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An Educated Guess on the Workplace Attenuation Variability of Ear Muffs

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The attenuation variability of hearing protector devices plays a primary role in determining compliance, or lack of, with occupational noise exposure limits. This study presents an estimate of the ear muff attenuation variability, which includes several factors (biological diversity, positioning, sound field, ageing) for which specific information from laboratory studies is available. A mean value of the attenuation variability for ear muffs σ_{FR} = 4.8 dB is found. This value is about 65% larger than the typical value measured according to existing test standards. Being marginally smaller than the mean variability resulting from field measurements, and certainly within the wide range of fluctuations of the latter, it represents a robust and reliable quantity for application in any workplace environment.

ear muffs attenuation variability

1. INTRODUCTION

In one of its most innovative and controversial points, Directive 2003/10/EC [1] mandates that compliance with the exposure limit value should be assessed taking into account the effect of hearing protector devices (HPDs). A long-standing agreement exists among occupational safety and health (OSH) experts on the large overestimate that manufacturer self-declared attenuation (hereafter nominal) values provide to field values (cf. National Institute for Occupational Safety and Health [2]; Berger [3]; Berger, Franks and Lindgren [4], etc.). Mean values for the field-to-nominal attenuation ratio are .6 for ear muffs, and even lower values apply to other types of HPDs [2, 5]. The strong underestimate of the field variability provided by nominal standard deviations is also well recognized [5], though its role is often overlooked. This is unfortunate since a statistically sound assessment of compliance with the exposure limit value must explicitly take into account the attenuation uncertainty.

Nominal standard deviations, which only include the effect of intersubject variability, are usually unrealistically low. On the other side, full-fledged field estimates are often uncomfortably large, and extremely uncertain themselves. Because of this negative combination, they have been largely ignored, if not rejected, by the acoustic community in general, and by the OSH officials in charge of enforcing exposure limits in the first place.

In this study we explore a possible compromise between those two extreme options. Its aim is to calculate a broadened laboratory variability (hereafter field-ready variability) which takes into account all factors amenable to laboratory studies. As such, it should represent a good approximation to typical field estimates, but with a higher (and better known) precision. While proximity to real world values has already been claimed for the so-called subject-fit laboratory estimates (e.g., Gauger and Berger [5]), this mostly applies to the mean attenuation. The missing contributions in the subject-fit test method (e.g., ageing, sound field) imply that substantial improvement on the variability side is still possible.

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This study is specifically focused on ear muffs. Despite the existence of effective alternatives, such as high-efficiency ear plugs, ear muffs are still the most widely adopted protection device in very noisy environments, and, when coupled with inserts, they are basically the only option in extreme environments (engine tests, aircraft operations, etc.). As such, it is crucial to have reliable information on their effectiveness.

The purpose of this paper is twofold: first, to obtain a quantitative estimate for each of the factors that contribute to the attenuation variability; second, to calculate the total field-ready variability, and its ratio to the nominal variability, thus opening the way to the computation of reliable attenuation values to be applied in actual workplace environments.

2. ATTENUATION METRICS

Attenuation of HPDs can be quantified with several methods. A well-known trade-off exists between higher reliability of methods such as OBM (octave band method), and to a lesser extent HML (high, middle, low), and the associated cost of additional measurement and/or computational effort. Most actual workplace situations are still handled with the basic synthetic index SNR (single number rating) [6]. Recently proposed alternatives with similar nature (e.g., NRS_A [5]), although intrinsically superior, trail far behind in terms of popularity.

While SNR is properly defined as the attenuation statistically provided to 84% of users (mean – 1σ), the general notation SNR_x is commonly used to identify the attenuation which is statistically provided to *x%* of users. In this paper, variability has accordingly been defined as the difference between the SNR-style mean attenuation SNR_{50} and the "true" (1σ) SNR_{84}.

Whenever standard deviations at individual octave band centre frequencies in the range 63–8 000 Hz are available, these have been used in this paper to calculate each individual contribution σ_Y, due to a specific effect, to the overall attenuation variability. When this has proven impossible (e.g., for age-related effects) a frequency-averaged value has been estimated.

