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Firearms and Noise: Risk Quantification for Soldiers

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Abstract:

Professional soldiers are often exposed to the risk of excessive noise during their work. The most common environment in which a soldier is exposed to excessive noise is regular shooter training. Excessive noise can lead to sudden acoustic trauma or barotrauma with perforation of the eardrum, and chronic hearing damage can occur with repeated exposure to noisy environments. Other complaints, such as tinnitus, can accompany these conditions. It is, therefore, important to prevent such damage and use hearing protection (such as earplugs or earmuffs) as these play an important role in preventing hearing damage. However, any aid is only as effective as its proper use. This article describes the risk of hearing damage when firing firearms.

Keywords:

noise, firearms, hearing protection

1 Introduction

Normally, it is necessary to protect oneself from noise because, without protection from excessive noise, health can be damaged. To ensure adequate noise protection, we need to know what noise the soldiers are exposed to. Noise can be considered as any unwanted sound, whether disturbing, annoying or harmful. In a military environment, it is most commonly caused by small arms fire. Noise is not only annoying to the body but can also have negative effects on the cardiovascular system [1], impair cognitive abilities, disrupt sleep [2, 3] and negatively affect the auditory system itself [4].

Several types of noise can be distinguished, but impulse noise is the typical noise of shooting. Impulse noise is a short-duration acoustic signal with a high intensity and a rapid rise and fall in sound level. The permissible exposure limits for impulse noise

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are set out in Government Regulation No. 272/2011 Coll. on the protection of health from the harmful effects of noise and vibration [5]. Specifically, the permissible exposure limits for impulse noise are set at 85 dB for the equivalent sound pressure level ($L_{Aeq,8h}$) and 140 dB for the peak sound pressure level (L_{Cpeak}). This means that it is necessary to protect users so that they are not exposed to noise levels that exceed these limits. The exposure limit values are associated with a categorization of work according to the degree of risk of noise exposure. This procedure makes it possible to determine the hazardousness of an activity and provides the basis for its assessment. The work is divided into four categories based on the risk of hearing damage to human health (Tab. 1).

Tab. 1 Categorization of work based on noise pollution according to Ordinance No. 432/2003 Coll., which sets out the conditions for categorizing work [6, 7]

Category	**Equivalent sound pressure level** $L_{Aeq,8h}$ [dB]	**Peak sound pressure level** L_{Cpeak} [dB]	**Recommendations for protection**
1	< 80.0	< 130.0	Safe, no special protection needed.
2	80.0-84.9	130.0-139.9	Availability of personal protective equipment (PPE).
3	85.0-104.9	140.0-149.9	Mandatory use of PPE.
4	> 104.9	> 150.0	Consistent hearing protection using PPE, high risk of damage to health.

Hearing is one of the five human senses and plays an important role in interpersonal communication. It is also essential for perceiving warning signals from the environment and helps us with spatial orientation. Impaired hearing can significantly reduce quality of life and can become a life-threatening complication in certain professions, such as of professional soldiers. It is, therefore, vital that protective equipment not only protects hearing but also ensures smooth communication and clear understanding of commands and signals.

Poor understanding can compromise the unit's mission and increase the likelihood of an accident. Sound is often the first source of information (in foggy environments, first hearing of the enemy/own unit is more common than visual contact). In contrast to visual signals, the information transmitted by sound comes from all directions, through darkness or obstacles. The ability to hear and recognize sounds is essential for combat and situational awareness in the tactical environment. Noise-induced hearing loss is a tactical hazard and impairs individual and unit effectiveness in combat [4].

Noise-induced hearing loss usually occurs at high frequencies, especially in the 4-6 kHz range. As speech sounds that give meaning to words (e.g. consonants such as /tʃ/, /t/, /ʃ/, /f/ and /p/) are also high frequency, as are sounds that allow the features of weapons and vehicles to be identified, hearing damage at these frequencies is particularly threatening to military operations. In a tense combat environment, many words can be difficult to understand – especially if hearing loss is present. At the same time, English is used in an international environment and correct understanding of individual words such as breach and break – engage and retreat, cease fire – continue firing, stay down – go around or right car – white car can be more difficult to recognize [4].

