A comparison of metrics for impulse noise exposure

Analysis of noise data from small calibre weapons

Ann Nakashima
DRDC Toronto Research Centre

Prepared For:
Directorate of Force Health Protection
1745 Alta Vista Drive
Ottawa, ON K1Z 0K6

Defence Research and Development Canada

Scientific Report
DRDC-RDDC-2015-R243
November 2015

IMPORTANT INFORMATIVE STATEMENTS

This work was funded by Defence Research and Development Canada, Personnel Portfolio, Diagnostics and Health Protection project.

Abstract

A previous analysis of the Department of National Defence (DND) training safety document concluded that the recommendations for hearing conservation during weapons training are outdated. Current impulse noise metrics being used by the United States (MIL-STD 1474E) and France (DTAT, 1983) were analyzed by way of literature review and feasibility assessment using weapon noise recordings from in-service weapons. The noise exposures for the shooter and potential observers, with and without the use of hearing protection devices, were considered in the analysis. Based on the critical reviews of the metrics from the literature and the current feasibility assessment, it is recommended that an equivalent energy approach (L_{Aeq8hr}) be implemented for the assessment of noise exposure from small calibre weapons. Large calibre weapons and blasts were not considered in the current analysis and should be further investigated.

Significance to defence and security

We make recommendations for changing the hearing conservation guidelines for small calibre weapon noise, the current CAF guidelines being outdated compared to the methods used by Allied forces.

Résumé

Dans le cadre d'une analyse précédente du document du ministère de la Défense nationale (MDN) sur la sécurité de l'entraînement, on avait conclu que les recommandations concernant la protection de l'ouïe pendant l'entraînement au tir étaient désuètes. Les mesures actuelles du bruit impulsif, utilisées par les États-Unis (MIL-STD 1474E) et la France (DTAT, 1983), ont été analysées dans une revue documentaire et une étude de faisabilité à l'aide d'enregistrements de bruits provenant d'armes de service. Dans cette analyse, on a tenu compte de l'exposition au bruit pour le tireur et les observateurs potentiels, avec ou sans dispositif de protection de l'ouïe. Selon un examen critique des mesures tirées de la revue documentaire et de la présente étude de faisabilité, on recommande de mettre en œuvre une méthode d'énergie équivalente (L_{Aeq8hr}) pour évaluer l'exposition au bruit des armes de petit calibre. On n'a pas tenu compte des armes de gros calibre et des explosions dans la présente analyse. Celles-ci devraient faire l'objet d'une autre recherche.

Importance pour la défense et la sécurité

Les lignes directrices actuelles pour la protection de l'ouïe des membres des FAC contre le bruit d'armes de petit calibre étant désuètes en comparaison de celles utilisées par les forces alliées, nous recommandons de les changer.

Table of contents

List of figures

List of tables

Acknowledgements

The author would like to acknowledge Capt Marsh, WO O'Neill and Maj Vaillancourt for coordinating the measurements at Canadian Forces Bases (CFB) Meaford and Valcartier. Dr. Sharon Abel (retired) is gratefully acknowledged for her comments on an earlier version of this document.

1 Background

Requirements for hearing conservation during weapons training are described in the Department of National Defence (DND) Training Safety document (DND, 2004). The document includes a table of maximum daily exposure (MDE), in terms of the number of rounds fired, for various Canadian Armed Forces (CAF) weapons. The method for calculation of the MDE is not given. A critical analysis of the document and a literature search (Nakashima, 2011) concluded that the weapon noise data was likely from measurements taken in the 1970s and the MDE were calculated using a method published by the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA [Ward, 1968]). The CHABA method has been criticized over the years (Shaw, 1985; North Atlantic Treaty Organisation [NATO], 2010), and has been replaced in the United States with other metrics that will be discussed in this report. Clearly, there is a need to update the training safety document with a current impulse noise exposure metric (hereafter referred to as “Metrics”), using data from in-service CAF weapon systems.

An important consideration of the Metrics is the inclusion of hearing protection devices (HPD). The Canadian Armed Forces range safety doctrine stipulates that hearing protection must be worn by the shooters and personnel within the vicinity of shooting (DND, 2004). HPD manufacturers do not provide ratings for their devices for impulse noise. The procedures for measuring the impulse peak insertion loss (IPIL), or reduction in peak noise level afforded by the HPD, are given in American National Standards Institute / Acoustical Society of America (ANSI/ASA) S12.42:2010. The IPIL of several types of HPDs were measured in a previous study (Nakashima, 2015) and are included in the current analysis.

To ensure that sound recommendations are provided to the CAF, the Metrics must be validated using data from CAF weapons. As noise data is not available for current in-service CAF weapons, we collected data in accordance with the current standard for impulse noise measurement (ANSI/ASA S12.7-1986[R2006]).

Our study aimed at:

1. Carrying out a literature review to identify the Metrics that are being used by other nations, and to understand the benefits and drawbacks of each;

2. Collecting noise data generated by CAF small arms weapons fire; and

3. Recommending a Metric to calculate the allowed number of exposures (ANE) based a thorough review of the literature and analysis using CAF weapon data.

Large calibre weapons and blasts are beyond the scope of the current analysis. Annex A presents a concise summary of the findings, conclusions and recommendations.

2 Impulse noise exposure metrics

This section provides brief descriptions of the Metrics that are currently in use. Although some of the Metrics appear to be similar, there are subtle differences in the calculations that will be highlighted here. The history of the various Metrics, physical assumptions, signal definitions and equations have been discussed extensively by several authors (e.g., Pfander et al., 1980; Shaw, 1985; Dancer and Franke, 1995; NATO, 2003; Nakashima and Farinaccio, 2015). Fundamental acoustic definitions and equations presented in this report are listed in Annex B, Table B.1.

The European Union Directive 2003/10/EC for noise exposure has been in effect since 2006 (EU-OSHA, 2003). The basic unit of acoustic pressure is called the sound pressure level, L_p, in units of decibels (dB). It is calculated as:

$$L_p = 10Log10\left(\frac{p^2}{p_o^2}\right) \tag{1}$$

where p is the sound pressure level in Pascals (Pa) and p_o is the standard reference level, equal to $2x10^{-5}$ Pa. The exposure limit values are expressed in terms of peak pressure level, P_{peak}, in Pa and the equivalent continuous A-weighted sound pressure level, in decibels (dBA) which is defined as:

$$L_{Aeq,T} = 10log\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_o^2}dt\right] \tag{2}$$

where t_2-t_1 is the period T over which the average is taken starting at t_1 and ending at t_2. Normalized to an eight-hour (8 hr) working day, the exposure is:

$$L_{EX,8hr} = L_{Aeq,Te} - 10log\left(\frac{T_e}{T_o}\right) \tag{3}$$

where T_e is the effective duration of the working day and T_o is the reference duration of 8 hr (International Organisation for Standardization [ISO] 1999:2013). The limit and action values are:

- Exposure limit: Lex, 8hr = 87 dBA and Ppeak 200 Pa;
- Upper action value: Lex, 8hr = 85 dBA and Ppeak 140 Pa; and
- Lower action value: Lex, 8hr = 80 dBA and Ppeak 112 Pa.

