

# Hearing Protectors: Topicality and Research Needs

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*Occupational noise specialists do not generally recommend hearing protection devices (HPDs) as a preferred solution to noise risk prevention. Nevertheless, these devices are widely used and are in fact often necessary. Selection of an HPD should take into account comfort and the capacity for perceiving external signals, when they are worn. Current European regulations require that HPD attenuation be considered, when comparing noise exposure to limit values. However, HPD attenuation is effectively unknown under real-world conditions. Some methods are designed to give approximate attenuation values and these provide results within a wide statistical range. Field measurement methods and current standards have been developed to deal with this situation. The specific characteristic of impulse noise requires establishment of dedicated criteria and tools for HPD selection and testing. This paper introduces a number of avenues for research, which could be of assistance in improving HPD selection, qualification and design.*

occupational noise   hearing protectors   human behaviour   attenuation   real world  
derating   subject-fit   comfort   research

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## 1. INTRODUCTION: TOPICALITY OF NOISE AT WORK AND HPD USAGE

Occupational noise still remains one of the most prevalent occupational health and safety problems, despite the efforts of European authorities and national prevention organisations. Approximately 10% of European Union (EU) “workers are exposed (almost) permanently to high-level noise” (p. 19) and noise-induced hearing loss is a prominent occupational disease in Europe (ranked 4th in 2001) [1].

This fact has led European authorities to publish Directive 2003/10/EC to provide fresh impetus to prevention actions [2]. It came into force in 2006. It resulted in a paradox: whilst the purpose was to prompt noise reduction preventive action, its implementation emphasised the use of individual

protection measures and this contradicted fundamental prevention principles. Individual protection was effectively promoted by the unforeseen role allocated to hearing protection devices (HPDs). The directive introduced the notion of exposure limit values, which can sometimes be considered in competition with conventional action values [3]. Moreover, the directive stated that “when applying the exposure limit values, the determination of the worker’s effective exposure shall take account of the attenuation provided by the individual hearing protectors worn by the worker. The exposure action values shall not take account of the effect of any such protectors” (p. 40). The HPD issue has been highlighted through discussion on limit value usage and technical questions involving implementation of this latter requirement.

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This paper introduces the current issue of *JOSE* and is, therefore, followed by two lists of references. The first one (letter identification) refers to articles in this issue. The second (number identification) refers to other sources.

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2. HPDs AND OCCUPATIONAL NOISE PREVENTION

Wearing an HPD is a common solution implemented by companies to reduce workers' noise exposure. European prevention philosophy is that this should nevertheless remain a last-resort solution. Companies should "[give] collective protective measures priority over individual protective measures" (p. 6) [4] and, as far as noise itself is concerned, HPDs should be used "if the risks arising from exposure to noise cannot be prevented by other means" (p. 41) [2]. There are of course many other means and collective actions, but they are often unknown or considered complicated [5]. Their selection requires minimum company involvement in analysing the problem and their efficiency requires careful monitoring of their implementation and further usage [6]. HPDs are, therefore, considered an easy solution offering guaranteed efficiency. Furthermore, HPDs allow the employer and

the employee to share responsibility for this efficiency. Searching for collective solutions should, therefore, be encouraged and aids should be made available to companies.

Whatever efforts are made to find collective solutions, there are many situations in which HPDs are a necessary complementary solution. Personal protection must often be worn when equipment noise cannot be enough reduced. Many situations can be encountered where HPD use cannot be avoided, e.g., at mobile workstations, when using portable tools and in outdoor work.

3. HPD REGULATIONS AND STANDARDS

Within the scope of European regulations, hearing protectors are not simply treated as noise reduction solutions; they are also products circulating inside the EU. From this standpoint, they are subject to minimum safety requirements,