The most common gunshot injury is acoustic trauma, which is caused by a sudden, extremely loud noise [8]. This type of trauma can lead to temporary or permanent hearing damage, ear pain or tinnitus. Acoustic trauma can also be caused by explosions, loud music or other loud noises. In the case of high sound pressure, barotrauma can occur. Hearing damage can be transductive (barotrauma – damage to the eardrum), perceptive (acoustic trauma – damage to the inner ear) or mixed (damage to both the transductive and perceptive components). Repeated exposure to excessive noise can lead to chronic noise-induced hearing loss, which can be recognized as an occupational disease under certain conditions. Even when soldiers wear personal protective equipment (PPE), acoustic trauma can be caused by the wrong choice of hearing protection, its incorrect use or poor combination with other protective equipment (e.g. eye protection, ballistic protection).

There are a number of factors that contribute to the severity of hearing impairment, such as the type and duration of exposure, personal predisposition and associated medical conditions, the characteristics of the ear system, the condition of the middle ear, the use of protective equipment and the acoustics of the ear canal itself [9, 10].

In the list of occupational diseases, hearing loss is defined as noise-induced hearing loss of the cochlea. According to Government Regulation No. 290/1995 Coll., Chapter II [11], which sets out the list of occupational diseases, the following criteria must be met for work with excessive noise exposure: *"The equivalent noise level during a shift exceeds 85 dB (A), or the peak level of frequency-unweighted sound pressure exceeds 200 Pa, and a certain degree of severity of the disease: For persons under 30 years of age, this is a complete hearing loss that reaches the Fowler threshold of 40 %. For people older than 30, the threshold increases by 1 % for every 2 years of age. For people over 50 years of age, this is a total hearing loss that reaches 50 % of the Fowler threshold"* [11, 12].

For these reasons, it is essential to protect your hearing with suitable PPE – hearing protection. The properties and overall attenuation of hearing protectors are assessed according to their ability to reduce noise levels. A key indicator for the assessment is the so-called SNR (Single Number Rating), which is a single numerical rating in decibels [dB]. The SNR indicates the average value by which the hearing protector can reduce the ambient noise level. This value is calculated based on the attenuation provided by the hearing protector at each frequency [13]. The SNR is actually the value that is subtracted from the measured C-weighted sound pressure to estimate the effective A-weighted sound pressure in the ear [13].

In the USA, you will find the NRR (Noise Reduction Rating) which is expressed in decibels, and like SNR, a higher value means better noise reduction. There is no direct conversion between NRR and SNR, so sometimes both values are given. NRR is measured according to the standards of the American National Standards Institute (ANSI), a similar body to the Office for Technical Standardization, Metrology and State Testing, which issues the CSN standards. In our context, the SNR value is important to us because it is defined by the relevant standards for the selection of protective equipment. Therefore, the NRR value is not used here and is not sufficient for evaluating the effectiveness of protective equipment.

The literature shows that neither SNR nor NRR standards are best suited for the measurement of impulse noise. Therefore, new methods are being developed, such as the Noise Reduction Statistic for Use with A weighting (NRSA) [14] or Impulsive Peak Insertion Loss (IPIL) [15, 16]. Various proposals for methods of selecting protective equipment to protect soldiers primarily from impulsive noise are being discussed in the scientific community [17].

The selection of appropriate hearing protection in a military environment should particularly take into account the prevalence of impulse noise with energy overlap in the higher frequencies and the variability of the mission, with the varying need to attenuate extremely high pressures encountered during shooting and the ability to hear the environment to obtain additional information through hearing [4, 18]. Shooting training is no different in this respect, although the demands on the shooter are not as extreme as in combat operations. In our country, current documents allow the use of SNR values (the most commonly used), the HML method (which is based on eight reference spectra with different values (Lp,C-Lp,A)) and the octave band method (this method requires sound pressure levels in octave bands and assumed APVfx attenuation values) in the selection of protective equipment [13, 19]. The selection of protective equipment should ideally reflect a 1/3 octave noise spectrum [14-16, 20, 21]. The aim of this article is to describe the risk of hearing damage when firing firearms.