The action values are exposure levels at which employers are obligated to provide (lower value) and enforce (upper value) the use of HPDs. Note that for a working day that does not exceed eight hours, Equation (2) reduces to Equation (1) with T = 8 hr. In most of the literature, the so-called “equivalent energy method” is denoted as L_{Aeq8hr}, which is what will be used in this document. Normalizing to an 8 hr working day, the exposure to N identical impulsive events (e.g., number of rounds fired) can be calculated as:

$$L_{Aeq8hr} = L_{Aeq,T} + 10log\left(\frac{t_2 - t_1}{T_o}\right) + 10logN \quad (4)$$

where T_o is the reference duration, set to 8 hr or 28800 seconds (Murphy and Kardous, 2012).

In Germany, the Pfander criterion is used for military impulse noise. The criterion is based on acceptable temporary threshold shift (TTS) in hearing levels measured in 95% of humans 24 hours after the impulse noise exposure (Pfander et al., 1980). In France, use of the L_{Aeq8hr} is recommended and unprotected exposures to unweighted peak sound pressure levels (dB SPL) over 160 dB SPL are prohibited (Direction Terrestre des Armements Terrestres [DTAT], 1983). The peak sound pressure level is defined as the maximum instantaneous sound pressure level that occurs during a specified time level (ANSI/ASA 12.7, 1986). The DTAT criterion limits L_{Aeq8hr} to 90 dBA, but it was later recommended that the limit be lowered to 85 dBA (Dancer and Franke, 1995).

In the United States, MIL-STD 1474E has been recently approved (Department of Defence [DoD], 2015). Two different Metrics are presented: Auditory Risk Units (ARU), calculated with the Auditory Hazard Assessment Algorithm for Humans (AHAAH) and the Equal Energy Equivalent Averaged Over 100 millisecond (ms) Intervals ($L_{IAeq100ms}$), which is used to calculate the noise dose. The AHAAH is a mathematical model of the ear that was developed to provide risk evaluation for impulse noise (Fidele et al., 2013). The software is available on the United States Army Research Laboratory (ARL) website. The user is required to input a pressure-time signal (e.g., a recording of a single gunshot) of a known peak sound pressure level. The software can then be used to process the signal and output the hazard in ARU or number of permitted rounds. The ARU can be calculated for “warned” or “unwarned” exposures. The “warned” calculation assumes that the exposed person had advanced warning of the impulse and has activated their middle ear muscle (MEM) reflex, a voluntary protective mechanism that is thought to reduce the damage to the ear (Danielson et al., 1991). This might be the case in training when the shooter has been given the order to fire, and anticipates the noise. The MEM reflex is absent in the “unwarned” condition, assuming that the noise exposure was sudden and unexpected. A full description and extensive user manual for the AHAAH software is available (Fidele et al., 2013).

The $L_{IAeq100ms}$ is similar to the L_{Aeq8hr} in that it is also an equivalent energy method. A key difference is whether a correction factor is applied to account for the duration of the impulse. The $L_{IAeq100ms}$ can be calculated with Equation (2) using T = 100 ms. MIL-STD 1474E also provides the discrete-time equivalent formula:

$$L_{IAeq100ms} = 10log\left\{\frac{1}{T}\sum_{i=1}^{n} 10log^{-1}\left[\frac{L_{Ai}}{10}\right] \times \Delta t_i\right\} \quad (5)$$

where L_{Ai} is the A-weighted sound pressure level at the discrete time interval, Δt_i. In the calculation of the dose normalized to 8 hr, a correction is applied using the A-duration in ms. The A-duration of an impulse is the time between the onset of the peak and the first crossing with the baseline; this is visualized with the Friedlander waveform shown in Figure 1. The corrected equivalent energy over 8 hr is calculated as:

$$L_{IAeq8hr} = L_{IAeq100ms} - 54.6 - 1.5 * 10 * log\left(\frac{\text{A} - \text{duration}}{0.2}\right) \quad (6)$$

for A-duration < 2.5ms and:

$$L_{IAeq8hr} = L_{IAeq100ms} - 71.0 \quad (7)$$

for A-duration ≥ 2.5 ms. The correction for the A-duration is intended to reduce the overprediction of noise dose for impulses that are longer than 0.2 ms. The dose percentage for a single impulse is then calculated as:

$$D_I(\%) = \frac{100}{2^{(85 - L_{IAeq8hr})/3}} \quad (8)$$

which is multiplied by the total number of impulses to obtain the total dose. While the dose is calculated with reference to continuous exposure for an 8-hour period, it is stated that the noise dose must not exceed 100% within any 24-hour period. Further guidance on the use of these equations is provided in MIL-STD 1474E (DoD, 2015).

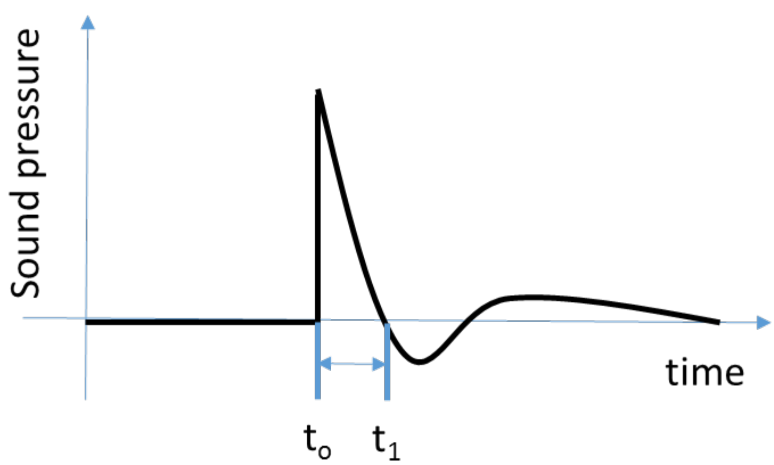


***Figure 1:** Idealized impulsive signal in the free-field (Friedlander waveform). The A-duration is the duration of the impulse, t1-to.*

An additional method that has been proposed to evaluate the hazard of a noise signal is a kurtosis statistic. In simple terms, kurtosis is the measure of the "peakedness" of a signal. Outlier-prone signals, such as complex noise containing both continuous and impact noise, have higher kurtosis values. While kurtosis analyses have been shown to be useful in the evaluation of industrial noise (Davis et al., 2009; Zhao et al., 2010), it is doubtful that this approach can be used to evaluate individual high-level impulses from weapons. Kurtosis will not be further explored in this document.

3 Comprehensive review of current impulse noise exposure metrics

3.1 Criteria used in Europe

The EU Directive for noise exposure (EU-OSHA, 2003) has been criticized as being too restrictive for military noise exposures. In particular, it has been argued that in order to comply with the exposure limit peak of 200 Pa, double hearing protection would have to be worn for all weapon firing. This would have a negative impact on speech communication during weapon use and compromise safety (Buck et al., 2010). Limiting the exposure to simply a peak value does not account for spectral content (or, equivalently, impulse duration) or combined noise exposures (e.g., noise from adjacent shooters or nearby vehicles), and is unreasonable for military applications.

In a comparison of the Pfander and L_{Aeq8hr} methods, it was concluded that the Pfander method was not suitable for assessing the risk for larger calibre weapons that produce longer impulses (Dancer and Franke, 1995). Longer impulses contain greater energy at low frequencies than short impulses, and the L_{Aeq8hr} was found to provide a better evaluation of risk. In addition, the L_{Aeq8hr} can be used in both free-field and reverberant environments, and it can deal with combined exposures (Dancer and Franke, 1995). Metrics that require the duration of the impulse, such as the CHABA (Ward, 1968), the Pfander (Pfander et al., 1980) and $L_{IAeq100ms}$ (DoD, 2015) will not be appropriate in reverberant environments, where reflections of the impulse significantly alter the idealized signal shown in Figure 1. It is important to consider combined exposures when dealing with multiple shooters or continuous noise sources (e.g., armoured vehicle noise). These points were reinforced by Buck et al., (2010).