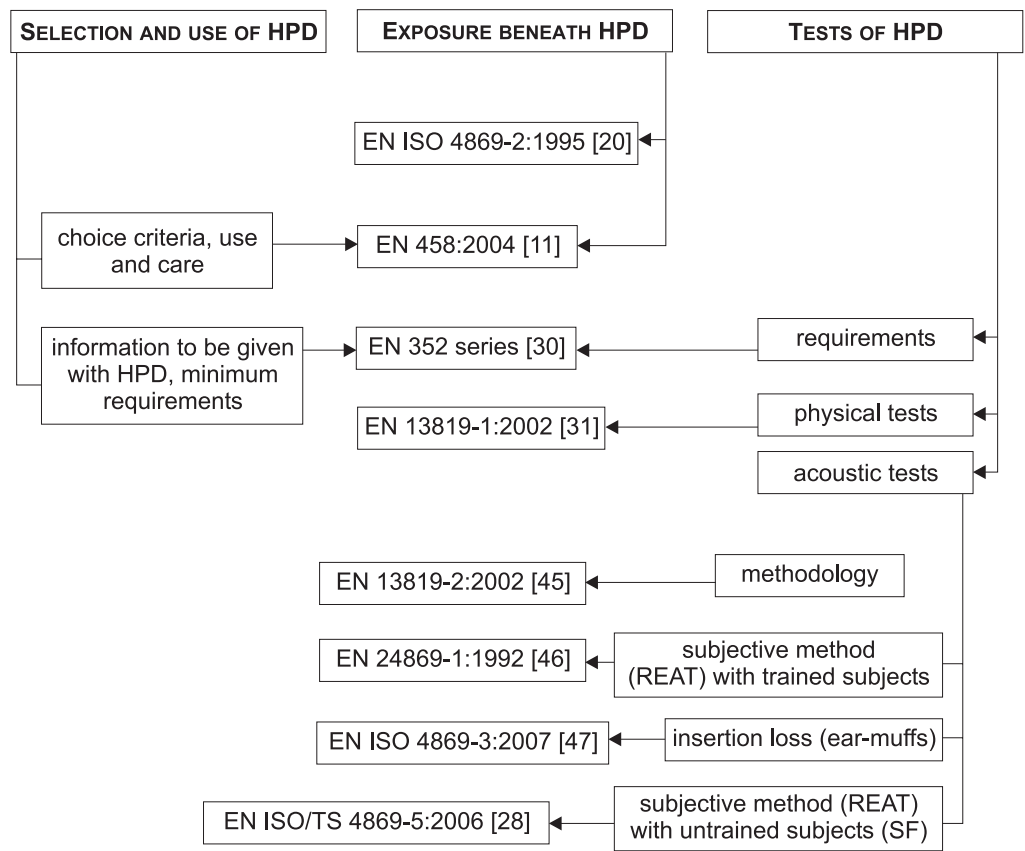


Figure 1. Standards for hearing protectors. Notes. HPD—hearing protection device, REAT—real ear attenuation at threshold, SF—subject fit.

which need to be checked by notified bodies. A CE (Conformité Européenne) mark on products certifies compliance with requirements.

European directives provide the legal basis for this: Directive 89/656/EEC on the use of HPDs [7] and Directive 89/686/EEC on their design [8]. The new approach, promoted by the EU in 1985 (the European Economical Community at the time), structures the relationship between the statutory texts and the relevant standards. Directives only set forth the legal requirements and standards specify the means of fulfilling these legal requirements [9]. This partition enables standardisation bodies, embracing both occupational and technical experts, to define the methodologies to be applied and to develop them. European standards supporting the legal texts are called harmonised standards. The new approach allocated them an important role, which contributed positively to their editing. In the case of hearing protectors, there are now many standards corresponding to the legal requirements [10].

The relatively numerous standards make it difficult for a lay person to know which one corresponds to needs. Furthermore, the content of some standards overlaps. Figure 1 will help the reader in learning (a) how to select and use a hearing protector, (b) how to evaluate noise exposure beneath hearing protectors and (c) what tests are conducted on hearing protectors to assess their compliance with legal requirements. The main reference for a lay person is Standard No. EN 458:2004, which provides basic information for HPD users [11].

#### **4. HPDs: PROTECTION OR INCONVENIENCE?**

Workers generally view personal protective equipment (PPE) as an inconvenience rather than a protective device.

