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Performance of Different Types of Hearing Protectors Undergoing High-Level Impulse Noise

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The paper describes the problems that may occur when hearing protectors, usually designed for industrial noise environments, are used for high-level impulse (weapon) noise. The military impulse noise environment is described, as are the different types of passive and active hearing protectors and the measurement procedures. The different mechanisms that may alter the effectiveness of the hearing protectors as well as their global efficiency when submitted to high-level impulse noise are presented. The paper also discusses how the performance values accessible to the user may be used in different damage risk criteria for continuous and impulse noise.

hearing protector impulse noise exposure test procedure damage risk criteria insertion loss measurement artificial head acoustic test fixture

1. INTRODUCTION

The current standard in the industrial community for the evaluation of hearing protectors uses the threshold of hearing as a reference. This method, called real ear at threshold (REAT), measures the threshold of hearing with and without a protection device, with the difference defined as sound attenuation or insertion loss (IL).

As no other normalized methods are available, the military community has used the same methods for the evaluation of their protection devices. However, the military noise environment may differ significantly from such found in workshops. Even if in some metal transforming industries impulse noise with peak pressure levels up 150 dB can be observed, the noise of weapon fire can hardly be compared with noise found in the civilian environment. Typical weapon noise may expose soldiers to peak pressure levels from ~150 dB (hand-fired weapons) to as high as 190 dB (antitank weapons). If the performance of a protection device is evaluated at threshold, this means that the found values have to be invariant for an amplitude range of >160 dB (for an amplitude that may vary over a range of 1–10^8 or more, if the most powerful weapons are considered). As it is not reasonable to think that no secondary effects or nonlinearities may be found throughout such a large range, the performance of hearing protectors should not only be evaluated at low levels, but also at levels and for signals that are typical for the military environment. To do this, the evaluation procedures and the associated tools have to be adapted to the high levels to which the devices will be exposed. As each different type of hearing protector may respond in a different way to impulse noise at very high levels, it is important to understand the specificities of the different protection devices.

The performance of hearing protectors has to be taken into account when the legislation for the protection of the exposed personnel is applied. Therefore, it is also important to know if the

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existing criteria for the civilian and the military communities can consider the metrics that are used to describe the performance of hearing protectors.

2. IMPULSE NOISE IN THE MILITARY ENVIRONMENT

An ideal wave created by an explosive would have a pressure time history as shown in Figure 1. This type of wave is usually called a Friedlander wave. It has a very steep initial pressure increase of <10 µs followed by an exponential decay. The time between the last zero-crossing before the maximal peak and the first zero-crossing after is defined as t_0 (*A*-duration). The short initial overpressure phase is followed by a rarefaction (suction) phase. It usually has an amplitude close to one third of the maximal overpressure and tends slowly back to the zero line (ambient pressure). Various factors (ground reflections, reflections on close subjects, etc.) may disturb this ideal signature.

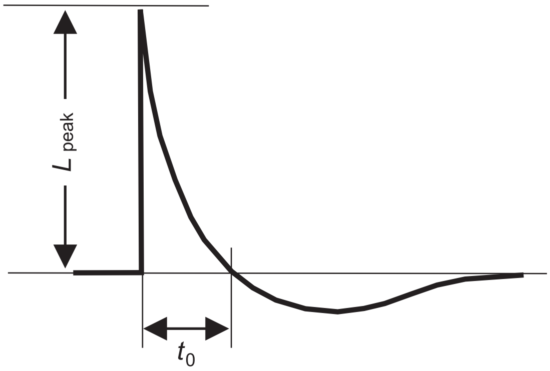

Figure 1. Ideal Friedlander-type pressure wave.
Notes. L_{peak}—peak pressure level, t_0—time stamp.

Figure 2 shows two typical pressure time histories due to the firing of weapons. Curve (a) shows the signature of small arms (e.g., a rifle or a handgun). The maximal pressure of this type of weapon is 150–170 dB with an *A*-duration of the signature of 0.3–0.6 ms. Curve (b) is the pressure time history of a large-calibre weapon (e.g., a howitzer or a mortar). For these large weapons, the maximal pressure may exceed 180 dB and the *A*-duration is in the range of 2–4 ms. Figures 3–4 display the spectral compositions of this type of impulse noise.

We can see in these figures how the spectral composition depends on the pressure time history of the signal. Figure 3 shows that for constant duration and for different amplitudes, only the level of the different components changes but not the envelope of the third-octave analysis. For impulse noise having the same peak pressure but different *A*-durations (Figure 4), the high-frequency components of the spectrum stay the same. However, the low-frequency energy of the spectrum becomes, with growing duration, more dominant. Figures 3–4 show that the spectral distribution of the energy, for shock waves with identical peak pressures, is the same for all frequencies higher than 1 kHz (if we consider realistic weapon noise) and extends towards the lower frequency bands if the duration of the impulse is longer. For waves with a constant duration, a change in amplitude only affects the amplitudes of the different spectral components. The time pressure histories in the two figures confirm that the rarefaction phase of the pressure signals is usually about one third of the maximal overpressure, but its duration may be 2–3 times longer (Figure 2). This component of the wave

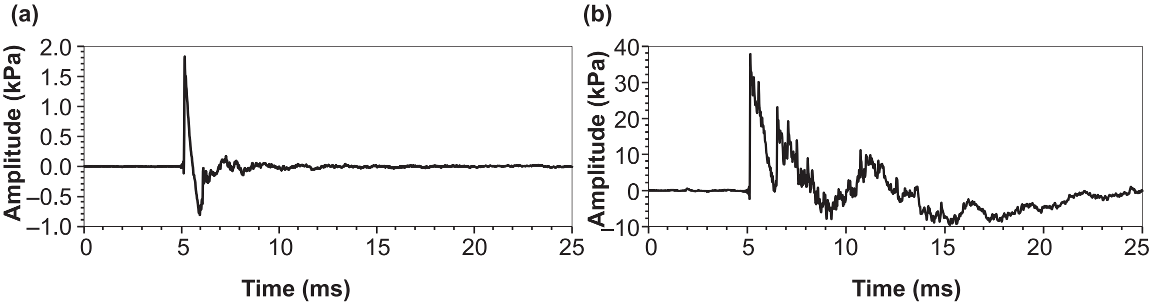

Figure 2. Typical pressure time history of (a) small- and (b) large-caliber weapons.