3.2 Criteria used in the United States

The AHAAH Metric that was developed in the United States (Fidele et al., 2013) has been a topic of controversy. In 2003, a NATO research study group on impulse noise concluded that they could not agree on the use of a single Metric. Some of the members felt that the AHAAH produced unsatisfactory results for several exposure conditions. The resulting report contained chapters written separately by experts who had conflicting opinions (NATO, 2003). While the group could not form a consensus on a Metric, it was generally agreed that short-duration impulses (e.g., rifle noise) should be treated differently from long-duration impulses and blasts.

The American Institute of Biological Sciences (AIBS) conducted a review of the impulse noise injury models to address the deficiencies in MIL-STD 1474D (DoD, 1997), which has since been replaced by MIL-STD 1474E (DoD, 2015). They also concluded that while the AHAAH is a step in the right direction as it incorporates aspects of the auditory function (e.g., MEM reflex), it is not yet fully developed and validated. Although the AHAAH is a good predictor of hazards for single, high-intensity impulses such as an automobile airbag, it is questionable as to whether it can model the hazard from a complex military environment, which may include hundreds of rounds from different weapons and continuous noise from diesel engines. The AHAAH is based on a cat model, so the validity of applying the results from a cat to a human was questioned. The panel unanimously recommended the use of the L_{Aeq8hr} until AHAAH is further developed, stating that "it is relatively easy to implement and should not perform more poorly than the AHAAH at this point in its development (AIBS, 2010)."

A separate review by the National Institute for Occupational Safety and Health (NIOSH) pointed out numerous deficiencies in the AHAAH model that were similar to the AIBS conclusions (Murphy and Kardous, 2012). It was argued that the MEM reflex is absent in enough people that the "warned exposure" calculation should not be used as a valid form of analysis. The use of the L_{Aeq8hr} was recommended for several reasons: 1) it provided the best fit to a set of blast overpressure TTS data (Murphy et al., 2009), 2) it provided the best fit to data from animal studies (Murphy et al., 2010), 3) it can easily account for combined exposures of impulsive and continuous noise, and 4) it is easier to work with than the AHAAH in its current state (at the time of the report publication), making it accessible for use. The report emphasized the importance of accurately including the performance of HPDs and the need for more data using the ANSI/ASA S12.42:2010 method. It also mentioned that the effects of secondary exposure, e.g., adjacent shooters and range safety personnel, have not been adequately addressed (Murphy et al., 2012).

The recently approved MIL-STD 1474E includes the AHAAH and $L_{IAeq100ms}$ without any specific guidance on their selection. There is no explanation regarding whether or not one metric is better suited for a particular exposure than the other. Analyses of the AHAAH have been extensive as described above. However, the $L_{IAeq100ms}$ is a new metric and it is stated explicitly in the MIL-STD that it has not been systematically peer-reviewed (DoD, 2015).

3.3 Summary

In summary, the benefits and drawbacks pertaining to the use of various Metrics have been clearly articulated by subject matter experts from several countries. The ideal Metric should include aspects of auditory function, be able to account for the contributions of complex noise in various environments (gunfire, continuous vehicle noise, blast, in-ear radio communication, etc.), and be able to account for ever-changing weapon systems, weapon suppressors and hearing protection technologies. From a practical perspective, the Metric should be easy to implement and produce unequivocal results so that it is accessible to military officers when planning weapon training activities. Clearly, such a metric does not exist. Thus, the current work aimed at selecting a Metric that is the most feasible for implementation in the CAF Training Safety document (DND, 2004). The following sections describe the data collection and analysis using three Metrics: 1) the L_{Aeq8hr}, 2), the AHAAH and 3) the $L_{IAeq100ms}$.

4 Experimental methodology

4.1 Equipment

Pressure-time signal recordings of impulsive signals are required for the calculation of the selected Metrics. For the weapon noise measurements, two ¼” and two ½” microphones (model 377C10 and 377B02, PCB Piezotronics, Depew, NY) were used with a four-channel Soundbook MK2 and SAMURAI data acquisition platform and software (SINUS Messtechnik GmbH, Germany). The ¼” microphones are capable of measuring sound pressure levels up to about175 dB peak and were used for data collection closest to the weapon. The ½” microphones measure levels up to about 140 dB peak. For all of the data collection, a 204.8 kHz sampling rate was used.

4.2 Weapon noise measurements

Noise data were collected for the CAF weapons listed in Table 1. The C8, C14 and C15 were measured with and without a noise suppressor attached to the weapon.

Table 1: *List of weapons tested for noise measurements without suppressor (unsup) and with suppressor (sup).*

9 mm pistol
C7, 5.56 mm semi-automatic / automatic rifle
C8, 5.56 mm carbine semi-automatic / automatic rifle (unsup/sup)
C14, 8.6 mm medium range sniper weapon (unsup/sup)
C15, 12.7 mm long range sniper weapon (unsup/sup)
C16, 40 mm automatic grenade launcher (inert rounds)

The 9 mm pistol and C7 rifle data were collected at Canadian Forces Base (CFB) Meaford in June 2014. The physical environment is of critical importance because it affects the propagation of the noise signal. Figure 2 shows the range environment at CFB Meaford, which is an open grass-covered space with no nearby reflective surfaces. Data for the C7 unsuppressed rifle were collected close to the ear of the shooter (microphone taped to ballistic eyewear); this measurement represented noise at the firing point. To measure the noise where adjacent shooters, range safety personnel or observers would stand, microphones were placed on tripods 4 m apart, to a maximum distance of 20 m, to the right and directly behind the shooter. Increments of 4 m were chosen because this is the distance between adjacent shooters on the range. Data for the 9mm pistol were taken at the firing point only, with a microphone on a tripod placed 1 m to the left of the shooter as shown in Figure 2.

Noise data for the C8, C14, C15, and C16 were collected at CFB Valcartier in September 2014. The weapons were fired from a gravel-covered area into an open field, with no other reflective surfaces around the weapon (Figure 3). The noise signal at the firing point was measured about 0.5m from the left and right ears, with microphones placed on tripods as shown in Figure 3. Microphones were placed on tripods 4 m apart to the left, right and behind the shooter as shown in Figure 3, to a maximum distance of 16 m.

For all of the weapons, three shots were recorded at each position, separated by at least 5 s.