The first inconvenience is practical: workers have to wear the PPE and they even have to take care of “their” hearing protectors. Workers need to be highly motivated to use and take care of HPDs: unlike most PPE, the need for HPD-based protection is not obvious with regard to

one’s health. Apart from the specific case of high-impulse noise created by blast and gunfire, deafness is a gradual degenerative disease that takes a long time to become apparent for the worker. There is no direct relationship between HPD use and risk reduction. Good use of HPDs is directly linked to workers’ risk perception: do workers feel at risk, when exposed to high noise levels and do they believe in HPD efficiency? Risk perception depends on many human factors (acculturation, age, etc.) and on workers’ risk awareness. This explains why good wearing of HPDs may vary widely, depending on the workers involved [12].

In other respects, workers may also feel that HPD use may effectively transfer some of the responsibility for risk reduction duties to workers, which is otherwise incumbent on the employer. Such a feeling may affect their perceived organisational support and, in turn, decrease motivation in relation to good use of safety devices on the part of the employee [13].

Protective equipment is invariably a physical interface between workers and their immediate environment. It alters their perception of what is happening and what they are doing. This close relationship is even more intimate for noise-related protective equipment: traditionally, workers do not consider noise as a hazard but as part of their natural environment. They may view noise as an expression of their work and, at the same time, as a feeling of being part of the whole workshop. Wearing HPDs creates an effect which may be considered similar to hearing impairment: noise level is decreased, but this reduction varies, depending on the sound frequency. Perceived sound becomes deformed and we know that many workers use sound as guidance in their work. Naturally, ambient noise changes, which interfere with workers’ perception of surrounding sounds, are caused by most physical noise abatement solutions (enclosures, screens, etc.). This drawback is nevertheless accentuated, when HPDs are worn: noise level change is continuous, wherever workers stand, and it may be perceived as linked to workers’ hearing capacity. In other respects, fitting HPDs inside or outside the ear creates an occlusion effect, mainly at lower

frequencies: workers' own voice perception is amplified, along with body vibration, when walking, or jaw movement, when chewing, effectively create artefact noises [14]. Spatial recognition of the sound location is altered.

## 5. INTELLIGIBILITY AND SIGNAL PERCEPTION

Hearing impairment induced by HPDs may have major consequences on workers' ability to perceive and understand signals. It may prevent them from hearing colleagues or at least understanding them. This can impede work progress, if it is linked to other workers' tasks. This problem becomes serious, when communication involves safety issues. Hearing impairment due to HPDs may prevent workers from understanding information signals or even from hearing danger signals. This should be taken into account in any risk assessment process and HPD selection should consider this factor [a].

As far as communication is concerned, theoretical methods can be applied to perceiving signal intelligibility. Studies showed that these methods may be efficient, even when HPDs are worn [15]. This offers an opportunity for taking the intelligibility parameter into account, when selecting a suitable HPD. A number of criteria have been established for assisting in selection of suitable HPDs for hearing danger signals on the basis on their noise attenuation characteristics [b].

However, the ability to perceive external signals is linked to HPD attenuation characteristics. Reliability of intelligibility criteria should, therefore, be based on actual HPD individual attenuation and this aspect is considered later in this paper.

## 6. COMFORT AND EFFICIENCY

Hearing impairment is not the only negative effect of HPDs. Physical inconvenience may produce significant discomfort. Regarding ear muffs, cushion pressure or headband force contribute to attenuation performance. Williams

shows how clamping pressure may affect blood circulation in the ear and create real discomfort [c]. Wearing ear muffs may generate heat on the ear and can lead to perspiration. The weight of the device and cushioning material can also cause discomfort. Ear plugs generate pressure and heat, too, and are also body-intrusive. Ear plugs may cause irritation of the ear canal. All these inconveniences can create extensive worker discomfort. In addition to the perception problems, this results in workers being frequently reluctant to wear HPDs. They often remove their HPDs for a while, when working. A retrospective study of different industrial fields in the 1980s revealed that the HPD nonwearing rate, when exposed to hazardous noise could vary from <20% to >80% [16]. Theoretically, impact on protection efficiency reduces very quickly: for 5 min of nonwearing time, HPD attenuation for 8-h exposure falls from 30 to 20 dB(A). We know that a real situation is more complex: this has been calculated on an energy equivalence basis and ear physical physiological recovery can be increased by adopting short protection times [17]. However, comfort becomes a major parameter in relation to HPD selection and is enhanced by HPD good fit in the ear. The feeling of comfort is very personal and experience shows that involving workers in HPD selection can only be beneficial [18].