3. FIELD VARIABILITY FACTORS

Several factors contributing to the observed variability of the field attenuation of ear muffs have been singled out to become the subject of laboratory and field investigations. The list includes

- differences in the shape and size of the human head among individuals, and between genders, particularly in the area around the ear (hereafter identified as biological variability);
- differences in the positioning of the device operated by the same individual under different circumstances (positioning repeatability);
- differences in age and/or maintenance of the equipment (ageing dispersion);
- differences in the sound field (diffuse versus direct or any combination in between), and in the angle of incidence of sound waves in direct fields (sound field variability).

These factors will be individually reviewed in the following sections, making use of statistical methods in accordance with the Guide to the expression of uncertainty in measurement [7]. There are other factors which are specific of actual workplace activity (e.g., displacements due to facial movements or to small hits); it is extremely difficult to assess them objectively. These elements account for any existing difference between the variability calculated in this paper and the observed field variability.

4. BIOLOGICAL VARIABILITY

4.1. Experimenter-Fit Tests

Intersubject variability, also known as biological variability (hereafter indicated as σ_B), is a very well-known source of uncertainty in ear muff attenuation. Because this is the only contribution which is taken into account both in North American [8] and in international HPD test standards [9], experimenter-fit standard deviations due to biological variability also double as nominal standard deviations.

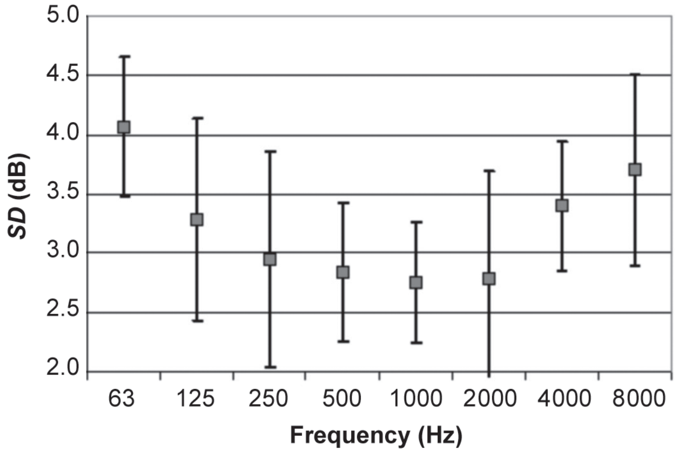

Figure 1. Standard deviations due to biological variability, and associated variability.

To obtain a reliable estimate of σ_B, nominal attenuation data for 19 currently commercialized ear muffs have been collected. Standard deviations are shown in Figure 1 as functions of frequency. The resulting mean standard deviation, averaged over 19 ear muffs as well as frequency-averaged as outlined in section 2, is $\sigma_B = 2.9$ dB.

In addition to displaying variations within each individual HPD, attenuation also varies across different HPDs. However, the nominal standard deviations within each HPD show surprisingly small fluctuations (of the order of $\lesssim 0.5$ dB). The mean value $\sigma_B = 2.9$ dB can accordingly be used as a reliable estimate of the experimenter-fit biological variability for all ear muff models.

4.2. Subject-Fit Tests

Data on σ_B from subject-fit tests are rare. The most extensive report on this issue includes 9 models [5]. However, while mean attenuation values are presented and compared to nominal and field data, less attention has been paid to data on intersubject variability. Data on 6 earmuffs hint at a mean value $\sigma_B = 3.5$ dB [5]. A very deep but narrow-focus study limited to a single earmuff has resulted in a value $\sigma_B = 4$ dB, leading to an overall weighted mean $\sigma_B = 3.6$ dB.

It may be tempting to associate the excess variability $(3.6^2–2.9^2)^{0.5} \approx 2$ dB to the partial relaxation of the traditional experimental set-up, which would naturally lead to claiming very good mutual agreement between the two results. It is fair to say, however, that the dearth of data and the proximity of these two estimates currently prevent any firm conclusions on this point.