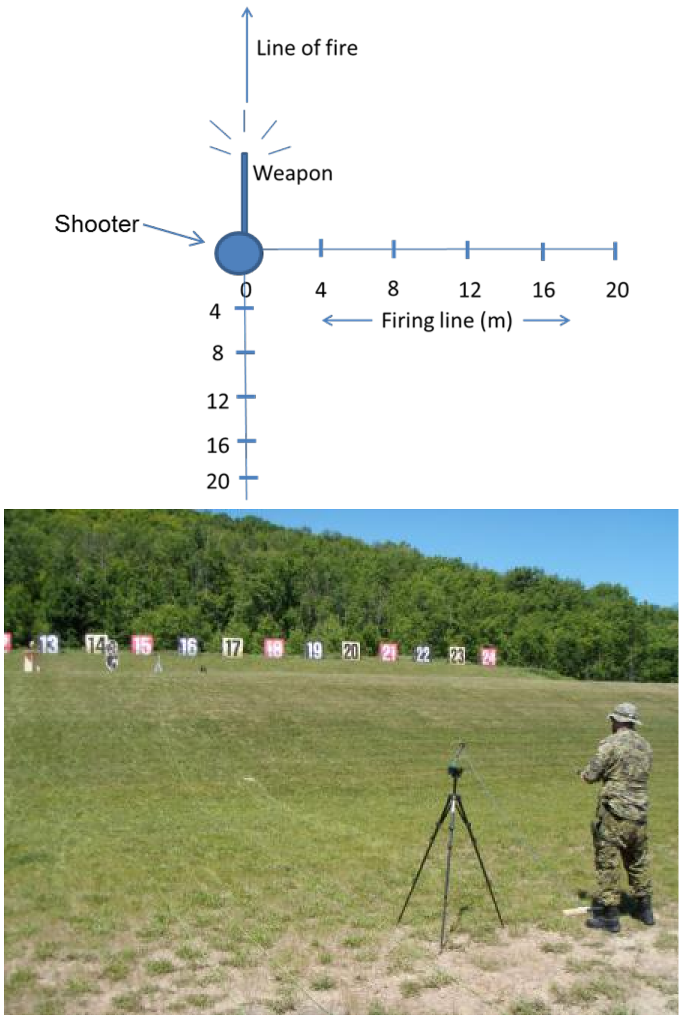


Figure 2: Measurement positions of the C7rifle noise at CFB Meaford (top), and photo of the range environment (bottom). Microphones were placed close to the shooter and on tripods at 4 m increments. The grass-covered ground surface is partially sound-absorbent, and there are no reflective surfaces near the weapon.

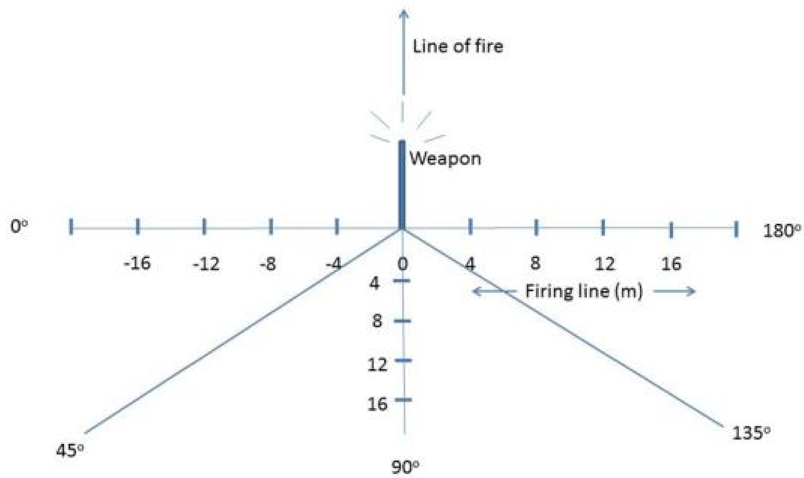


Figure 3: *Measurement positions of the C8, C14, C15 and C16 weapon noise at CFB Valcartier (top), and photo of the range environment (bottom). Microphones were placed close to the shooter and on tripods at 4 m increments. The gravel-covered ground surface is partially sound-absorbent, and there are no reflective surfaces near the weapon.*

5 Data analysis

5.1 Peak noise levels

The peak sound pressure levels were calculated for each weapon, at each measurement position using a Matlab script (The Mathworks, Inc, R2013b, Natick, MA). The threshold for applying the Metrics for impulse noise is 140 dB SPL (DTAT, 1983; DoD, 2015). For the noise levels measured away from the firing point (adjacent shooter, safety personnel and observer positions), it is of interest to calculate the reduction of noise with distance and compare it to the "6 dB rule." In the free field, in the absence of environmental factors, the acoustic pressure falls off inversely with distance. This means that the acoustic energy decreases as the inverse of distance squared, which, when converted to decibels, means that sound pressure level falls off by 6 dB per doubling of distance. We compared our results to the 6 dB rule.

5.2 Inclusion of HPDs

The IPIL is measured objectively using an acoustic manikin as specified in ANSI/ASA S12.42:2010. The actual amount of protection that is provided when an HPD is worn depends greatly on how well it fits an individual. It can be misleading to quantify the IPIL for a particular brand or model of HPD because it does not apply to users who cannot attain a good fit with the device. Instead, it can be useful to look at the range of IPIL values than can be achieved for different types of HPDs and allow the user to select the brand or model within that category that fits the best. HPD manufacturers do not provide IPIL data with their devices and as such, this type of data is not readily available. We measured the IPIL of several types of devices in a previous study (Nakashima, 2015) and de-rated them by 10 dB for the current analysis as suggested by Buck et al., (2009). The resulting IPIL values listed in Table 2 were used with the Metrics to account for HPDs in the noise exposure calculations. More information about HPDs and examples of the different types are given in Appendix C. Briefly, passive HPDs reduce the noise by providing a physical barrier to block the sound waves. Level-independent devices provide the same reduction of sound regardless of the level. Level-dependent devices provide little protection for low-level sounds, such as speech, and greater reduction for high-level impulses (Berger, 2000).

Table 2: *Impulse peak insertion loss (IPIL) values used for the ANE calculations.*

HPD type	IPIL (dB)
Earplug, passive level-independent	28
Earmuff, passive level-independent	22
Earplug, passive non-linear	10
Double protection	39

5.3 Allowed number of exposures

Using the pressure-time signals recorded from the weapons, the L_{Aeq8hr} (Equation (4)) and the $L_{IAeq100ms}$ (Equation (5)) were calculated using Matlab. The allowed number of exposures (ANE) were calculated for unprotected and protected exposures. The ANE represents the number of rounds that can be fired within the exposure limit of 85 dBA for the L_{Aeq8hr} (Dancer et al., 1995) and $L_{IAeq100ms}$ (DoD, 2015). The protected exposures were calculated using IPIL values listed in Table 2.

Setting the daily eight-hour equivalent energy limit to 85 dBA, the ANE can be calculated as:

$$ANE = 10^{(85 - L_{Aeq8hr} - IPIL)/10} \quad (9)$$

where the IPIL represents the measure obtained for a given HPD, and IPIL = 0 for unprotected exposures (Brueck et al., 2014). For the $L_{IAeq100ms}$ method, the L_{Aeq8hr} term in Equation (9) was replaced by $L_{IAeq8hr}$ using Equation (6).

Calculation of the ANE using the AHAAH program is more complex. There are multiple options in the AHAAH program for processing the input files. The first is the measurement position: free-field, ear canal entrance or eardrum. The free-field assumption implies no reflection or absorption, which is not possible in the case of weapon firing since the presence of the shooter disturbs the free-field signal. Measurement at the ear canal entrance is not possible because the shooter wears an HPD, and measurement at the eardrum requires the use of an in-ear microphone or an acoustic test fixture (manikin head). Although none of the choices describe the placement of the microphones in this study, the free-field option was chosen for the unprotected exposures.

When applying hearing protection within the AHAAH, there are two modes: default and power user. The default mode applies preset earplug, earmuff and double protection settings as described in the user guide (Fidele et al., 2013). The power user mode allows the user to select a specific HPD or combination of HPDs. Once a hearing protector setting is chosen, the program defaults the microphone position to the eardrum, and the angle of incidence to be normal (90 degrees to the ear). The user is able to change the default settings when prompted. For the current analysis, the default settings were used. An impulse at normal incidence to the ear represents the worst case scenario.