This information shows that, despite common industrial practice, choosing the best hearing protector should not only be guided by its attenuation performance with respect to noise exposure objectives. The ability to communicate and comfort are parameters of comparable importance.

## 7. EVALUATION OF NOISE EXPOSURE BENEATH HPDs

The conventional way of assessing occupational noise exposure is to measure the ambient noise in the vicinity of the worker's ear. Its outcome can be directly compared to relevant control thresholds. HPD protection requires us to position the microphone inside the ear canal (behind the HPD). We then have to calculate what the

noise level would be in the vicinity of the ear for comparison with the control limit values. Two international standards are extrapolated, when doing this. They were originally drafted to evaluate exposure for sound sources close to the ear. Standard No. EN ISO 11904-1:2002 proposes the microphone-in-real-ear (MIRE) method, in which a miniature microphone is placed inside the ear canal [19]. Standard No. EN ISO 11904-2:2004 includes the use of a human body-shaped manikin [20]. A measuring chain inside the manikin head is connected to its ear, which is assumed to behave similarly to a human hearing system. In both methods transposition from inside-the-ear to the vicinity-of-the-ear is ensured by applying theoretical transfer functions. These methods require complex instrumentation and are technically delicate. They are not dedicated to common industrial usage, so computation methods are preferable for industrial applications.

The general computation principle is to subtract the HPD attenuation from conventional ambient exposure. Standard No. EN 24869-1:1992 (or ISO 4869-1:1990<sup>1</sup>) describes the procedure for measuring HPD attenuation in the laboratory [21]. Standard No. EN ISO 4869-2:1994 takes into account the attenuation parameters shown on the HPD packaging and included in the user information [22]. It proposes three calculation methodologies using these parameters for computing the exposure behind the HPD. These methods are summarised in Standard No. EN 458:2004, along with an additional method [11]. They reflect three levels of accuracy, themselves corresponding to different parameters for assessing HPD attenuation [d]. The octave-band method uses assumed protection values (APV) for the HPD, which are given for each octave band. This method requires the exposure octave-band spectrum, but this is seldom available. The HML method uses three parameters, which qualify HPD attenuation based on three frequency ranges: H (high), M (medium) and L (low). This method requires data on the A- and C-weighted sound pressure levels. Finally, the

simplest (but less accurate) method uses the SNR (single number rating) value, representing global HPD attenuation. The SNR is subtracted from the overall exposure level measured in dB(C). Similar methods are used outside Europe. Their differences may in fact consist in their methods of determining attenuation parameters and their names (SNR corresponds to noise reduction rating, NRR, in the USA,  $SLC_{80}$  in Australia, etc.) and the equations they apply to compute exposure using these parameters.

## 8. LABORATORY AND REAL-WORLD HPD ATTENUATIONS

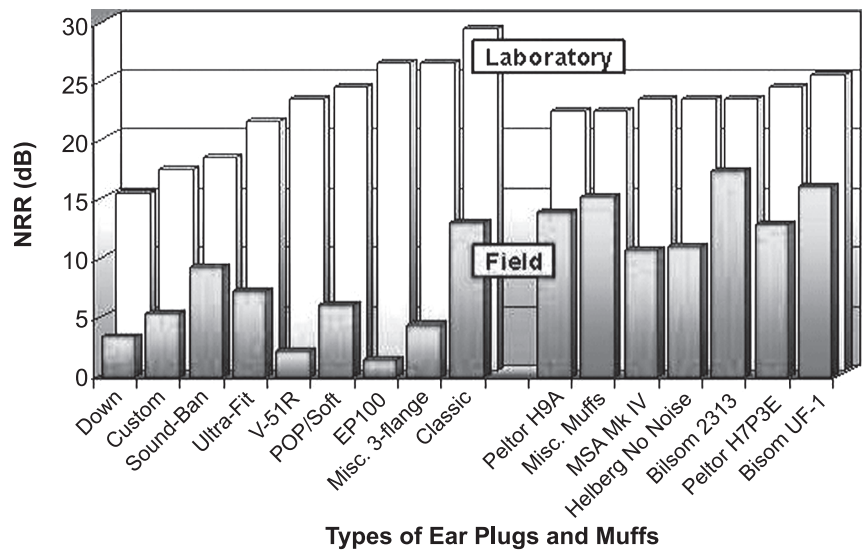
Field conditions in industry are very different to those of laboratories at which HPD tests are conducted. This produces major differences between the declared and actual performance of HPDs. Many studies highlight this discrepancy.