Inter-HPD variability appears to be significantly larger in subject-fit data, possibly several decibels, but hardly quantifiable at present. We ignore it in this paper's analysis, which implies that the estimate for the biological variability, $\sigma_B = 3.6$ dB, is not as robust and conservative for subject-fit tests as it is for experimenter-fit tests.

There have been claims of an asymmetrical distribution of the attenuation loss linked to biological variability, due to a similarly asymmetric distribution of facial profiles, i.e., the skull shape and the hair volume [10]. Custom planned experimental tests have confirmed that an asymmetric bimodal probability density function (pdf) provides the least square fit to data [11]. However, a Kolmogorov Smirnov test does not reject a symmetric, normal pdf at the 95% level. Evidence on this issue is inconclusive and awaits further investigation.

5. POSITIONING REPEATABILITY

There is little available information that can be used to derive an estimate of this contribution. Luckily, while positioning is a major source of uncertainty for inserts and plugs, it is unlikely to play any sizeable role for ear muffs. This is obviously due to the fact that ear muffs require less skill and time to be positioned, so an

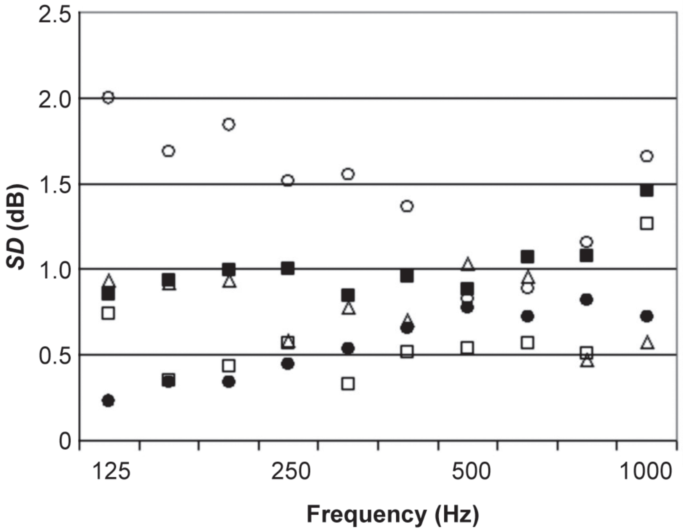

Figure 2. Standard deviations due to positioning repeatability for 5 subjects.

acceptable result can be found with very large probability.

Recent laboratory tests were run on 5 subjects with no previous experience of HPD testing, and no specific formation on ear muff positioning [11]. The subjects were exposed to a direct sound field, with both line-of-sight and lateral incidence. The number of repetitions was varied between 6 and 13 for each subject. Figure 2 shows the data for each of the subjects. Apart for one subject, standard deviations were very low for most of the investigated frequency range, whereas an appreciable rising trend showed up only beyond 1 000 Hz. Calculated standard deviations for the SNR ranged between 0.5 and 1 dB for individual subjects exposed in a sound field characterized by line-of-sight incidence. The resulting average value was $\sigma_P \approx 0.8$ dB. Results for lateral incidence on just one subject did not show significant departures from this value.

Claims that the probability density function of the attenuation loss may be asymmetric also in this case have not been supported by significant experimental evidence. The effect may indeed be too small to be detectable. In the light of the small entity of this contribution, however, this issue is immaterial.

6. AGEING

6.1. General Facts

While several HPDs are meant to be disposable, ear muffs are built to last. A significant degradation of the acoustical performance in time is expected, as a result of changes in the mechanical (elastic) properties of the head band and damage to the foam pads.

There is a dearth of experimental studies on this topic. Existing data have been used in this work to synthesize an evolutionary model that deals separately with the external (overhead band + cup shells) and the internal (foam pads) modules [12, 13, 14]. Decoupling has been made possible by recognizing that the acoustical performance of undamaged foam pads is statistically undistinguishable from that of new pads. Any attenuation loss change in ear muffs with undamaged pads has accordingly been attributed to a degraded performance of the external module.

6.2. External Module

Figure 3 displays the existing information on the mean ear muff attenuation loss due to the external module. Attenuation has again been quantified using the SNR, and a conversion factor 1 year = 1 000 h of use has been adopted.

