBM—octave-band method; (b) OBsm—octave-band with a safety margin; (c) HML—high, medium, low; (d) SNR—single number rating.

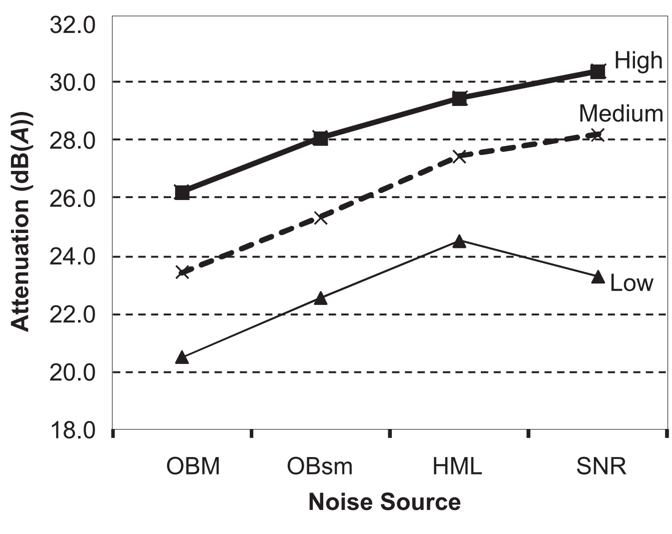

Figure 3. Estimated attenuation for each noise source type. *Notes*. OBM—octave-band method; OBsm—octave-band with a safety margin; HML—high, medium, low; SNR—single number rating.

were considered. Depending on the estimation method, the differences could be quite marked, as in the SNR method, or slighter, as in the case of the HML.

In most cases, ear muffs presented higher attenuation than ear plugs. However, when the OBsm method was considered, ear plugs performed better in the predominantly high- and low-frequency spectrum noise sources. This can be explained by the fact that this method did not reflect the variability associated with this type of HPD, since it used a constant safety margin of 2 dB, instead of a correction based on the attenuation device variability for that particular frequency.

According to Lundin, HML seems to provide slightly more predictive accuracy than SNR [2], hence greater proximity to the long methods. Figure 3 illustrates the mean for the estimated attenuation values considering the different noise source types.

Assuming that all the methods should ideally estimate the same attenuation value for the same noise source type, lines across the different methods should be horizontal, i.e., the estimated values should show consistency. This means the values should be equal irrespective of the method used for attenuation estimation.

Obviously, the existence of several methods assumes that some precision, with respect to the estimation, can be sacrificed in favour of a reduction in computation complexity. Therefore, it was expected that estimation values might be different. Accordingly, the main goal of this discussion was to analyse to what degree these values were different, as well as to try to understand the orientation of these differences.

The results obtained seem to show that there were some differences when more complex methods were compared with simpler ones, such as HML and SNR. It was also possible to verify that long methods were most probably the most accurate methods, as well as the most consistent, when HPDs were used in different noise environments.

Despite that, the most attractive or appealing methods for end users are obviously the simplest methods. This is because the added complexity of using OB data may confuse them. However, if the selection of HPDs should be based on the most accurate data, the workplace noise spectral analysis should be available. This leads to another issue: noise measurements can be simplified, and thus it might be possible to avoid additional effort involved in acquiring, storing, and using OB noise data solely for the purpose of selecting hearing protectors [5].

According to a new draft standard on strategies for measuring occupational noise exposure [14], noise exposure assessment might be carried out using different strategies, according to the specific requirements of the considered noise environment. These strategies include job-based and full-day measurements. In both cases the use of a logging instrument, such as a personal sound exposure meter or a dosimeter, is necessary. However, almost all available dosimeters on the market do not allow logging long-term OB data. Therefore, it is essential that some alternatives to OB methods, such as the HML and SNR methods, remain applicable to allow the estimation of effective levels based on personal sound exposure assessment techniques.

Considering this, Gauger and Berger [5] suggested the use of a new HPD attenuation rate, the noise reduction statistic (NRS_A), which is expressed in terms of the range of a value and was adopted as a standard through the publication of Standard No. ANSI/ASA S12.68-2007 [15]. Beyond other advantages, the authors claimed that the implementation of the proposed rate would also divert the attention of the buyer from a single value and, therefore, the associated tendency to select HPDs based on a single value.

Figure 3 shows that there was a positive trend when all methods were analysed transversally. As methods were sorted (from right to left) according to information needs and consequently according to decrease in simplicity, it was possible to conclude that the estimated attenuation and computation complexity were inversely related, i.e., when long methods were applied the estimated attenuation values were lower.

The SNR method and the low noise source were an exception. In fact, as this method depended largely on the *C*-weighted value, it was possible that this result was somehow inconsistent, as it visibly depended on the types of noise source used in this study. Even though all the considered noise sources presented similar *A*-weighted SPLs (cf. Table 1), the *C*-weighted SPLs in the low noise sources were significantly higher. Therefore, when applying the SNR method, the attenuation estimation was computed from the difference with this level, according to Equation 7. As a consequence, the estimated attenuation values would be lower when this low noise source was considered.

In terms of consistency, it is important to note that the SNR method was most likely the most affected method when varying the type of noise environments, in particular when differences between the *C*- and *A*-weighted SPLs were higher.

4. CONCLUSIONS

This paper compared different methods for estimating effective noise exposure, using a specific sample of hearing protectors and noise environments. The results obtained showed that even though all the compared methods are previewed in European standards, they generated different results, in particular in the case of the long and short methods.

The results demonstrated that the long method (i.e., OBM) in recent Portuguese legislation seemed to be an adequate choice as far as workers' protection was concerned, as well as reflecting the attenuation data variability of the devices for each OB frequency.

Concerning the noise environment in which HPDs are to be used, the results showed that typically HPDs presented minor estimated attenuation values when the low frequency noise sources were considered. Depending on the estimation method, the differences could be quite marked, as in the SNR method, or slighter, as in the HML case.

Despite the differences, the adoption of some noise measurement strategies will imply a lack of noise spectrum data, thus it is essential that some alternatives to long methods, such as the HML and SNR methods, or other simplified rates, can be used to estimate effective levels.

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