The reference parameter is the attenuation measured in compliance with Standard No. EN 24869-1:1992 [21]. Its values are termed declared or labelled values because they are measured by notified bodies (in Europe) and are stated on official labels accompanying the product. They are also called laboratory values because Standard No. EN 24869-1:1992 is implemented in laboratories. The EN 24869-1:1992 method uses human subjects. HPD adjustment is evaluated using a test noise around the human listener's head. Noise is emitted in the laboratory and listeners state when the sound level reaches their hearing threshold. The difference between the two hearing thresholds (with and without the HPD) provides the HPD attenuation. This method is commonly called (real ear attenuation at threshold, REAT).

The 1998 criteria for a recommended standard published by the U.S. Department of Health and Human Services reported that, in almost all studies, real-world attenuation was much lower than the corresponding REAT values [23]. A popular reference for this summary is

<sup>1</sup> International Organization for Standardization (ISO). Acoustics—hearing protectors—part 1: subjective method for the measurement of sound attenuation (Standard No. ISO 4869-1:1990). Geneva, Switzerland: ISO; 1990.





**Figure 2. Comparison of labelled and mean field-attenuation values for various hearing protection devices [24].** Notes. NRR—noise reduction rating.

Berger, Franks and Lindgren [24]: the difference between laboratory-measured and real-world attenuations evaluated in a number of studies is provided for hearing protectors of various types. This difference may vary widely, depending on the studies and the HPD: real-world or field attenuation may be 5–76% of the laboratory-measured value (Figure 2). In general, the difference is lower for ear muffs than for ear plugs. However, it is difficult to give an absolute rule: even the same HPD may be subject to major differences, depending on the way it is worn and the testing conditions [e].

Most of these studies give different values overall and very few, such as Lenzuni [f], separate the various parameters that may cause the discrepancy, and there are many such parameters. Listing them and arranging them into homogeneous families should provide a better understanding of the problem and should direct analysis towards relevant compensation actions [25]. Some of these parameters are associated with human behaviour: improper wearing of HPDs, insertion of items between the ear and the HPD (hair, spectacles, etc.), bad choice of HPDs with respect to the environment (temperature, humidity) and damaging of the HPD. Nonwearing time has probably not been considered in the studies on this topic, but we need to be mindful that this factor is a major possible cause of the

difference between expected and real exposure. Other parameters are related to the HPD quality itself: the influence of aging on performance loss is known [26], but statistical performance variation due to the device manufacturing process may also have a significant impact [27]. Finally, differences between real-world and laboratory acoustic fields may have a major influence: key discrepancy parameters would be noise level, spectral range and source directivity. As far as laboratory test methodology is concerned, questions could be raised concerning the basis of the test: HPD attenuation is assessed by measuring the difference in subject hearing threshold with and without HPD. The subjectivity of this method may prompt slight differences between subjects.

**9. A NUMBER OF RULES FOR REACHING REAL-WORLD VALUES**

Health and safety organisations have proposed a number of rules to allow for this discrepancy between real-world and laboratory-measured attenuation values. We can divide these rules roughly according to two principal notions.

The first notion, most common in Europe, involves derating the attenuation value measured in a laboratory using the current methodology. The

amount of derating usually depends on the type of HPD, e.g., German derating currently amounts to 9 dB for ear plugs, 5 dB for ear muffs and 3 dB for custom moulded ear plugs [28]. HPD type classification and derating values may vary from one country to another.

The U.S. Occupational Safety and Health Administration recommends derating for certain applications, but since 1997 there has been a method B that is intended to obviate the need for derating [29, 30]. The main difference compared with the conventional method is that the subjects are inexperienced in the use of HPDs and are no longer trained by the tester. In this method, the tester issues the instruction manual for the HPD to the subjects and it is up to them to read and understand it. These tests result in a so-called subject fit (SF) attenuation value. This method is proven and appears to give attenuations closer to real-world ones [31]. U.S. standards have subsequently been transposed into ISO/TS 4869-5:2006 [32]. Some HPD manufacturers now make method-B data available upon request, but none print it on the HPD packaging. The SF method has been used outside the USA for many years (Australia and New Zealand codeveloped a similar method, for some years Brazil has required method-B data on all HPD packaging, and Canada provides it as an option).