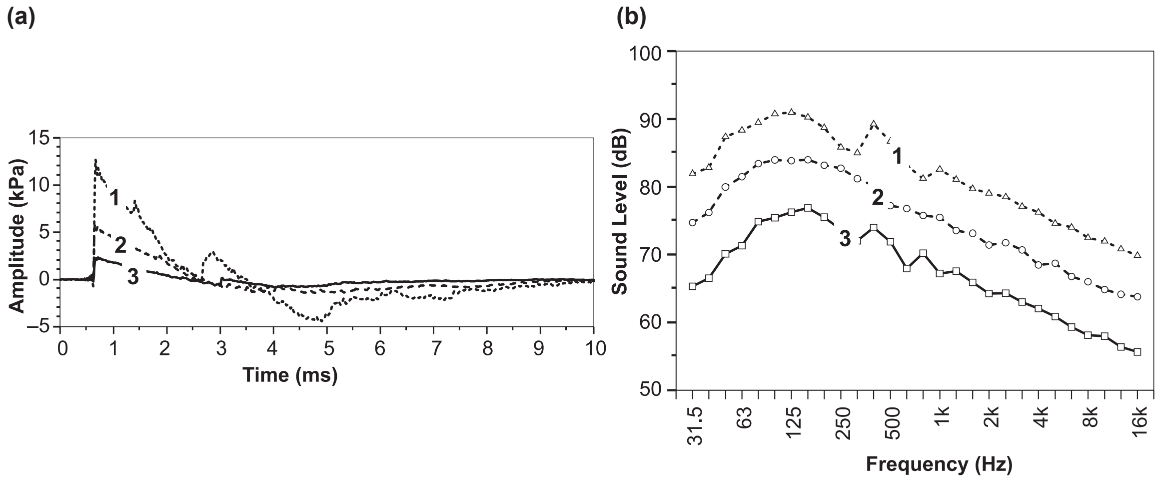

Figure 3. Spectral composition (third-octave analysis) for weapon noise with constant *A*-duration and different peak pressure levels. The numbers in the spectrum (a) relate to the corresponding pressure time history (b).

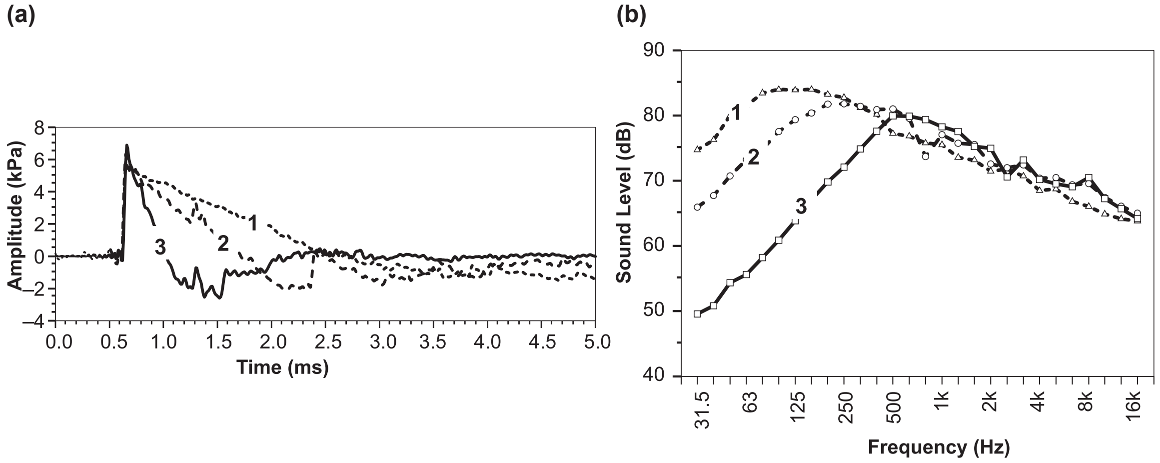

Figure 4. Spectral composition (third-octave analysis) for weapon noise with constant peak pressure level and different *A*-durations. The numbers in the spectrum (a) relate to the corresponding pressure time history (b).

may be very important for the responses of a hearing protector at very high impulse noise levels. As the spectral compositions of the weapon noise varies with the duration of the impulse (Figure 4), the performance of the hearing protectors should also be evaluated as a function of frequency.

3. METHODS FOR EVALUATING HEARING PROTECTION DEVICES IN IMPULSE NOISE

Different standards normalize the evaluation of hearing protectors for use in continuous noise. There are two types of evaluation procedures: subjective methods, in which the subjective response of a human subject is needed to obtain the result; and objective methods, in which the result is obtained with physical noise measurements.

3.1. Subjective Methods

The best known subjective evaluation method for hearing protectors is the REAT method [1]. Its principle consists of measuring the threshold of a subject's hearing in free sound field conditions with and without a hearing protector. The difference of the threshold between the measurement with protected and unprotected ears is defined as the IL. This method is widely used and accepted. However, as the behavior of a hearing protector exposed to a 180 dB peak pressure level impulse noise is not the same as when it is exposed to continuous noise at threshold, the REAT method may not give realistic values for the IL when the hearing protector is used in a military impulse noise environment.

3.2. Objective Methods

Objective methods determine the IL with physical measurements. There are two principal types: the microphone-in-real-ear (MIRE) method [2] and the method using an artificial test fixture (ATF) (an artificial head).