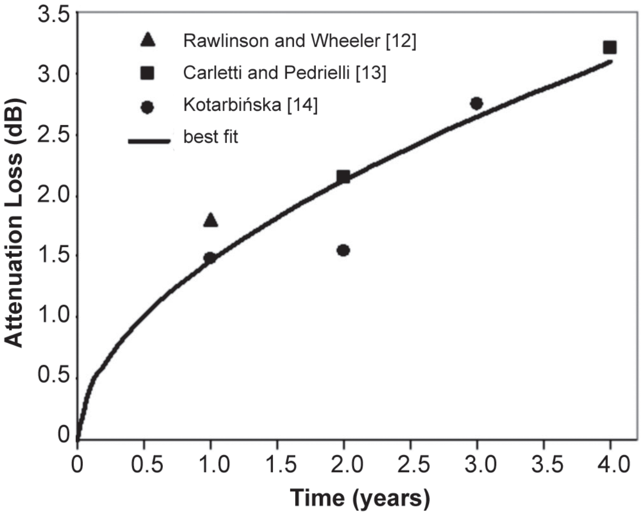

Figure 3. Mean time evolution of attenuation loss of the external module, due to ageing.

A straight line provides a very poor fit (r^2 = .37) to data, once the constraint to give zero attenuation loss at $t = 0$ is enforced. A much better fit (r^2 = .74) has been found using a power law:

$$L_{\text{EXT}} = \alpha \times t^{\beta}, \tag{1}$$

with $\alpha = 1.46$ and $\beta = 0.54$. Finally, rounding of best fit coefficients has led to a modelling of the time evolution of the attenuation loss due to the external module with Equation 2:

$$L_{\text{EXT}} = 1.5 \times t^{0.5}. \tag{2}$$

Units are years for t and decibels for L_{EXT}, as well as for all other attenuation losses that are calculated in this section. The square root functional dependence on time also accomodates the very steep initial rise of the attenuation loss which was tentatively identified by Rawlinson and Wheeler [12].

6.3. Internal Module

In recognition of the considerable wear that foam pads are subjected to, these have a relatively short replacement time in the order of one year. There is evidence, however, that a significant fraction of pads F_{D} gets damaged on even shorter timescales, which may result in a strong decrease in the muff performance [12, 13]. Available experimental data on F_{D} indicate $F_{\text{D}} = 9/22 = 41\%$ for a usage time of less than one year and $F_{\text{D}} = 12/22 = 55\%$ for a usage time equal to one year [13]. On the basis of these data, the following time evolution of F_{D} has been assumed:

$$F_{\text{D}} = 1 - \exp\left(-\, {}^{t}\!/_{\tau_{\text{D}}}\right), \tag{3}$$

where $\tau_{\text{D}} = 1\,250$ h. The average value of F_{D} over one year resulting from Equation 3 is 31%. This value is somewhat lower than the corresponding experimental figure of 41%, as expected given that a usage time of less than one year can presumably be read as somewhere between 6 and 12 months. The fraction of undamaged pads F_{UD} is trivially computed from Equation 3:

$$F_{\text{UD}} = \exp\left(-\, {}^{t}\!/_{\tau_{\text{D}}}\right). \tag{4}$$

The time evolution of the attenuation loss of damaged foam pads has been calculated by subtracting the attenuation found for undamaged pads from the total attenuation. Carletti and Pedrielli's information leads to estimates of 5.2 dB after 2 years (9 samples) and 5.1 dB after 4 years of use (12 samples) [13]. Rawlinson and Wheeler's similar analysis on a single ear muff leads to an attenuation loss for the internal module of 7.9 dB over one year [12].

This pool of information is consistent with the mean attenuation loss of a damaged foam pad being time independent. A weighted mean of available data gives an attenuation loss of 5.3 dB.