2 Methodology

Normally, for the evaluation of impulse noise, field measurements were carried out with long handguns, which are the usual armament of most professional soldiers. The measurements were carried out at the Brezina military training area on the infantry firing range on two days, August 2nd and 3rd, 2023.

The first measurement on August 2nd, 2023, was carried out with a model 58 (Sa58) assault rifle with 7.62 mm model 43 (7.62-43) ammunition with an FMJ round with a mild steel core. A total of 16 individual shots were recorded. The measurement conditions were as follows: Air temperature 18.6 °C, relative humidity 59.3 %, atmospheric pressure 94.71 kPa. To determine the equivalent noise level during an 8-hour shift ($L_{\mathrm{Aeq,8h}}$), the background noise level measured before the start of shooting was used at $L_{\mathrm{Aeq,2s}}$ = 39.8 dB.

The second measurement on August 3rd, 2023, was conducted with 5.56 mm CZ 805 BREN (BREN1) and 5.56 mm CZ BREN 2 (BREN2) using 5.56 × 45 mm NATO ammunition with FMJ SS109 mild steel core ammunition and 20 single shots were fired from both weapons for the recording. Due to 2 faulty recordings, only 18 recordings were used for the BREN 2 calculations. The climatic conditions during the shooting exercises remained unchanged, with an air temperature of 20.8 °C, a relative humidity of 65.7 % and an air pressure of 94.79 kPa. To determine the equivalent noise level during the 8-hour shift, the background noise level measured before the start of shooting was used at $L_{\mathrm{Aeq,2s}}$ = 36.3 dB.

Two Bruell&Kjaer 4941-A-011 microphones and an ACOEM 01dB DUO noise meter were used to measure the sound pressure. *Microphone 1* (M_1) was set up in the longitudinal direction at the height of the muzzle of the rifle at a height of 1.6 m above the ground and in the transverse direction at a distance of 1 m to the right (from the point the view of the shooter) perpendicular to the barrel axis. *Microphone 2* (M_2) was positioned longitudinally at the level of the shooter's ear, at a height of 1.6 m above the ground, in a lateral direction at a distance of 0.15 m to the right (from the shooter's point of view) of the shooter's right ear. The 01 dB DUO noise measuring device (*Mi-*

crophone 3 (M_3)) was positioned 5 m from the muzzle behind the shooter at a height of 1.6 m above the ground. The position of the individual sensors can be seen in the drawing in Fig. 1. The sampling frequency (f_s) of the measurement card for recording the signal from microphones 1 and 2 was set to f_s = 200 kHz. The sampling frequency fs of the DUO noise meter for recording the signal from *Microphone 3* was set to f_s DUO = 51.2 kHz. The resulting data was processed in MATLAB software version R2023b from The MathWorks, Inc. using the Python programming language. The uncertainty of a noise measurement is the parameter associated with the measurement result in the form of the standard deviation given in the results. To simplify interpretation, the measurement error is not taken into account in further calculations. For more detailed information on the measurement methodology, please contact the corresponding author.

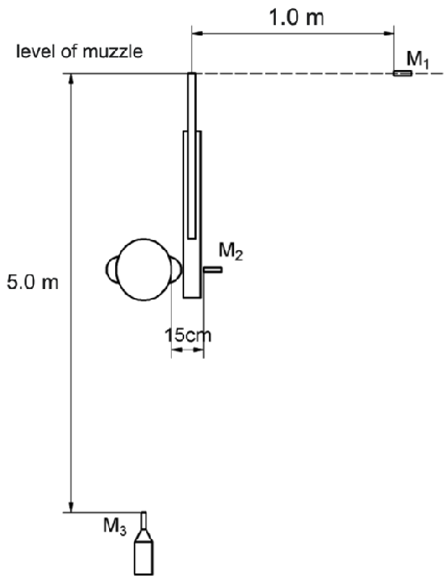

Fig. 1 Diagram of the sensor layout on an outdoor shooting range

3 Results

The individual measurements show that the peak sound pressure levels of all three weapon types at the height of the shooter's head are around 154 dB, with average differences between the weapons of up to 2 dB (Tab. 2, M_2). At a point of 5 m behind the shooter, the noise differences between the weapons are also minimal, with average differences of up to 1 dB (Tab. 2, M_3). There are only clearer differences at *Microphone 1*, placed 1 m from the barrel, where BREN2 reaches the highest peak sound pressure level of up to 170 dB (Tab. 2, M_1).