The derating method used in Europe has the major advantage of being simple and easy to implement. However, there are certain reservations. Derating can only be considered as an overall compensation embracing all the discrepancy parameters. We may justifiably ask whether combined derating is relevant to such different causes as product quality and worker behaviour. In other respects, the derating value is the same for an entire type of HPDs and this can discredit, e.g., good ear muffs featuring only a slight difference between real-world and laboratory-measured attenuations.

The SF method has the advantage of introducing compensations, which are specific to each HPD. However, this method is mainly dedicated to compensating improper wearing of HPDs. It would seem to be a shame to compensate, *a priori*, what should be corrected

with worker training. In some ways, this process could lead to endorsing nontraining, a worker-related parameter. Simultaneously, a trained worker could even be overprotected, resulting in all the commonly known negative effects.

A different proposed methodology has been developed in other countries. The idea is to use statistical results of conventional tests conducted on trained subjects. Each test provides a certain number of results. In current methodology, the APV of an HPD is calculated by subtracting one standard deviation from the mean of the test results. Statistically, this corresponds to a confidence that 84% of the HPD population will have at least this APV [22]. The proposed methodology involves widening this statistical range, e.g., by subtracting two standard deviations from the mean (which would give a statistical confidence of 98%). This method is used in Portugal [d], France and Italy with different statistical ranges. It ensures compensation specific to each HPD. It does not consider worker training, to the extent that it is applied to values given by tests on trained subjects.

There are various compensation methods and the same method can be implemented in different ways, depending on the country. The aim of achieving a compensated attenuation closer to the real-world value should not preclude the relevance of the method in a global prevention policy [33].

However, all these derating or method-B testing approaches only deal with group data; none of them provide a valid approach for making predictions for individual employees. This approach is addressed through the use of field tests.

## 10. HPD FIELD TESTS

The aim of HPD field tests development is to deal with some of the important aforementioned questions: taking into account the real-world situation and using methods that could be individually implemented to avoid statistical dispersion associated with laboratory methods.

For a given HPD, the uniqueness of the real-world situation, compared with laboratory

conditions, can be due to ambient noise conditions and human usage of the HPD. Ambient noise conditions alone can be analysed using objective methods, e.g., a manikin at a workstand [34]. The parameters taken into account are the sound field itself (level, frequency distribution, time variation) and the position of the HPD in this field (influence of directivity).

Subjective tests are required for considering human reactions and behaviour. Many attempts have been made to adapt the REAT method to portable systems: Berger described a system using circumaural earcups with enclosed earphones [35].

Today's most popular methodologies are designed to adapt the MIRE method, which combines objective measurements and the effect of HPD wearing and fitting. One microphone is placed inside the ear (behind the HPD), another one outside the ear on the HPD itself. A transfer function is used to adjust measurements inside the ear with respect to ear canal influence combined with HPD presence. There have been numerous comparative studies of MIRE and REAT results, at least under laboratory conditions [36]. When used in the field, the MIRE method (called the F-MIRE method, for Field-MIRE) allows us to evaluate real-world HPD attenuation as well as individual real noise exposure [37]. In this process, certain measurement errors and variability of results may be due to different microphone positions inside the ear canal and possible interference between microphone, ear canal and HPD surface. Custom ear plugs have, therefore, been instrumented with double-microphone probes sealed inside them [g]. A specific transfer functions adjusts for the influence of the probe mounting system. This solution offers quick, simple field measurements and has been adapted to foam and premoulded earplugs. Such devices are useful for developing personalised hearing conservation programmes [38].

It may be helpful to distinguish field tests for measuring individual attenuation of HPDs in real-world conditions from field tests to assess real-world noise exposure. In the latter case, noise exposure is then compared to control thresholds. In this situation, the attenuation should be

evaluated for an ambient noise in the vicinity of the worker's ear. Two methods are applicable. The first one involves subtracting the field-measured attenuation from the ambient exposure, whereas the second one uses the noise measured behind the HPD, adjusting it to the ambient noise outside the ear. Whichever method is implemented, it should take into account not only the transfer function for the measurement chain, but also the transfer function between the inner ear (occluded) and the outside of the ear. These transfer functions may give rise to uncertainties, which should be considered in relation to the statistical uncertainty of laboratory results.