3.2.1. MIRE

The MIRE method consists of measuring the pressure at the entrance of or inside the ear canal of a human subject. The microphone can be placed with appropriate means near the entrance and with the ear canal left open. The advantage of this method is that it preserves the input impedance of the ear canal, which is important for the evaluation of active noise reduction (ANR) devices. Alternatively, it can be fixed on top of an ear plug inserted in the ear canal. As the protection of the subject is assured with the ear plug, this method can be used (to a certain degree) for measurements with high noise levels.

The evaluation of hearing protectors with this method has the advantage of taking into account more accurately the soft tissue surrounding the ear and the morphological differences between subjects. However, the evaluation of ear plugs is not possible with this method. There are also ethical problems related to exposing human subjects to levels that may damage the hearing organ.

3.2.2. ATF

The limitations of use that are found with the MIRE method are not applicable when an ATF is used. The artificial heads are equipped with ear simulators that are designed to represent the acoustic impedance of the human ear drum at the place of the microphone. So, it is possible to measure the signal present at the ear drum when the ear canal is closed with an ear plug. Therefore, ATFs allow open ear measurements and the evaluation of ear plugs up to the physical limits of the transducers. Moreover, as the ear simulator reproduces the acoustic impedance at the drum comparable to human data, ANR headsets can be tested. However, when an ATF is used for evaluating hearing protectors, the artificial head has to be suitable for those tests. Therefore, it is important that the acoustic insulation, when the outer ear canal is acoustically sealed (e.g., with a metallic ear plug), be better than the attenuation of the hearing protector

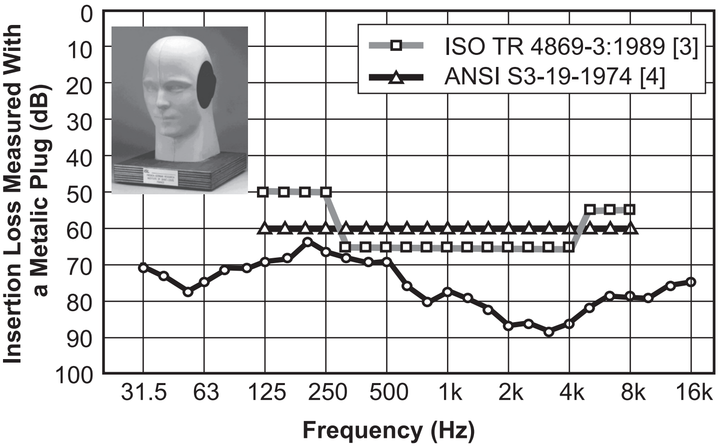

Figure 5. Self-isolation of the artificial test fixture developed at the French-German Research Institute of Saint-Louis (ISL) compared with the American National Standards Institute (ANSI) and International Organization for Standardization (ISO) minimum requirements.

tested. Specifications to comply with these requirements are given in Standards No. ISO TR 4869-3:1989 [3] and No. ANSI S3-19:1974 [4]. As many of the commercially available devices do not comply, an ATF fulfilling these requirements has been developed at the French-German Research Institute of Saint-Louis (ISL) [5]. The acoustic insulation (Figure 5) is >60 dB for all frequencies; therefore, it complies with the requirements of the International Organization for Standardization (ISO) and the American National Standards Institute (ANSI).

To obtain the IL of a hearing protector, the procedure is the same as already described for the MIRE method: two measurements are made, one with and one without the hearing protector. The difference between these measurements is the IL.

3.3. Generation of Impulse Noise

As it is practically impossible to generate impulse noise with a maximum level of 190 dB with loudspeakers or other electrical devices, there are two possibilities: shots with real ammunition and detonation of explosives.

As real shots are very expensive and involve many people, we used explosive charges (C4 or primers) of different weight, placed at different distances from the artificial head. This technique allowed us to obtain well-defined acoustic waves in the free field with peak pressure levels of 130–190 dB with *A*-durations of 0.4–2 ms, which represented most signals generated by weapons.

Figure 6 shows how the artificial head and the free field microphone were situated. The distance from the explosive charge varied depending on the requirements (signal duration and peak level).

4. HEARING PROTECTORS EXPOSED TO HIGH-LEVEL IMPULSE NOISE

There are two basic types of hearing protectors: ear muffs, which insulate the ear from outside noise with a barrier shell sealed with a circumaural seal of elastic material to the head; and ear plugs, in which the insulation is realized by occluding the external ear canal with soft, acoustically insulating material. Depending on the noise and the tasks of the wearer of the protection device, different types have been derived from these basic approaches.

4.1. Ear Muffs

The noise insulation of an ear muff is mainly determined by the following variables:

- mass of the shell + seal + effective part of the head band;
- characteristics of the seal material (density, stiffness, damping, etc.);
- characteristics of the shell material (density, stiffness, damping, etc.);
- residual volume underneath the shell and acoustic damping inside this volume;
- overall damping of the system, including head band, seal, and shell.

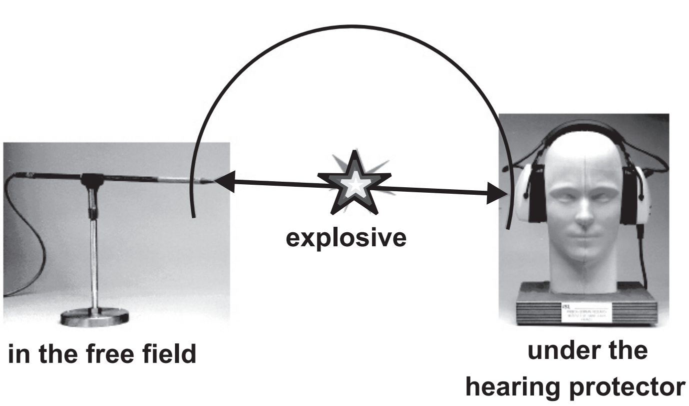

Figure 6. Setup for the evaluation of hearing protectors using high-level impulse noise.