Similarly, the equivalent sound pressure levels correspond to L_{Aeq} for the 1 s record, where Sa58 reaches the lowest values and firing this weapon represents the lowest noise burden of the weapons measured (Tabs 2 and 3). BREN2 represents the highest noise burden for the shooter (Tabs 2 and 3).

Tab. 2 Peak sound pressure levels when firing long handguns at an outdoor shooting range

Type of weapon	M_1, L_{Cpeak} [dB]		M_2, L_{Cpeak} [dB]		M_3, L_{Cpeak} [dB]	
	mean	*SD*	*mean*	*SD*	*mean*	*SD*
BREN1 (n = 20)	168.5	0.40	154.0	0.57	142.6	0.32
BREN2 (n = 18)	170.0	0.54	154.7	0.71	142.0	0.25
Sa58 (n = 16)	165.7	0.32	155.4	0.34	142.5	0.23

Values were obtained as the arithmetic mean of individual shot values, SD = standard deviation, M_1 *= peak sound pressure level 1 m from the muzzle,* M_2 *= peak sound pressure level at the shooter's ear,* M_3 *= peak sound pressure level 5 m from the muzzle behind the shooter (microphone layout diagram in Fig. 1), BREN1 = 5.56 mm CZ BREN, BREN2 = 5.56 mm CZ BREN 2, Sa58 = 7.62 mm Sa model 58.*

Tab. 3 Equivalent sound pressure levels ($L_{Aeq,T}$) *for* $T = 1$ s

Type of weapon	M_1, $L_{Aeq,T}$ [dB]		M_2, $L_{Aeq,T}$ [dB]		M_3, $L_{Aeq,T}$ [dB]	
	mean	*SD*	*mean*	*SD*	*mean*	*SD*
BREN1 (n = 20)	131.1	0.35	124.2	0.28	113.1	0.30
BREN2 (n = 18)	132.2	0.53	122.8	0.39	112.3	0.29
Sa58 (n = 16)	127.9	0.19	122.4	0.30	111.5	1.24

Values were obtained as the arithmetic mean of individual shot values, SD = standard deviation, M_1 *= for 1 s microphone recording at 1 m from the muzzle,* M_2 *= microphone recording representing the distance at the shooter's ear,* M_3 *= noise meter recording 5 m from the muzzle behind the shooter (microphone layout diagram in Fig. 1), BREN1 = 5.56 mm CZ BREN, BREN2 = 5.56 mm CZ BREN 2, Sa58 = 7.62 mm Sa model 58.*

4 Discussion

From the measured values it is evident that the L_{Cpeak} impulse noise of the modifications of individual weapon types (CZ BREN 2 in 5.56 mm NATO caliber, CZ BREN 1 in 5.56 mm caliber and Sa model 58 in 7.62 mm caliber) reaches a peak sound pressure level of more than 150 dB at the shooter's head (Tab. 2, M_2). Our measurements are in accordance with the results measured by the Military Health Institute (MHI), which, based on its findings, recommended the use of hearing protectors with an attenuation of 35 dB (SNR).

The calculation of appropriate hearing protection should adequately reflect the noise level in the shooting environment. Such a calculation should take into account not only the noise generated by the shooter but also the noise in his environment (noise from other shooters). Realistic measurements are also a trend in foreign armed forces. The transnational discussion and cooperation within the NATO Science & Technology Organization project (*Military implications of acute noise-induced changes in hearing*) led to the clear recommendation to measure the noise exposure of soldiers not only during a shooting shift but during the entire working day with an individual noise dosimeter [22]. This recommendation refers not only to the noise assessment at the workplace but primarily to the description of the actual and expected noise exposure under combat conditions.