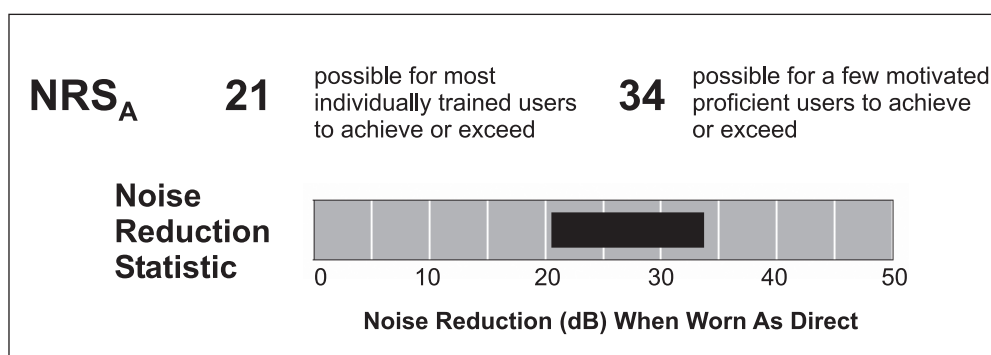
## 11. DEALING WITH INDIVIDUAL VARIATION

Standard No. EN 352 [39] requires marking HPD attenuation on the product or its packaging. This allows the purchaser to acquire information on product performance, which assists in selecting the most suitable HPD for the worker situation. The label attenuation value is derived from laboratory tests. It is quoted for a statistical protection range (supposedly 84%) and does not take into account differences in relation to real-world values. The actual individual attenuation of an HPD can vary widely within a very large statistical range. Two opposing risks emerge from this. In the lowest range of attenuations, workers are not sufficiently protected and they are exposed to risks of noise-induced hearing loss. In the upper range of attenuations, workers may be overprotected, which would increase the risks described in section 5.

This situation has led to development of a new U.S. standard, aimed at evaluating the HPD attenuation statistical range, based on the real-world situation, and labelling the attenuation value such that the purchaser is aware of various possible protection features, depending on the worker situation.

Standard No. ANSI/ASA S12.68-2007 calculates HPD attenuation, which can then be subtracted from the ambient noise exposure [40]. This standard can be applied to any HPD attenuation measurement methodology (i.e.,





**Figure 3. A statistical range of hearing protection device attenuation values corresponding to various worker situations [40].**

trained subject or SF). The method allows us to compute the HPD attenuation statistical range on the basis of the various individual laboratory test results and a set of representative industrial noise spectra. It provides a dual-rated attenuation, which can be subtracted from the overall exposure level measured in dB(A). The attenuation parameter,  $NRS_A$ , is, therefore, used in a simple, educational way [41]. Its values cover a statistical range, whose limits are two extreme user situations described on the product label (Figure 3).

Aspects concerning real-world HPD performance, statistical range of HPD attenuation and field measurement of HPD attenuation are closely related and they provoke debate amongst specialists. A recent international meeting enabled a number of viewpoints to be expressed [h].

## 12. CASE OF IMPULSE NOISE

Standard methods for evaluating HPD attenuation focus specifically on stationary noise signals, i.e., signals varying continuously but with stable statistical characteristics. The same kinds of signals are considered in establishing noise exposure thresholds. Certain populations are exposed to another type of signal, commonly called impulse signals, which are transient in that they are of very short duration (a few milliseconds) and may reach peak levels exceeding 140 dB. In industry, tasks corresponding to impulse noise are those that generate impacts: forging, nail-hammering, etc. Weapons, of course, represent an even more specific case because they are associated with

noise levels up to 190 dB peak. The physical laws governing this type of signal are clearly different to those governing conventional situations. It is hard to imagine assuming linearity for such high discrepancies. On the other hand, impulse noise has various time-signal profiles and its peak factor (ratio peak/root mean square) varies from one to another. This makes it difficult to use methods based on comparing only energy levels. Differences also concern physical acoustics (wave propagation, noise attenuation) and human hearing sensitivity. They are even more obvious when considering conventional attenuation tests of HPDs based on human hearing threshold. That is why several alternative methods have been developed. This topic is highly relevant to the military domain with its extreme impulse conditions. Specific measurement tools and hearing damage criteria have been developed for such conditions [i].