By combining this value with Equation 2, the attenuation loss time evolution for ear muffs with damaged pads has been modelled as

$$L_D = 1.5 \times t^{0.5} + 5.3. \qquad (5)$$

There is no attenuation loss in time for undamaged pads. The attenuation loss for ear muffs with undamaged pads is, therefore, limited to that found for the external module:

$$L_{UD} = 1.5 \times t^{0.5}. \qquad (6)$$

6.4. Attenuation Loss Time Evolution

The time evolution of the attenuation loss

$$L = L_{UD} \times F_{UD} + L_D \times F_D \qquad (7)$$

is presented in Figure 4. The gradual growth due to the declining elasticity of the overhead band and the abrupt cyclic jumps due to the replacement of foam pads are clearly visible.

Computation of the mean attenuation loss time evolution for samples of ear muffs requires that the four functions $F_D(t)$, $F_{UD}(t)$, $L_D(t)$, $L_{UD}(t)$ shown in Equations 3–6 are complemented with a further equation for the fraction of HPDs which is still in use at time t, $F_{OP}(t)$. The latter has been modelled as a very steep exponential

$$F_{OP} = 1 - \exp\left[-\left(\frac{t}{\tau_{OP}}\right)^6\right], \qquad (8)$$

where τ_{OP} = 4000 h. Equation 8 is consistent with experimental data indicating $F_{OP} \approx 1$ up to about 2500 h, and $F_{OP} \approx 0$ after a time $t = 4000$ h [13]. The associated attenuation loss probability density function $p(L)$ shows a broad maximum in the range 2.9–3.7 dB. Despite the fact that the overall probability density function $p(L)$ results from the convolution of two very asymmetric functions, this distribution is itself remarkably symmetric, as predicted by the central limit theorem [7]. Once $p(L)$ is known, the calculation of the attenuation loss mean and standard deviation is straightforward [15]:

$$L_A = \int_0^\infty L \times p(L)dL \qquad (9)$$

$$\sigma_{A1} = \left[\int_0^\infty (L - L_A)^2 \times p(L)dL\right]^{0.5}. \qquad (10)$$

The latter is the relevant quantity in this paper's context. Available data lead to σ_{A1} = 1.2 dB.

6.5. Variability of Attenuation Loss Evolution

Variability across different muff models is very strong for ageing. Data for three different ear muffs clearly show very large fluctuations of ageing effects, with attenuation losses ranging from zero to almost 10 dB for usage times of 2–3 years [14]. Unfortunately, no additional

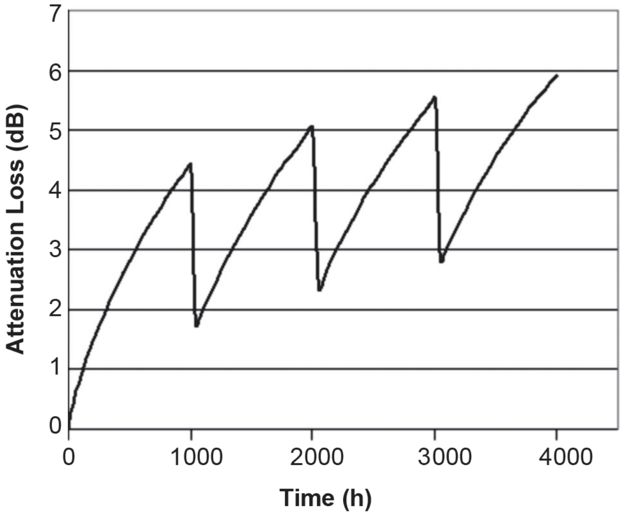

Figure 4. Mean time evolution of the attenuation loss of an ear muff.

information on this topic is presented in other studies. However, because the size of the effect appears to be quite large, inclusion of an additional contribution taking into account inter-HPD variability has been deemed appropriate. A rough estimate has been derived by exploring the changes in the mean attenuation (Equation 9) associated to changes in the fit parameters α and β (cf. Equation 1). Taking into consideration that the standard deviation is roughly of the same order of magnitude as the mean attenuation loss, this gives an estimate of variability among different muff models of $\sigma_{A2} \approx 2$ dB.

The global contribution to attenuation uncertainty due to ageing has been estimated as the root mean square of σ_{A1} and σ_{A2}, i.e., $\sigma_A \approx 2.3$ dB. This value likely provides a somewhat conservative estimate, which might be revised downward should additional data become available.