Noise exposure calculations based solely on weapon noise on the firing range are very limited and even biased. Therefore, the next line of research should reflect as much as possible the typical situations in which soldiers may find themselves during training or deployment. Here it would be appropriate to measure the total noise exposure outside the shooting range and thus work with a more accurate value of the total noise exposure. In addition, personal sound exposure meters meeting adequate requirements could be suitable [23].

However, the essential question remains how often soldiers are exposed to this noise and what PPE they have available. The frequency of firing exercises for regular soldiers, except for specific units and functions, is only a small fraction of the total monthly noise burden. Existing legislation, such as Regulation 432/2003 (setting out the conditions for the categorization of work) and Government Regulation 272/2011 (on the protection of health against the adverse effects of noise and vibration), cannot effectively address such infrequent noise incidents [5, 6].

Given the low frequency of shooting exercises in a typical work month, the measured noise exposure values should have a rather marginal effect on the job categorization. Even if, logically, this is an irregular workload (it does not take place every day), the recalculation of the average (weekly or monthly) exposure cannot be used for more accurate calculations because the condition of paragraph 4, § 4 of Government Regulation No. 272/2011, which stipulates that individual daily exposures may differ from each other by a maximum of 10 dB in equivalent sound pressure level A is not met [5].

Therefore, the measured noise exposures from firearms should primarily be used as a starting point for selecting appropriate PPE, rather than blanket assignment of soldiers to a higher work category based on noise exposure. Ensuring adequate protection for soldiers is essential and has significant short- and long-term effects on their health and ability to perform their duties. An important factor after noise exposure is the recovery period, when the auditory system has room to recover its functions, and this is sufficient in the case of less frequent noise exposure.

Because of the irregularity of the noise load, soldiers completing marksmanship training, with the weapons we tested, would not necessarily be universally classified as third or fourth category work. To ensure the safety and health of servicemen and women from the noise burden of marksmanship exercises, we propose that screening audiometric examinations occur for selected groups. This screening could take place as part of the extended medical examinations that are every five years. Another option for more regular observation is screening questionnaires that could detect incipient hearing problems. Future discussion on the selection of an appropriate tool that would be easy to use and have sufficient predictive value in the Army setting, including early detection of members with difficulties, would be useful.

Particular attention should be paid to marksmanship instructors, fire controllers, section leaders, and soldiers in preparation for overseas operations, for whom marksmanship exercises are more frequent. In these and similar cases, soldiers are exposed to noise more frequently than other military occupations. For these soldiers, it is, therefore essential to focus on the selection of appropriate personal protective equipment (PPE) to ensure safety during firing exercises and other noise-intensive occupations.

4.1 Protection of the Individual

Whether it is a regular or irregular activity, it is undoubtedly necessary to adequately protect soldiers from the risks of noise. When choosing hearing protectors, the key is to ensure that they provide adequate noise reduction but, at the same time, do not interfere with normal communication. For the needs of noise reduction and at the same time maintaining the ability to communicate, it is necessary to choose from a series of electric hearing protectors that allow passing the residual noise level (70-80 dB) so as to prevent excessive attenuation, which is also undesirable [14]. These protectors therefore retain the ability to perceive important audio signals and spoken instructions. However, their overall attenuation is at the time of writing and market research, approximately 32 dB.

It is now recommended to choose hearing protection that attenuates at least 35 dB (for calculation using the SNR method [19] and to achieve such attenuation it is possible to use a combination of earmuffs and earplugs to achieve the recommended attenuation. Therefore, it seems appropriate to use earplugs and electronic earmuffs that are able to transmit low-intensity sounds. One of the problems with combining two earmuffs is that the attenuation of the individual aids does not add up, so it would be advisable to use only tested combinations of hearing muffs available on the market products (specific product names not given) which together provide SNR = 39 dB, ($H = 36$ dB, $M = 38$ dB, $L = 36$ dB), while the earmuffs achieve SNR = 28 dB ($H = 31$ dB, $M = 25$ dB, $L = 16$ dB) and plug SNR = 28 dB ($H = 30$ dB, $M = 24$ dB, $L = 22$ dB).