Objective methods are preferred because of the very high noise levels involved. Conventional methods are adapted for cases of impulse noise: special manikins are designed, the MIRE method is implemented on an artificial torso. Artificial fixtures used for HPD quality tests can also be adapted. Specific noise sources are developed to create an impulse noise producing high, repeatable levels. Sources may be shots, explosions, bursts of stretched diaphragms, pressurized gas release, etc. Most of these acoustic sources are spherical and the difficulty is then to approach acoustic plane waves, which can be ensured either by moving away from the source or by using wave drivers, such as tubes.

Whilst these objective methods take into account the physics of impulse noise, they overlook the

specific nature of human hearing behaviour when exposed to this type of noise. HPD fit in real ears, bone and tissue conduction pathways to the inner ear, real transfer function for a human ear canal are all neglected [42]. Physiological objective methods have, therefore, been developed and these are adapted to HPD efficiency tests by taking measurements after an HPD has been worn. One of these methods uses otoacoustic emissions from the human ear. When the ear receives a sound, the outer cells of the inner ear transmit a feedback sound. Measuring this otoemission allows us to qualify the human ear's reaction to noise aggression. HPD efficiency may be assessed by wearing the device and comparing these reactions before and after an impulse noise [43]. Auditory brainstem response is a test which measures brain response to acoustic stimuli (clicks). It illustrates the release of physiological load. The comparison of these responses, with and without hearing protectors, may enable their performance to be evaluated [44].

### 13. RESEARCH PROSPECTS

Most of the issues referred to in this paper have been the subject of research studies. This review allows us to highlight the main aspects, in which progress is required.

There are many parameters influencing the actual efficiency of hearing protectors. The relative weight and crosswise influence of these parameters could be established and this type of parametric study could highlight further research priorities.

HPD performance could be improved by working on the comfort, aging and manufacturing dispersion of these devices. Setting up parameters for qualifying these aspects would further stimulate HPD development. The subjective quality of HPD comfort could be quantified, either with physical tests (force, pressure, uniformity of contact, etc.) or with subjective tests, such as those conducted on consumer goods (cars, household appliances, etc.). Aging can be tested with fatigue tests. Quality tests are currently compulsory for assessing ear muff dispersion: they could be adapted to ear plugs.

Subjective testing of hearing thresholds currently represents a golden standard in terms of HPD attenuation assessment. The possibility of using high-level noise sources, various noise source frequency contents or objective test implementation could be usefully researched. Further development of field tests could produce references for real-world attenuation and could also be used to check proper wearing of HPDs in the field. The confidence range of FAM method-based results could be also studied in detail. Extending the use of physiological tests could provide greater understanding of HPD efficiency.

Research on HPDs frequently overlooks impulse noise, which should be dealt with as a separate issue. Specific impulse-noise HPD attenuation could be developed.

Noise attenuation is not the only parameter that could be taken into account in assessing the acoustic performance of HPDs: audibility, intelligibility and perception of danger signals all play key roles in worker protection and requirements with respect to these factors can still be improved and extended.

Simulation methods are little employed in HPD research compared to other occupational noise topics. Modelling and calculation tools would help greatly in studying physical parameters, such as behaviour of the occluded ear canal, coupling conditions between HPDs and human ear, sound propagation from the HPD vicinity to the ear canal.

### 14. CONCLUSION

The use of hearing protectors is widespread and these devices are considered by employers as a simple, permanently efficient solution for reducing noise exposure. However, employers should be aware of the many issues raised concerning the real-world performance of hearing protectors. Human behaviour is a key factor in HPD efficiency, which cannot be evaluated with a mathematical rule-of-thumb. Progress can be made on more representative assessment of the physical characteristics of HPDs and by considering performance parameters beyond simple noise attenuation. International discussions

and research would enable various efforts and experiences to be combined. At the same time, a minimum international agreement on some points would promote confidence in companies and employers for providing new proposals.

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