The AHAAH outputs the results in ARU, which can be converted to ANE based on a 24-hour-sliding-window limit of 200 ARU (for occupational exposures occurring 2 or more times per week) or 500 ARU (for occasional exposures occurring no more than once per week). For the current analysis, the 500 ARU limit was used. The software can calculate ARU for “warned” and “unwarned” exposures.

For the current analysis, the ANE were only calculated for the shooter (firing point). Analysis of the ANE at secondary positions should consider combined exposures from multiple weapons and is left for future work.

6 Results

6.1 Peak noise levels

The peak noise levels measured at the firing point (0.5 to 1 m away, or at the head for the C7) are listed in Table 3. The data shown are the highest levels that were measured rather than the average, thus representing the worst case scenario. Since the ANE calculations for secondary exposure are excluded from the current analysis, the peak levels at the adjacent shooter and potential observer positions are listed in Annex D, Tables D1 to D8 for information. To show the effectiveness of the weapon suppressors, the suppressed and unsuppressed peak noise levels at a distance of 4m from the shooter are shown in Figure 4.

Table 3: *Peak noise levels of the weapons at the firing point, measured 0.5 to 1m to the side of the shooter.*

Weapon	**Unweighted Peak Noise Level (dB SPL)**
9mm pistol	163
C7	162*
C8 unsup	143
C8 sup	165
C14 unsup	142
C14 sup	171
C15 sup	145
C15 unsup	177
C16	151

*Microphone was taped to the ballistic eyewear worn by the shooter.

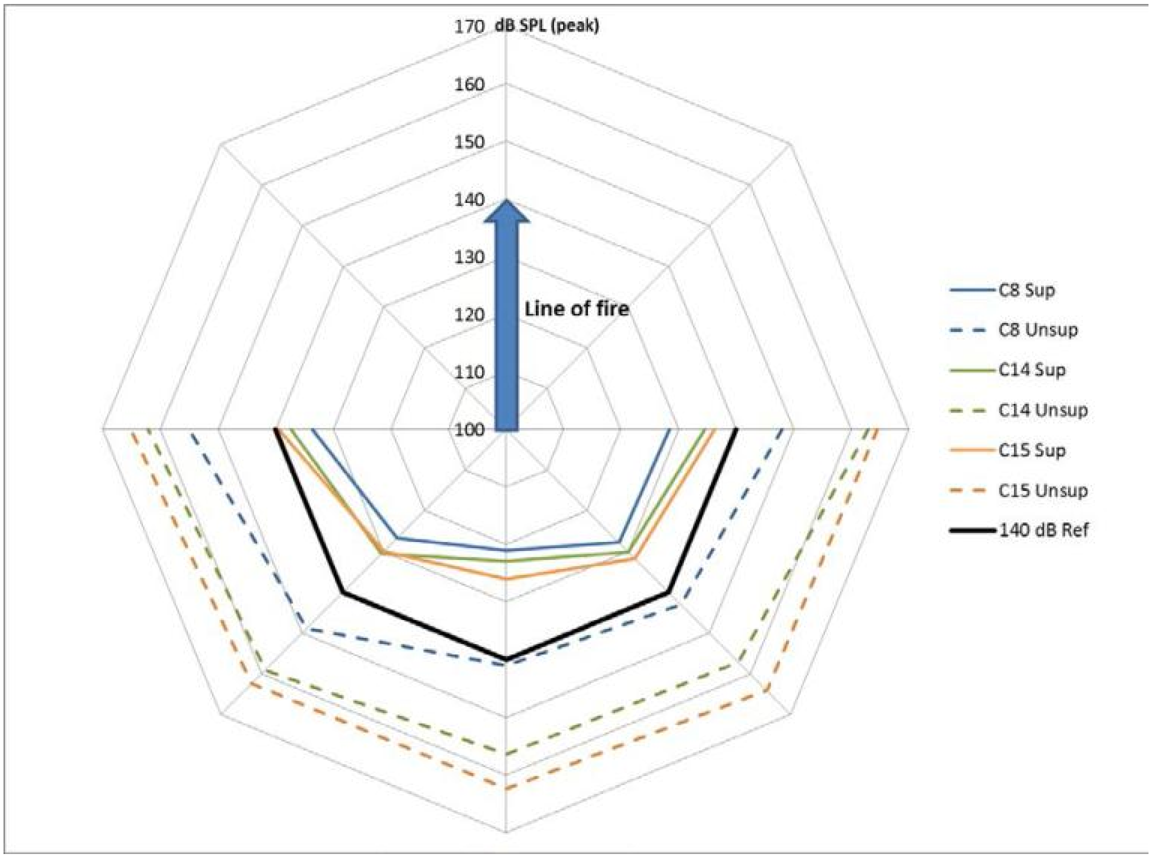


Figure 4: *Peak noise levels at 4 m from the shooter. The radial lines indicate the peak noise level in dB. The unsuppressed noise levels are represented by the dashed lines (Unsup) and the suppressed levels by solid lines (Sup). The 140 dB line, which is the threshold for applying the Metrics, is indicated in black for reference.*

It is of interest to illustrate the reduction in the peak noise levels with distance from the weapon. The average reductions are shown in Figure 5, relative to the measurement position closest to the weapon (represented as 0.5 m in the figure). The predicted levels by the 6 dB rule are also shown for reference. The noise levels directly to the left of the shooter (0 deg) had the smallest reduction with distance.