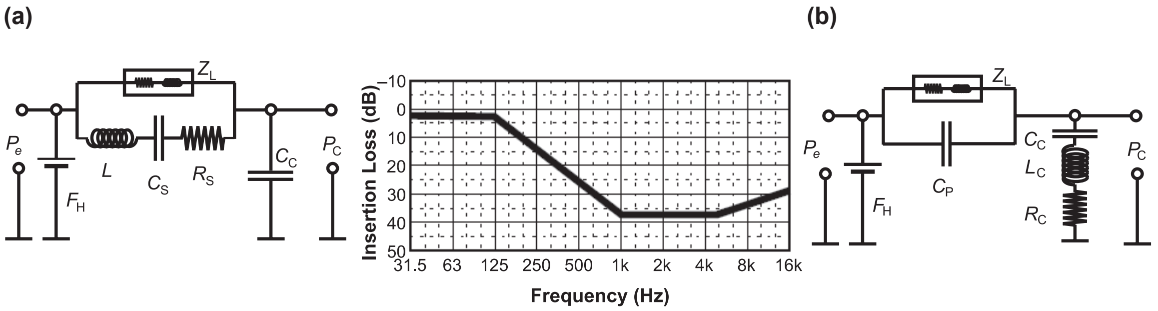

Figure 7. Typical insertion loss of an ear muff and the associated very simplified electrical equivalents for (a) low and (b) medium frequencies. *Notes.* P_e—pressure in free field, P_C—pressure underneath the muff, L—equivalent mass of one ear cup, L_C—compliance of the air in the volume, R_S—resistance (damping) of the seal, F_H—application force of the head band, R_C—resistance (damping) in the volume, C_S—compliance of the seal, C_C—compliance of the air volume underneath the cup, C_P—compliance of the shell material, Z_L—impedance of the leakage in the seal.

The graph in Figure 7 shows a typical curve of the IL of an ear muff. This curve can be split into two frequency regions, where the different physical parameters of the ear muff govern the behavior. Figure 7a represents a simplified electrical equivalent of an ear muff at low frequencies ($f < 1000$ Hz). It shows that in this frequency rage the predominant parameter is the volume (air compliance underneath the cup, C_C) if the mass (L), the impedance of the leakage in the seal (Z_L), and the compliance of the seal (C_S) are kept constant. The transient phase (or the cut-off frequency of the low pass filter) is mainly determined by L and C_S. The IL for higher frequencies (1–4 kHz) may be modelled following Figure 7b. It shows that the attenuation will mainly depend on the material constants of the cup (C_P) and on its volume.

However, this is only true as long as the different parameters may be considered constant, and as long as the force of the head band holding the cup can be considered much bigger than the suction force of the rarefaction phase of the shock wave. For pressure levels where this is not true (peak pressure level >150 dB), the ear muff cannot be considered to behave linearly anymore.

Figure 8a illustrates the normalized pressure time history underneath an ear muff. With increasing peak pressure of the shock wave, the normalized positive peak pressure decreases and the negative peak pressure increases. Due to this increase in normalized peak-to-peak amplitude, the IL of the hearing protector decreases (Figure 8b). This shows that for these pressures of the shock wave, the models in Figure 7 cannot be used anymore.

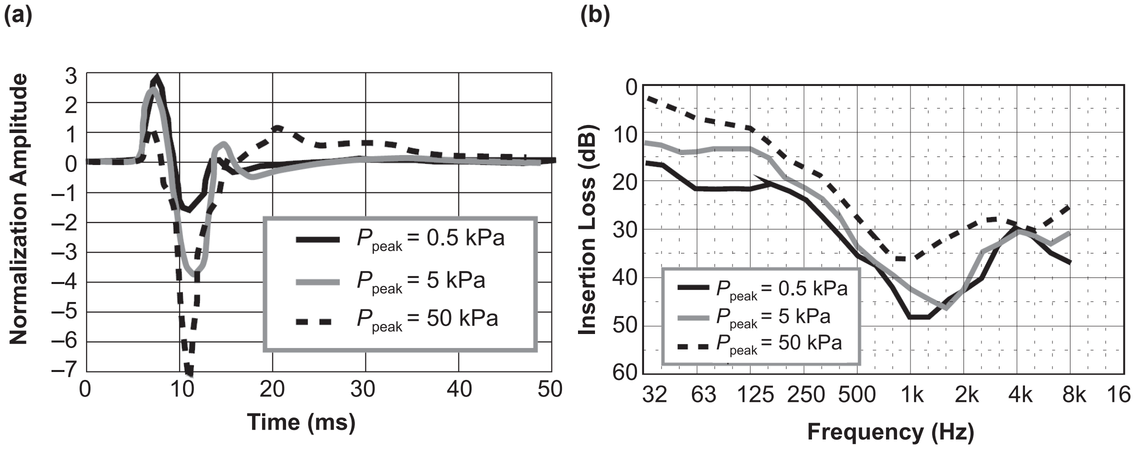

Figure 8. (a) Pressure time history (amplitude is normalized relative to the peak pressure of the shock wave in the free sound field) of the signal underneath the hearing protector and (b) the insertion loss for shock waves with different peak pressure levels. *Notes.* P_{peak}—peak pressure.

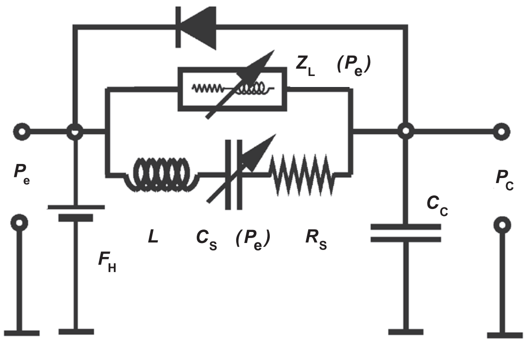

Figure 9. Very simplified electrical equivalent of an ear muff adapted high-level exposure. *Notes.* P_e—pressure in free field, P_C—pressure underneath the muff, L—equivalent mass of one ear cup, R_S—resistance (damping) of the seal, F_H—application force of the head band, C_S—compliance of the seal, C_C—compliance of the air volume underneath the cup, Z_L—impedance of the leakage in the seal.