However, even a combination of earplugs and electronic earmuffs can lead to excessive attenuation in combat situations. This effect can be potentially dangerous as the shooter may miss important audio signals from the surroundings. Although this risk can be mitigated by higher volume settings on the earmuffs, which allow low-intensity sounds to be filtered out, there will still be some attenuation due to the earmuffs. The result is also higher battery consumption of electronic protectors at increased volume [19].

Last but not least, it should be remembered that SNR or NRR values alone are not sufficient for selecting hearing protectors, as they cannot accurately assess the effectiveness of protection when exposed to impulse noise such as the sound of gunfire. When selecting appropriate hearing protectors, the specifications should clearly focus on protection against this type of noise, which is typical gunfire noise.

Therefore, hearing protectors should be explicitly designed to protect against impulse noise. Since universal values similar to the American IPIL (Impulse Peak Insertion Loss) standard do not yet exist for all types of protectors, it is advisable to use information on the specific protection effectiveness in different frequency bands. This information should be requested from manufacturers/suppliers and should be selected with regard to the type of weapon used by the soldier. The use of the HML method or octave bands according to EN 458 or EN ISO 4869 would also seem to be a suitable complement [13, 19].

4.2 Reduction in the Effectiveness of PPE Through Improper Use

Improper use of personal protective equipment can significantly reduce its protective function. Poor application of earplugs can reduce their effectiveness by up to 50 % compared to the values declared by the manufacturer [24]. Also, anatomical differences between users, including gender variations, require the use of protectors of appropriate sizes for optimal protection, while standards and recommendations for the selection of protective equipment themselves work with the term assumed protection value of a hearing protector (APVf), which is expressed as the difference of the standard deviation from the mean attenuation value [19, 25].

Other problems include incorrect combinations of protective equipment, such as wearing earmuffs with glasses, where the feet of the glasses prevent the earmuffs from fitting tightly against the head and create gaps through which noise can penetrate. Similarly, improper fitting of ballistic helmets can lead to inadequate hearing protection. The use of headgear in extreme conditions such as high temperatures, direct sunlight, or cold weather, while important for the body's thermoregulation, can negatively affect the effectiveness of protective equipment [24]. In practice, the most effective method of hearing protection has been shown to be the use of electronic earmuffs with a high level of attenuation. In addition to selecting good quality protectors, it is also crucial to conduct thorough training of users so that they are familiar with the rules of proper fitting and use of these protectors.

5 Limit

The resulting noise transmission from the gun to the shooter also depends on wind, temperature, humidity and other obstacles such as helmet and goggles. These protective gears can reduce the effectiveness of hearing protectors, especially for muzzleloader types. For ease of interpretation of the results, these variables have not been included and only the average values found during field measurements have been used to calculate exposure limits. For a more accurate interpretation of the results obtained, further measurements are needed and are currently being carried out by the Military Institute of Health and collaborating organizations. The aim of the study is to present the results in a way that can be understood by a wider readership. Individual variations and measurement errors are negligible for the practice itself in this case and, according to the authors, do not affect the conclusions of this paper. At the same time, it should be taken into account that not all firings are performed with the weapons we tested (e.g. firings from short handguns, weapons on vehicles, etc.), which represents an unknown noise burden.

6 Conclusion

Hearing is essential to the safe and effective performance of military tasks, which highlights the need to protect it not only for personal health but also for operational requirements. Firing and shooting exercises often exceed the maximum noise limits set by Government Regulation No. 272/2011 on the protection of health against the adverse effects of noise and vibration, both at peak and equivalent levels. Therefore, it is essential to carefully select appropriate protective equipment.

When selecting protective equipment, it is important to consider not only noise attenuation but also comfort and communication ability. While the combination of plug and shell protectors can provide a high degree of protection (attenuation in dB), it can also lead to overdamping, making important signals difficult to hear and communication difficult, which is detrimental to the task at hand.

It is also essential to regularly train personnel on the proper use and maintenance of protective equipment to ensure maximum effectiveness. The authors also recommend that consideration be given to introducing new methodologies for determining appropriate protective equipment, such as Noise Reduction Statistic for Use with A weighting (NRSA) or Impulsive Peak Insertion Loss (IPIL) and integrating them into practice. This would ensure the best possible hearing protection in a variety of conditions.

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