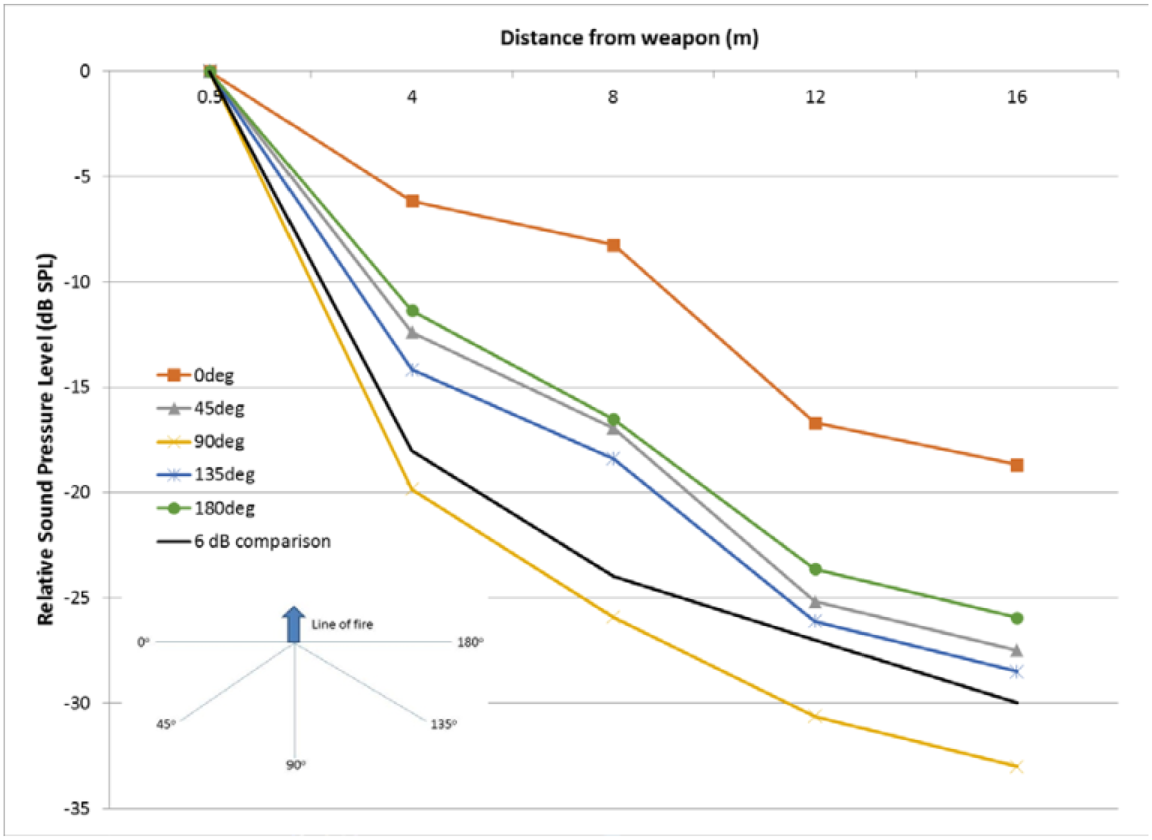


Figure 5: *Unweighted peak sound pressure levels behind the weapon, relative to the closest point of measurement (shown as 0.5m). The data shown are the averages for C8 suppressed and unsuppressed, C14 suppressed, C15 suppressed and C16. The 6 dB reduction with doubling of distance is shown for reference (black line).*

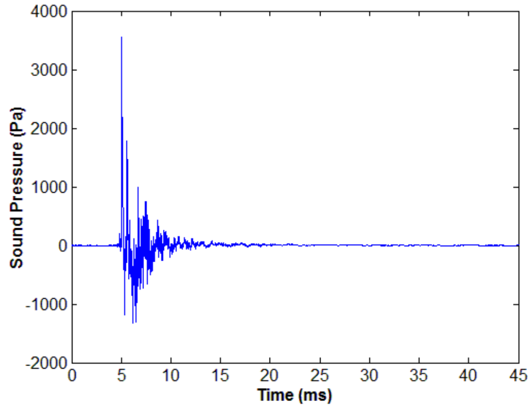
6.2 Allowed number of exposures (ANE)

The ANE for the unsuppressed weapons are shown in Table 4, in the unprotected and protected conditions, and were calculated using the three Metrics. The results shown were calculated from the signals with the highest peak levels for each weapon, representing the worst case scenario. The ANE for suppressed weapons and the C16 were not calculated because the peak levels at the shooting point were close to 140 dB SPL threshold for applying the Metrics. The AHAAH "warned" and "unwarned" calculations produced the same values for ANE and are therefore not distinguished in the table. The differences in the ANE for the L_{Aeq8hr} and the $L_{IAeq100ms}$ Metrics can be attributed to the A-duration correction (Equation (6)), which reduces the dose for impulse durations longer than 0.2 ms. Figure 6 shows the pressure-time signals from the C8 unsuppressed weapon recorded at different positions, illustrating that the A-duration is not as clearly defined as in the idealized signal shown in Figure 1.

Table 4: *Allowed number of exposures (ANE) for unsuppressed weapons at the firing point. ANE were calculated using the highest peak levels for each measurement, indicating the worst case scenario and therefore the most conservative result.*

Type of Hearing Protection Device	L_{Aeq8hr}	**AHAAH**[1]	$L_{IAeq100ms}$
C7			
Unprotected	1	2	3
Earplug, passive level-independent (IPIL 28)	977	237	1622
Earmuff, passive level-independent (IPIL 22)	245	313	406
Earplug, passive non-linear (IPIL 10)	15	24	25
Earplug and earmuff, passive level-independent (IPIL 39)	12300	495	20600
C8			
Unprotected	2	4	3
Earplug, passive level-independent (IPIL 28)	1737	456	2052
Earmuff, passive level-independent (IPIL 22)	436	750	513
Earplug, passive non-linear (IPIL 10)	27	95	32
Earplug and earmuff, passive level-independent (IPIL 39)	21800	1100	26000
C14			
Unprotected	0	2	2
Earplug, passive level-independent (IPIL 28)	323	125	950
Earmuff, passive level-independent (IPIL 22)	81	320	238
Earplug, passive non-linear (IPIL 10)	5	29	5
Earplug and earmuff, passive level-independent (IPIL 39)	4073	497	12000
C15			
Unprotected	0	2	1
Earplug, passive level-independent (IPIL 28)	95	141	1042
Earmuff, passive level-independent (IPIL 22)	23	108	113
Earplug, passive non-linear (IPIL 10)	1	18	7
Earplug and earmuff, passive level-independent (IPIL 39)	1202	279	5747
9mm Pistol			
Unprotected	6	10	20
Earplug, passive level-independent (IPIL 28)	3981	1574	13400
Earmuff, passive level-independent (IPIL 22)	1000	1910	3355
Earplug, passive non-linear (IPIL 10)	63	90	210
Earplug and earmuff, passive level-independent (IPIL 39)	50000	3340	170000

[1]AHAAH calculation for unprotected used microphone placement 1 (free-field). Protected exposures were for default settings (microphone placement 3 [at eardrum], normal incidence).



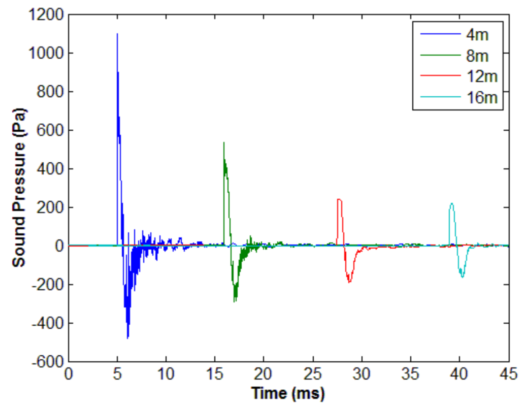


Figure 6: *Pressure-time signal of the C8 (unsuppressed) measured 0.5m from the shooter (top) and 4, 8, 12 and 16m directly to the left of the shooter (bottom).*

7 Discussion

7.1 Peak noise levels

The peak noise levels measured at the firing point (i.e., 0.5 m to 1 m to the side of the shooter; Table 3) are all in excess of 140 dB SPL, even when a weapon suppressor was used. The suppressors were effective at reducing the peak noise levels for both the shooter and potential observers. As illustrated in Figure 4, the suppressors reduced the peak levels below 140 dB SPL at a radial distance of 4 m away from the shooter. Despite this, HPD use is still recommended for observers as a precaution to reduce the risk of noise-induced hearing loss, especially for susceptible individuals. HPD use for shooters must be mandatory for all weapons training.

The 6 dB rule might be a reasonable estimate for peak noise levels directly behind the shooter (see Figure 5, 90 deg data); however, the peak noise levels at other positions were clearly higher than predicted by this rule. During training, there are often many shooters firing concurrently from the firing line. The noise from adjacent shooters must be included in the calculation of an individual's noise dose. As shown in Annex D, Tables D1 through D8, the peak noise levels from adjacent shooting positions often exceeds 140 dB SPL. The combined exposures from multiple shooters must also be considered for adjacent shooters, range safety personnel and observers.