7. SOUND FIELD

Nominal attenuation values result from experimental data obtained in a mostly diffuse sound field. However, many workers are exposed to direct sound fields where wave incidence is often concentrated in a narrow cone about a specific angle.

The sensitivity of ear muff attenuation to the sound field has been investigated in some detail [16]. Because the focus is mostly on the attenuation to impulsive noise, results are not easily applicable to continuous noise. A recent experimental study has investigated the matter in some depth, with measurements performed in both diffuse (reverberant room) and direct (anechoic chamber) sound fields [17]. Four angles of incidence were tested ($\phi = 0^\circ, 45^\circ, 90^\circ, 180^\circ$) in the latter, all of them in the horizontal plane which included the subject's head and the loudspeaker.

Figure 5 shows the results as a function of frequency and angle of incidence. Each point is the average of three measurements, one for each of 3 subjects. The trend observed in the low- to mid-frequency range is quite regular, with maximum attenuation occurring for $\phi = 0^\circ$, and declining as the angle of incidence increases. The declining trend appears to be steeper close to $\phi = 0^\circ$, flattening out to give almost no variation between $\phi = 90^\circ$ and $\phi = 180^\circ$. All in all, the observed variability with the angle of incidence is quite limited, spanning a total range of the order of 5 dB from 50 to ~1 000 Hz. However, despite the fact that the SNR is mostly sensitive to the frequency range between 250 and 1 000 Hz, the very strong fluctuations observed in the

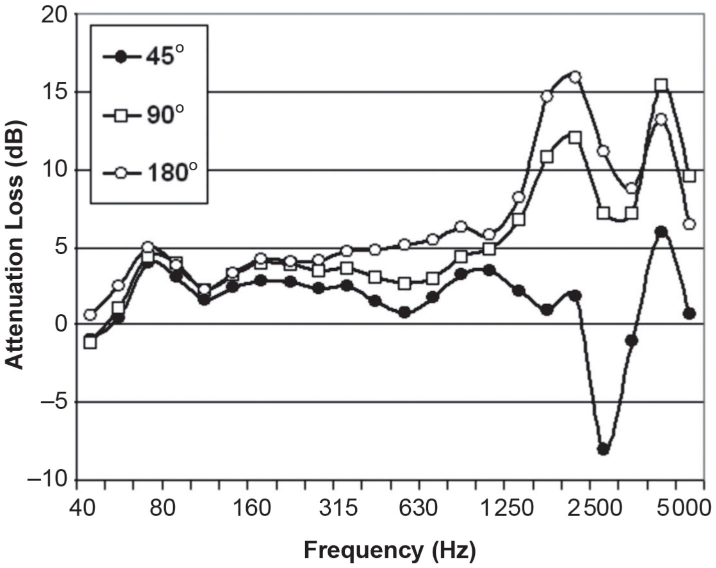

Figure 5. Attenuation variability as a function of the angle of incidence of sound waves.

attenuation loss between 1 000 and 5 000 Hz imply that this frequency range has a non-negligible effect in the uncertainty of the SNR.

A synthesis of available data for direct sound fields has been performed calculating a mean value of attenuations for the SNR and an associated standard deviation. Both calculations assign equal weight to $\phi = 0^\circ$, 45° and 90°, and neglect $\phi = 180^\circ$ assuming that work situations with no visual contact with the sound source are unlikely. This leads to $\sigma_{SF} = 2$ dB.

As expected, the attenuation in diffuse fields is virtually indistinguishable from the mean attenuation calculated for direct fields, except in the very high frequency regime $f \geq 3\,150$ Hz, which is irrelevant for the scope of this paper.

8. DISCUSSION

8.1. Synthesis of Laboratory Studies

A synthesis of individual contributions to variability discussed in previous sections is presented in Table 1. Because there are no reasons to hypothesize that such factors are mutually correlated, the total variability has been calculated as the simple quadratic mean of individual contributions [7].