Figure 10. Ear muff on an artificial head exposed to a shock wave with a 190 dB peak pressure level.

For these cases an adapted model can be used (Figure 9). In this model the impedance of the leak, $Z_L(P_e)$, is a function of the pressure as well as the compliance of the seal, $C_S(P_e)$. The force of the headband is introduced as a battery (offset potential, F_H, in Figure 9). The diode is introduced for the case that the negative pressure (rarefaction phase) becomes stronger than the application force of the headband. In this case, the cup will no longer be coupled to the head and there will be a short circuit, via the diode, between the free sound field and the volume underneath the cup. Figure 10 shows how an ear muff may get lifted off the head when it is exposed to high-level shock waves.

4.1.1. ANR ear muffs

Ear muffs equipped with ANR systems are usually designed to improve the attenuation in the low-frequency range. Using this principle (Figure 11), hearing protectors with lower volume and weight can be developed. However, as the

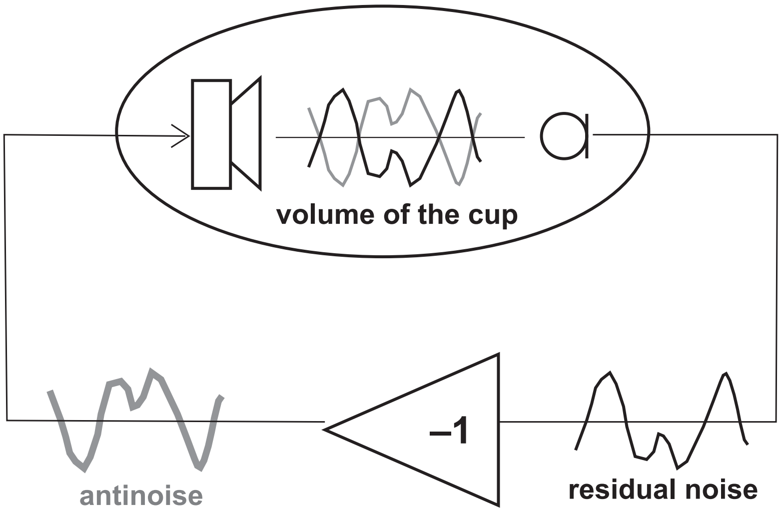

Figure 11. Simplified principle of active noise reduction.

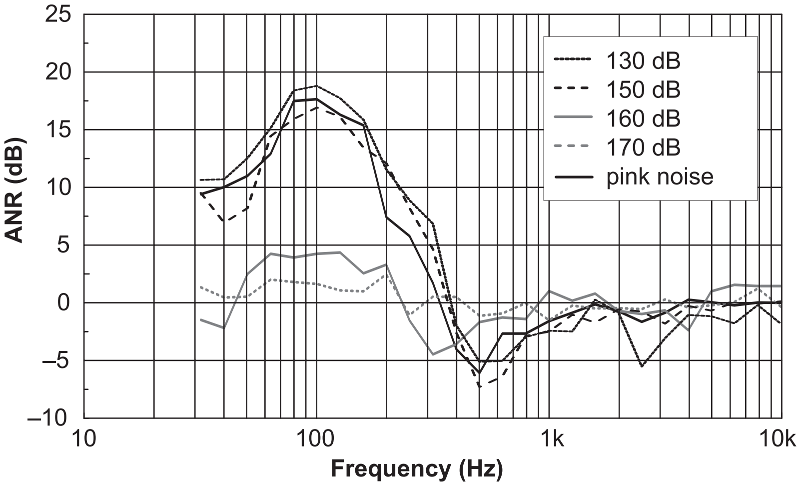

Figure 12. Contribution of active noise reduction (ANR) when exposed to impulse noise of different peak pressure levels.

loudspeakers which produce the antinoise in the cavity underneath the ear muff can only produce a limited sound pressure level, the effectiveness decreases when the peak pressure levels increase. Figure 12 shows that the contribution of the ANR is the same as for pink noise, if the peak pressure level does not exceed 150 dB. For levels higher than that, this contribution collapses. ANR systems, therefore, must be considered as passive hearing protectors when used for weapon noise exposure. However, the stability of the electronic systems when driven into overload has to be ensured.

4.1.2. Level-dependant (noise restoring) hearing protectors

Talk-through hearing protectors have been designed for working places that require verbal communication. In this type of device the external sound is captured with a microphone and fed into the cavity of the hearing protector. To avoid hearing damage due to excessive noise these systems have an amplitude limitation in the amplifier of the receiver (loudspeaker) inside the cavity. Therefore, this type of protector may be considered as a passive ear muff for levels that exceed the limitation of an electronic system. For levels lower than the limitation level it may be considered as transparent.

4.2. Ear Plugs

The noise insulation of an ear plug is mainly determined by the following variables:

- mass of the ear plug;
- characteristics of the ear plug material (density, stiffness, damping, etc.);
- interface between the ear plug and the ear canal (shear stiffness);
- residual volume under the ear plug and its acoustic damping.

Figure 13a illustrates the typical attenuation of an ear plug. For a properly fitted ear plug, the attenuation at low frequencies is already very good. However, if the ear plug is not fitted well in the ear, the IL in the low-frequency range will be degraded (dashed line). These effects become understandable, if we look at the simplified electrical equivalent in Figure 13b. Although the electrical equivalent is the same as that of an ear muff, the values of the different components are largely different and affect the behavior. Especially, as the compliance of the residual volume (C_C) is very small, any leakage will affect the low-frequency behavior very strongly as shown in Figure 13b (the difference between a well- and a badly-fitted ear plug). Unlike ear muffs, ear plugs behave almost linearly through the whole range of levels of weapon noise (Figure 14a).