7.2 Allowed number of exposures (ANE)

The ANEs listed in Table 4 show inconsistent differences between the three Metrics. In the case of unprotected exposures, the ANE differ by only one or two rounds. In all cases except one (C14 with a passive non-linear earplug), the $L_{IAeq100ms}$ was less protective than the L_{Aeq8hr}, resulting in a larger ANE. This was due to the correction for A-duration as shown in Equation (6). If the A-duration is longer than 0.2ms, the $L_{IAeq8hr}$ is reduced, resulting in a lower noise dose. However, the A-duration is defined by the idealized Friedlander waveform (Figure 1). Although the measurements were performed in open fields, as free from obstructions as possible, the presence of the ground, the shooter and other personnel disturbed the free-field signal. This can cause unexpected results in the calculation of the A-duration. Figure 6 shows the pressure-time signal of the C8 unsuppressed, close to the firing point and at distance up to 16 m from the firing point. There are reflections and oscillations in the signals measured closest to the weapon and it is unclear if the A-duration can be determined in accordance with its definition. MIL-STD 1474E states that when the A-duration is not measured, a value of 0.2 ms should be used, which effectively reduces Equation (6) to the equivalent of L_{Aeq8hr} (Equation (3)). Because of the uncertainty of using the A-duration with the $L_{IAeq100ms}$, the L_{Aeq8hr} is likely a more reliable choice of Metric for operational settings.

The AHAAH was used in both the "warned" and "unwarned" modes, but it was found that there were no differences in the calculated ARU, or equivalently, the ANE, for any of the exposures. The results for unprotected exposures were within one to two rounds, with the AHAAH being less protective. The AHAAH results were considerably more protective than the L_{Aeq8hr} for double protection. For the C7, C8 and C14 exposures, the ANE was greater for the earmuffs than the passive-level dependent earplugs. Since the earplugs had a larger IPIL values than the muffs (28 dB versus 22 dB), this result was surprising. It is otherwise difficult to compare the ANE calculated with the AHAAH and L_{Aeq8hr}, since one was not consistently more protective than the other.

7.3 Usability of the metrics

The L_{Aeq8hr} Metric requires the use of a high-quality pressure-time signal, which should be measured according to ANSI/ASA S12.7:1986. The calculation is likely not significantly affected by the exact microphone placement as it is with the AHAAH, and the A-duration is not required as with the $L_{IAeq100ms}$. A software program can be written to take the pressure-time signal and calibration value as input and apply the A-weighting, then output the L_{Aeq8hr} and ANE. Hearing protection can be taken into account if the IPIL of the HPD is known, or default values for common HPDs can be included in the program. Reading of the pressure-time signals can be automated so that multiple files can be batch-processed. With all of these factors considered, the L_{Aeq8hr} Metric is easy to use and understand.

The AHAAH software and manual is available for download from the ARL website. Like the L_{Aeq8hr}, a pressure-time signal and calibration value are required as input. Several steps are required to prepare a signal for analysis. The prepared signal is then saved and re-loaded into the software to calculate the ARU. The following issues were encountered when using the software:

- Only one waveform can be processed at a time through the multiple-step procedure;
- Some features of the graphical interface caused the program to crash unexpectedly;
- Input file size was limited and caused unexpected errors;
- Selection of microphone position (free-field, ear canal entrance, eardrum) might not be obvious for all users;
- Menu selection of hearing protection mode (default and power user) was cumbersome;
- Angle of incidence for hearing protection (grazing, normal, head-shadow) might not be obvious for all users; and
- Screen often blanks out when waveforms are supposed to be shown.

Many of these issues are programming errors that will likely be fixed in future releases of the software. However, there are significant concerns with the assumption of the microphone placement in the evaluation of weapon noise (free-field, ear canal entrance or eardrum). Free-field microphone placement indicates no reflective surfaces, including the shooter, so the weapon would have to be fired remotely. A microphone at the ear canal entrance would mean that the shooter could not wear an HPD, putting the shooter at risk. For the eardrum option, an in-ear microphone would have to be placed under an earmuff, or an acoustic manikin would have to be used. Realistically, the weapon signal would be recorded with a microphone on a tripod near the shooter as we did in this study; however, this microphone placement is not an option in the AHAAH. With all of these factors combined, the AHAAH Metric is not recommended for use in its current state.

The $L_{IAeq100ms}$ Metric also requires a calibrated pressure-time signal as input. From that signal, the A-duration is calculated. As discussed in the previous section, this can be problematic for real weapon signals because of reverberation and reflections within the weapon and the environment.

For example, it would not be possible to calculate the A-duration by its definition in the case of a weapon with a suppressor, or a weapon fired in an enclosure. In cases where the A-duration is not measured and assumed to be 0.2 ms, this Metric gives the same result as the L_{Aeq8hr}. The alternate calculation of this Metric for A-durations longer than 2.5 ms (Equation (7)) was not used because this type of impulsive signal corresponds to large calibre weapons and blasts. For small calibre weapons, the $L_{IAeq100ms}$ Metric can only be used in cases where the A-duration can reliably be quantified.

7.4 Commentary on the current metrics

It was concluded in 1985 (Shaw, 1985) and again in 2003 (NATO, 2003) that the treatment of impulse noise is at an impasse. The experts in the field could not agree on the basis for an impulse noise metric. Should it be based on human or animal studies of TTS, a mathematical model of the ear, or equivalent energy? The only TTS-based Metric that is currently in use is the Pfander criterion (Pfander et al., 1980). Further development of TTS-based Metrics is unlikely given the present-day human research ethics requirements. The release of MIL-STD 1474E (DoD, 2015) served as confirmation that there is still disagreement over energy-based and model-based Metrics. The AHAAH was presented with the caveat that it needs more development and that the L_{Aeq8hr} can be used as an interim metric. The $L_{IAeq100ms}$ was presented with the caveat that it has not yet been systematically evaluated or peer-reviewed. However, it was agreed that both Metrics are superior to MIL-STD 1474D (DoD, 1997), which, like the Pfander criterion, was based on TTS data.

There is a limited amount of literature on intermittency of impulses. In all three of the Metrics examined here, it is assumed that the noise exposure or dose from a number of rounds, can be added together. There is no specific guidance for handling bursts from automatic weapons, or closely spaced impulses from adjacent shooters. This is an important consideration not only for the shooters, but for the exposure of observers and range safety personnel. The data shown in Tables D1 to D8 show that observers are exposed to levels exceeding 140 dB SPL.

Although the treatment of impulse noise still appears to be at an impasse, there have been significant advances in the technology of HPDs and our understanding of how they work in impulse noise through the use of ATFs (Buck, 2009; Buck et al., 2010; NATO, 2010; Khan et al., 2013; Hamery et al., 2015). The development of level-dependent earplugs and Tactical Communication and Protection Systems (TCAPS; see Table C1) has improved communication capability while providing protection from impulse noise. Previous Metrics such as the CHABA method (Ward, 1968) and MIL-STD 1474D (DoD, 1997) allowed for the same increase in the ANE for any earplug or earmuff. A standardized procedure for measuring the IPIL (ANSI/ASA S12.42:2010) has significantly improved the way that HPDs are included with the Metrics. The IPIL can be measured for new types of devices, such as TCAPS, allowing us to keep up with changing technology.

7.5 Recommendations

Based on our findings and the current State-of-the-Art, it is recommended that:

- The LAeq8hr Metric be used for the assessment of noise exposure for small calibre weapons;
- The exposure limit should be 85 dBA within a 24-hour sliding window; and
- HPDs be accounted for in the assessment of noise exposure using the IPIL.

We also recommend that the Metrics presented in this report be further assessed using data for large calibre weapons (artillery) and blast exposure.

This page intentionally left blank.

References

American Institute of Biological Sciences (AIBS). (2010). Peer review of injury presenting and reduction, Research Task Area, Impulse noise injury models.

ANSI/ASA S1.4-1983(R2006) (1983). Specifications for sound level meters. Acoustical Society of America, New York, NY.

ANSI/ASA S12.7-1986(R2006). (1986). Methods of measurement of impulse noise. Acoustical Society of America, New York, NY.