TABLE 1. Summary of Calculated Contributions to Field Variability

Variability Factor	Symbol	*SD* (dB)
Biological	σ_B	3.6
Positioning	σ_P	0.8
Ageing	σ_A	2.3
Sound field	σ_{SF}	2.0
Total	σ_{FR}	4.8

It is important to stress that the field-ready standard deviation σ_{FR} calculated in this paper only incorporates effects which have been tackled by laboratory studies. As such, although it represents a substantial improvement over the nominal standard deviation (2.9 dB, cf. section 4.1.), some future revision upward is still possible.

8.2. Field-Ready SNR

Once the field-ready standard deviation σ_{FR} is known, the calculation of the field-ready single number attenuation $(\mathrm{SNR})_{FR}$ is a straightforward three-step sequence:

1. calculate the nominal laboratory mean SNR_{50}, using the same scheme that leads to SNR, but subtracting no multiple of the standard deviation;
2. estimate the field-ready attenuation mean A_{FR}, by scaling down the nominal mean by an appropriate factor ψ. The well-known reduction factor $\psi' = 0.75$, which is advocated by the National Institute for Occupational Safety and Health [2] for ear muffs, does not quite match this definition, as it applies to the quantity NRR (noise reduction rating), rather than the attenuation mean. It may, however, represent a good zero-th order approximation, awaiting more accurate estimates;
3. subtract α times σ_{FR} to calculate the field-ready SNR customized to any desired percentage x of users to be protected:

$$
\begin{aligned}
(\mathrm{SNR}_x)_{FR} &= A_{FR} - \alpha(x) \times \sigma_{FR} \\
&= \psi \times \mathrm{SNR}_{50} - \alpha(x) \times \sigma_{FR}.
\end{aligned}
\tag{11}
$$

TABLE 2. Comparison Between Nominal and Field-Ready Descriptors of Ear Muff Attenuation

Quantity	Symbol	Value (dB)
Nominal SNR	SNR_{84}	29
Nominal attenuation mean	$A = \mathrm{SNR}_{50}$	32
Field-ready attenuation mean	A_{FR}	24
Field-ready attenuation variability	σ_{FR}	4.8
Field-ready SNR	$(\mathrm{SNR}_{84})_{FR}$ [1 σ_{FR}]	19
	$(\mathrm{SNR}_{95})_{FR}$ [1.65 σ_{FR}]	17
	$(\mathrm{SNR}_{98})_{FR}$ [2 σ_{FR}]	15

Notes. SNR—single number rating.

Table 2 illustrates an example of the application of the results of this paper. Because A_{FR} is significantly lower than the nominal mean, while σ_{FR} is 65% higher than the nominal variability, the end result for the field-ready SNR may severely cut the initial estimate of the attenuation of the muff.

8.3. Field Studies

A handful of field studies of the ear muff attenuation that have been performed in the last 30 years may shed light on the acceptability of the predictions of this paper. Although over 10 years old now, Berger, Franks and Lindgren's extensive review still provides an excellent summary of existing data [4]. Mean standard deviations show some unfortunate sensitivity to the measurement methodology across the frequency range of 250–1 000 Hz that is most relevant for the SNR calculation (σ_{FIELD} = 4.5 dB for MIRE versus σ_{FIELD} = 6.5 dB for REAT). Because most lab studies have adopted the REAT method, which is also widely recognized as the most accurate in field studies [4], the latter (largest) value has been selected in this work for a fair comparison with σ_{FR}.

It must be stressed that σ_{FIELD} incorporates biological, positioning and ageing variability, while there is no contribution from the sound field. There are no obvious arguments to indicate that the value of σ_{SF} estimated from laboratory studies should not be extrapolated to field studies as well. Therefore, after the due correction for the missing contribution from the sound field variability, the resulting final estimate is given by the standard quadratic sum [7]:

$$\sigma^*_{\text{FIELD}} = \left(6.5^2 + 2.0^2\right)^{0.5} \approx 7\text{dB}. \qquad (12)$$

In the light of the limited databases supporting both estimates, and considering that σ_{FR} has built-in limitations (cf. section 8.1.), whereas field estimates suffer from a non-negligible method-related uncertainty, the resulting 2 dB gap between σ_{FR} and σ^*_{FIELD} is fully consistent with the expected discrepancy.

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