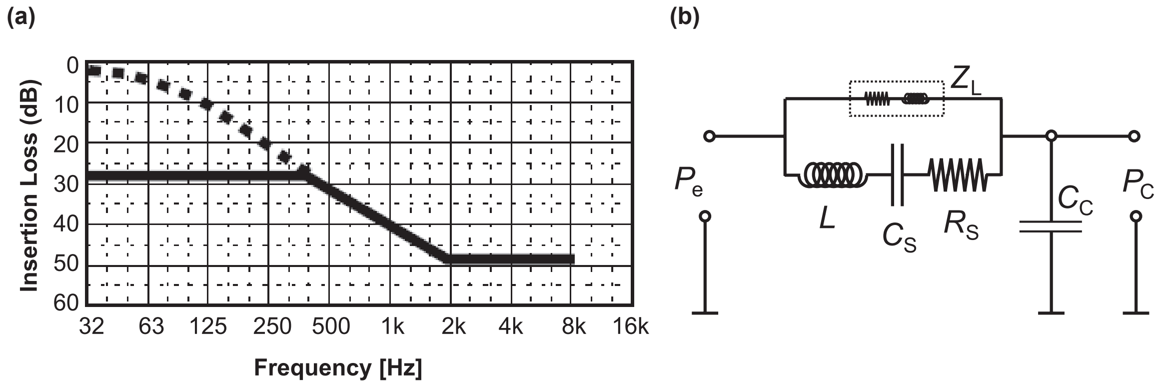

Figure 13. Typical attenuation of (a) an ear plug and (b) a very simplified electrical equivalent. *Notes.* solid line—well-fitted ear plug, dashed line—badly fitted ear plug (leakage); P_{e}—pressure in free field, P_{C}—pressure underneath the muff, L—equivalent mass of one ear cup, C_{S}—compliance of the seal, R_{S}—resistance (damping) of the seal, C_{C}—compliance of the air volume underneath the cup, Z_{L}—impedance of the leakage in the seal.

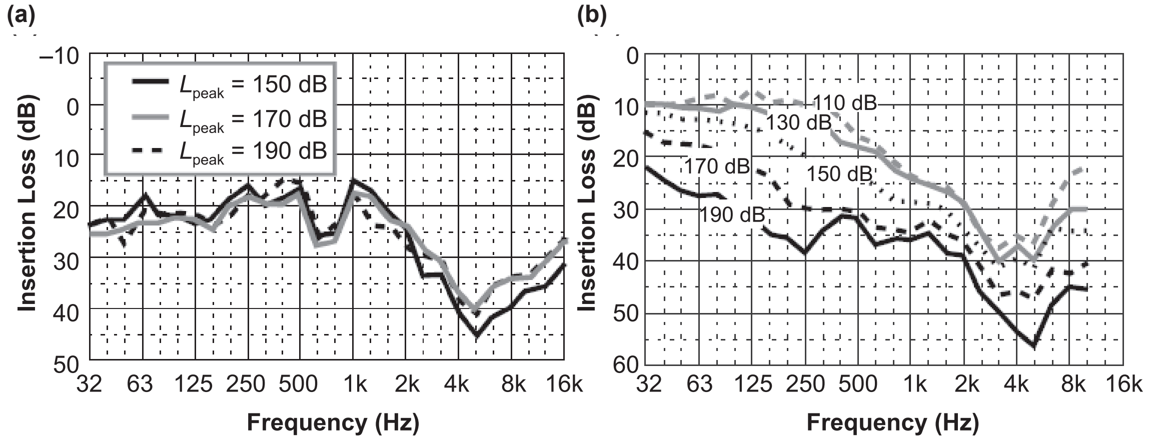

Figure 14. Insertion loss of (a) a linear and (b) a nonlinear ear plug for exposure at different peak pressure levels. *Notes.* L_{peak}—peak pressure level.

For many tasks and environments within the military community it is often very important that the soldiers be able to communicate directly (mouth to ear), to hear and to interpret the acoustic environment. However, the soldiers also have to be protected against weapon noise.

In those cases, nonlinear ear plugs are a good choice. This type of protector only protects against high-level noise and allows almost unaltered hearing in moderate sound fields. The main principle is based on the nonlinear acoustic behavior of small orifices [6]. The acoustic resistance of such an orifice is a function of the gas flow and it grows with increasing flow. So, for small amplitudes of the noise, the orifice is acoustically almost transparent, whereas for high-level impulses, it becomes almost acoustically blocked. Figure 14b shows the nonlinearity of this protection device. For signals with a peak pressure level of 110 dB, IL ≤ 30 dB for any frequency. For spectral components <500 Hz the nonlinear ear plug is practically transparent (well-fitted standard ear plugs have an attenuation of 30 dB in this frequency range). For impulse noise with peak pressure levels rising from 130 to 190 dB the attenuation increases gradually over the whole frequency range. Finally at the peak pressure level of 190 dB, the attenuation is almost the same as that of a good linear ear plug. The reduction of the peak pressure level (NR) from the free field to the microphone of the artificial head follows the same scheme. At a peak pressure level of 110 dB, $NR = 8$ dB, and it reaches 25 dB for a peak pressure level of 190 dB.

5. CONSIDERATION OF THE PERFORMANCE OF HEARING PROTECTORS IN HEARING PROTECTION REGULATIONS

The evaluation of the performance of hearing protectors for impulse noise measured with an artificial head usually shows sound attenuation that is comparable to the sound attenuation measured with REAT, as long as the behavior of the hearing protection device (HPD) is linear (<160 dB_{peak} for ear muffs; <180 dB_{peak} for ear plugs). However, these data are not available to the user of hearing protectors. Therefore, the question arises if the metrics available to the user are suitable to be used with the noise exposure criteria for different types of noise.

5.1. Continuous Noise Exposure

For continuous noise, different countries implement different noise exposure limits. All these criteria have one thing in common: they are based on the *A*-weighted energy of the noise to which the worker is exposed. When a person exposed to noise has to wear an HPD, the performance of this device is taken into account in calculating the noise exposure level. Different countries use different metrics: noise reduction rating (NRR); single number rating (SNR); and high, middle, low (HML) [7]. A common feature of all these metrics is that they are based on the performance of the HPD, measured with the REAT method. As in the case of industrial noise exposure where the functionality of the HPD (ear muff or ear plug) may be considered linear, this method is fully adequate. In some military noise environment, e.g., with ground crews close to the jet engines of fighter aircraft, the linear range of the HPD may be exceeded. In these cases, however, the performance of single hearing protection is not sufficient. Double (ear muff + ear plug) or even triple hearing protection (ear muff + ear plug + helmet) has to be considered.

5.2. Impulse Noise Exposure

In the armed forces of different countries, special damage risk criteria (DRC) are used to avoid hearing damage when soldiers are exposed to weapon noise. These impulse-noise DRC proposed or used in different countries can be divided into four categories, each category being based on a different basic principle.

- ***Criteria based on the peak pressure level and action time***

The U.S. CHABA [8], German Pfander [9], and Dutch Smoorenburg [11] criteria are representative for this type of criteria. Figure 15 illustrates the calculation schemes for *A*-, *B*-, *C*-, and *D*-durations used by the different DRC. To compare the different DRC, the durations are normalized to the *D*-duration (τ_{-10}), i.e., the time during which the envelope of the signal is above a line drawn 10 dB below the peak of the signal. The chart shows the exposure limits for the different criteria. The peak pressure level of the impulse and the duration (if more shots are to be considered, the time of one shot is multiplied by the number of shots) are to be plotted on the chart. If the point is below the limiting line, the exposure is acceptable; if it is above, the exposure is prohibited.

In these criteria, hearing protection is taken into account by a shift of the limiting line towards higher levels. In Standard No. MIL-STD-1474D (CHABA), a fixed number (29 dB) is used for all approved hearing protectors [8]. The German Armed Forces (Pfander) use the average IL at medium and high frequencies [9]. A simple shift of the limit towards higher levels implies that all spectral components of the signal are attenuated by the same amount when a hearing protector is worn. This means only the amplitude of the signal is modified and not its duration. However, the use of a hearing protector modifies the duration and the amplitude of the pressure signal. Therefore, the simple shift does not reflect fully the measured performance of hearing protectors. It is, however, the only practical way to take the performance of HPDs into account for this type of DRC.

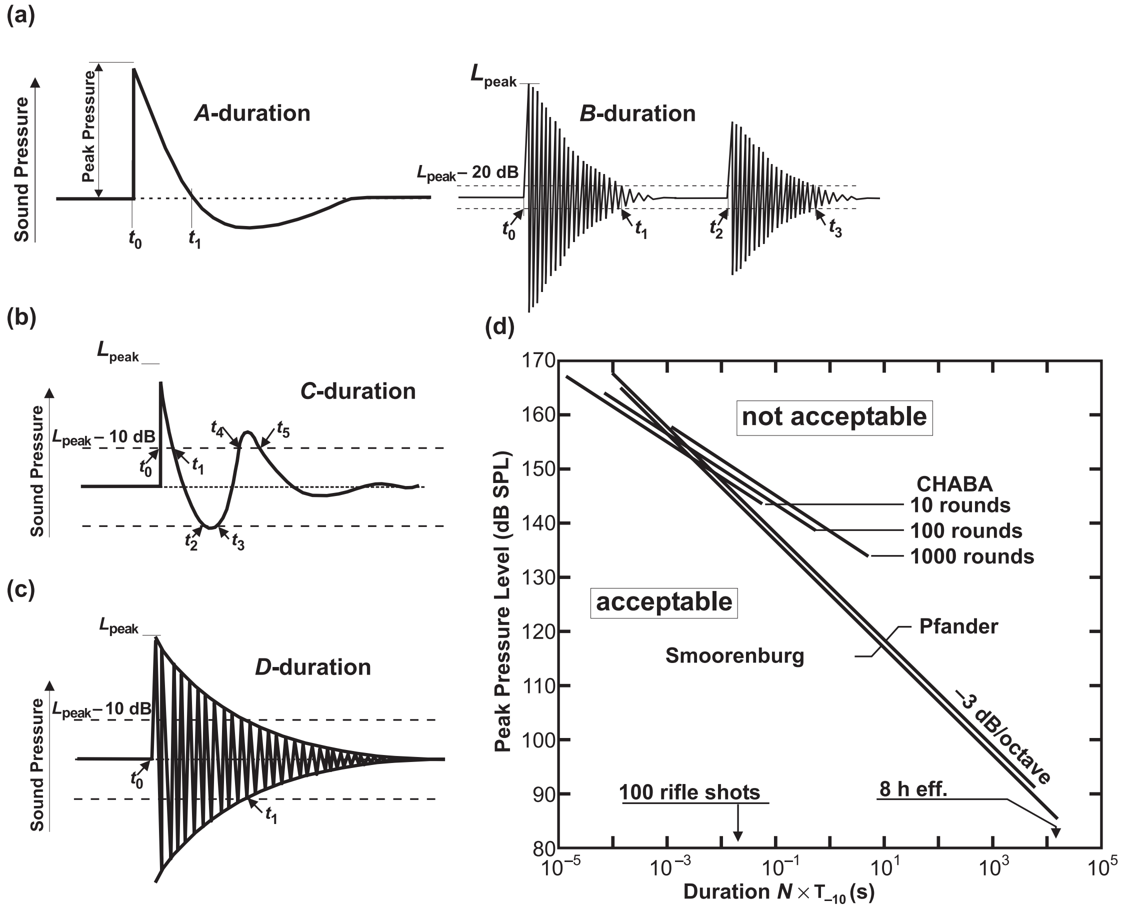

Figure 15. Calculation methods for the different exposure durations for impulse noise: (a) CHABA [8], (b) Pfander [9] and (c) Smoorenburg [11] damage risk criteria; and (d) a chart for graphic determination of the auditory damage risk of those criteria. *Notes.* L_{peak}—peak pressure level; SPL—sound pressure level, eff.—effective; τ_{-10}—time during which the envelope of the signal is above a line drawn 10 dB below the peak of the signal; A-duration = $t_1 - t_0$; B-duration = $(t_1 - t_0) + (t_3 - t_2)$; C-duration = $(t_1 - t_0) + (t_3 - t_2) + (t_5 - t_4)$; D-duration= $t_1 - t_0$, where t_0, t_1, t_2, t_3, t_4, t_5—timestamps.

- ***Criteria based on the noise dose (L_{EX}) delivered by impulse noise***

Atherley and Martin [10] and Dancer [11] proposed to evaluate weapon noise in the same way as continuous noise (comparable to Standard No. ISO/R 1999 1971(E) [12]), i.e., to determine an A-weighted equivalent noise level for 8 h ($L_{AEX,8h}$) for every round. The maximum daily exposure is reached for $L_{AEX,8h}$ of 85 dB(A). The advantage of this proposal is that it fits perfectly into the noise protection standards for continuous noise (Standard No. ISO/R 1999 1971(E) [12], National Institute of Occupational Safety and Health [7], etc.) and, therefore, allows assessment of the combined risk of continuous and impulsive noise. In this case, the performance of the hearing protector is taken into account in the same way as it is for continuous noise.

- ***Criteria based on the pressure time history of impulse noise***

Price and Kalb developed the auditory hazard assessment algorithm for the human, which takes into account the whole transmission line of the signal from the free sound field to the cochlear structures [13]. Auditory hazard units (AHUs) are calculated on the basis of the computed time history of the displacement of the basilar membrane (mechanical stress, elongation, number of cycles, etc.). The number of AHUs then determines the auditory hazard of the single shot. If more shots are present, the AHUs are simply added.

The use of this type of DRC is only valid if the pressure time history of the impulse is precisely known. As the use of an HPD inserts an additional transfer function, this function also has to be known precisely. J. Kalb (personal communication) and Młyński and Żera [14] have attempted to determine the impulse response of HPDs, but none of the methods were conclusive. Therefore, it is not clear how the HPD performance may be included with sufficient precision.

- ***Directive 2003/10/EU***

  The exposure limit in Directive 2003/10/EU [15] is defined using one single parameter, the peak pressure level underneath the hearing protection. It does not, however, mention how this parameter should be determined when HPDs are used. As the peak pressure of an impulse noise depends on its spectral composition, only algorithms using the frequency dependency of the IL should be applied. Single number metrics like NRR or SNR cannot be used for this purpose, because they do not include frequency related information. Appendix B of Standard No. EN 458:2004 describes a method for determining the peak pressure level of the signal underneath the HPD [16].

Finally, we should note that only DRC based on the A-weighted L_{EX} are suitable for using the HPD performance indices based on REAT measurements (NRR, SNR, HML), as long as the levels are in the linear range of the hearing protector. The other DRC only allow an approximate evaluation of the risk. If the exposure levels are higher than the linear range of the HPD, no exact response can be given, and degraded indices should be used. However, there are no studies which could, at this time, support a given number for this degradation. If nonlinear hearing protectors are used, only the use of the IL data related to the peak pressure level of the noise exposure can be used (Figure 14b).

6. CONCLUSIONS

The acoustic environment of the soldier is very different from the noise that is usually found in industry. However, standards and measurement procedures are made for the civilian environment. When using only these methods, some of the specificities of the military environment may not be taken into account. Therefore, the hearing protectors should be evaluated with signals and in an environment to which soldiers are exposed.

The testing of different types of hearing protectors with high-level impulse noise has shown that the attenuation is not constant over the whole range of levels. Especially ear muffs are very dependent on certain design features. Some very effective features for low levels or continuous noise (e.g., low application force combined with seals made with materials with strong damping) may impede the protection at high levels. We have seen that the IL may decrease by as much as 15 dB for the highest levels compared to the lowest level.

If new types of hearing protectors like ANR systems or talk-through protectors are evaluated, there is not only the IL to be looked at, but also the behavior of the electronics which can be driven into saturation. ANR systems are well able to add extra attenuation to impulse noise at low levels; at high levels, however, they behave like passive ear muffs.

If no electronic communication requirements are needed, ear plugs may be the best choice to assure protection against very high levels of impulse noise. Standard ear plugs can almost be considered as linear protectors for the complete range of levels, as their characteristics change only very little. However, it is always necessary to have them inserted properly in the ear canal. If they are not, the protection capabilities degrade. If verbal communication and acoustic awareness of the surrounding area are important, the most effective way to protect soldiers is for them to use nonlinear ear plugs. These devices are the only protecting devices which have a better IL for higher levels. They always give the needed protection against exposure to weapon noise, but allow perception of the acoustic environment. As these protectors are designed to attenuate impulses only, they are not suitable against continuous noise. As the attenuation of these devices depends on the peak pressure level of the noise, they have to be evaluated with impulse noise at different levels. If these devices are evaluated with present standardized methods, the results will not reflect their real protection capability in impulse noise environments. The protection capability of any type of hearing protector is, to some extent, dependent on the type of signal to which it is exposed. It is, therefore, important to evaluate HPDs with signals they will be used for and not with signals that have no relevance.

As far as the use of the performance values in different types of DRC is concerned, it should be noted that IL data, collected with artificial heads and high-level impulse noise, are usually not available. Therefore, the user depends on performance values derived from REAT measurements. Moreover, only DRC based on the A-weighted L_{EX} are well-suited for use with the performance values based on the REAT measurements (NRR, SNR, HML), as long as the levels are in the linear range of the hearing protector. The other DRC (CHABA [8], Pfander [9], etc.) only allow an approximate evaluation of the risk when hearing protectors are used. If the exposure levels are higher than the linear range of the HPD, no exact response can be given. Degraded performance values should then be used. However, there are presently not enough studies which could support a given number for this degradation. If nonlinear hearing protectors are used, only the use of the IL data related to the peak pressure level of the noise exposure can be used (Figure 14b), and these data are usually not available to the user.

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