ANSI/ASA S12.42:2010. (2010). Methods for the measurement of insertion loss of hearing protection devices in continuous noise or impulsive noise using microphone-in-real-ear or acoustic test fixture procedures. Acoustical Society of America, New York, NY.

Berger, E.H. Hearing protection devices. In: Berger E.H., Royster L.H. Royster, J.D. et al., editors. The noise manual, 5th ed. Falls Church, VA: American Industrial Hygiene Association; 2000. pp. 379–454.

Brueck, S.E., Kardous, C.A., Oza, A., Murphy, W.J. (2014). Measurement of exposure to impulsive noise at indoor and outdoor firing ranges during tactical training exercises. Report No. 2013-0124-3208.

Buck, K. (2009). Performance of different types of hearing protector undergoing high-level impulse noise. *International Journal of Occupational Safety and Ergonomics*, 15(2):227–240.

Buck, K., Hamery, P., Zimpfer, V. (2010). The European Regulation 2003/10/EC and the impact of its application to the military noise exposure. Proc. 20th International Congress on Acoustics, Sydney, Australia. Available at: http://www.acoustics.asn.au/conference_proceedings/ICA2010/cdrom-ICA2010/papers/p495.pdf, (Access date: 26 August 2015).

Dancer, A., Franke, R. (1995). Hearing hazard from impulse noise: A comparative study of two classical criteria for weapon noises (Pfander criterion and Smoorenburg Criterion) and the LAeq8 method. Acta Acustica, 3:539–547.

Danielson, R., Henderson, D., Gratton, MA, Bianchi, L., Salvi, R. (1991). The importance of "temporal pattern" in traumatic noise exposures. J. Acoust. Soc. Am. 90(1):209–218.

Davis, R.I., Qiu, W., Hamernik, R.P. (2009). Role of the kurtosis statistic in evaluating complex noise exposures for the protection of hearing. Ear and Hearing, 30:628–634.

Department of Defense, MIL-STD-1474D. (1997). Design criteria standard, noise limits. Superseded by MIL-STD 1474E.

Department of Defense, MIL-STD 1474E. (2015). Design criteria standard, Noise limits.

Department of National Defence (DND). (2004). Training Safety. B-GL-381-001/TS-000.

Direction Terrestre des Armements Terrestres (DTAT). (1983). Recommendation of evaluating the possible harmful effects on noise on hearing. Translation AT-83/27/28.

European Agency for Safety and Health at Work (EU-OSHA). (2003). Directive 2003/10/EC – noise. Available at: https://osha.europa.eu/en/legislation/directives/82, (Access date: 5 August 2015).

Fidele, P.D., Binseel, M.S. Kalb, J.T., Price, G.R. (2013). Using the Auditory Hazard Assessment Algorithm (AHAAH) with hearing protection software, release MIL-STD-1474E. Army Reseach Laboratory, ARL-TR-6748.

Hamery, P., Zimpfer, V., Buck, K., De Mezzo, S. (2015). Very high impulse noises and hearing protection. Proc. EuroNoise 2015, Maastricht. Available at: www.coforg.fr/euronoise2015/output_directory/data.articles/000101.pdf; (Access date: 6 August 2015).

International Organisation for Standardisation (ISO) 1999:2013E. (2013). Acoustics – Determination of occupational noise exposure and estimation of noise-induced hearing impairment. Geneva, Switzerland.

Khan, A., Fackler, C.J., Murphy, W.J. (2013). Comparison of two acoustic test fixtures for measurement of impulse peak insertion loss. EPHB Report No. 350-13a, National Institute for Occupational Safety and Health, Cincinnati, OH.

Murphy, W.J., Khan, A., Shaw, P.B. (2009). An analysis of blast overpressure study data comparing three exposure criteria. EPHB Survey Report 309-05h, National Institute for Occupational Safety and Health, Cincinnati, OH.

Murphy, W.J., Khan, A., Shaw, P.B. (2010). An analysis of chinchilla temporary and permanent threshold shifts following impulsive noise exposure. EPHB Survey Report 338-05c, National Institute for Occupational Safety and Health, Cincinnati, OH.

Murphy, W.J., Kardous, C.A. (2012). A case for using A-weighted equivalent energy as a damage risk criterion. EPHB Report No. 350-11a.

Nakashima, A. (2011). Review of hearing conservation guidelines (impulse noise) in training safety manual B-GL-381-011/TS-000. Defence Research and Development Canada Toronto, Letter Report 3771-1.

Nakashima, A., Farinaccio, R. (2015). Review of weapon noise measurement and damage risk criteria: Considerations for auditory protection and performance. Mil Med, 180(4):402–408.

Nakashima, A. (2015). A comparison of different types of hearing protection devices for use during weapons firing. *Journal of Military, Veterans and Family Health*, 1(2):43–51.

North Atlantic Treaty Organisation. (2003). Reconsideration of the effects of impulse noise. Research and Technology Organisation Technical Report TR-017.

North Atlantic Treaty Organisation. (2010). Hearing Protection – Needs, Technologies and Performance. Research and Technology Organisation Technical report TR-HFM-147.

Pfander, F., Bongartz, H., Brinkmann, H., Kietz, H. (1980). Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. J. Acoust. Soc. Am. 67(2):628–633.

Shaw, E. A. G. (1985). Occupational noise exposure and noise-induced hearing loss: Scientific issues, technical arguments and practical recommendations. National Research Council Canada, NRCC No. 25051.

Ward, W.D. (1968). Proposed damage-risk criterion of impulse noise (gunfire). Report of Working Group 57, National Academy of Sciences-National Research Council Committee on Hearing, Bioacoustics, and Biomechanics.

Zhao, Y-M., Qiu, W., Zeng, L. et al. (2010). Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. Ear and Hearing 31:527–532.

This page intentionally left blank.

Annex A Assessment of impulse noise exposure metrics for weapon training safety

Background

At the request of the Directorate Force Health Protection, a study was conducted to recommend a Metric for impulse noise exposure for weapon training. The current hearing conservation guidelines in the Training Safety document [1] were previously analyzed and determined to be outdated [2]. The recommendations presented herein are based on a thorough review of current impulse noise exposure Metrics and an analysis using noise data from in-service small calibre weapons. Full details are provided in a DRDC scientific report [3].

Statement of results

Three Metrics were selected based on critical reviews of the State-of-the-Art carried out by a North Atlantic Treaty Organisation (NATO) group [4], the American Institute of Biological Sciences (AIBS) [5] as well as the National Institute of Occupational Safety and Health (NIOSH) [6]. The three Metrics selected were 1) the equal energy equivalent averaged over eight hours (L_{Aeq8hr}), 2) Auditory Risk Units (ARU) calculated using the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model, and 3) the equal energy equivalent averaged over 100 ms intervals ($L_{IAeq100ms}$). The first Metric is used in France [7] and the others are from the recently released Military Standard, MIL-STD 1474E [8]. The Metrics were evaluated from a feasibility perspective using noise recordings generated during the firing of Canadian Armed Forces (CAF) small calibre weapons. Table A.1 shows the peak noise levels of CAF weapons that were measured at the firing point.

Table A.1: *Peak noise levels of the weapons at the firing point, measured 0.5 to 1m to the side of the shooter.*

Weapon	Unweighted Peak Noise Level (dB SPL)
9mm pistol	163
C7	162*
C8 unsuppressed	143
C8 suppressed	165
C14 unsuppressed	142
C14 suppressed	171
C15 suppressed	145
C15 unsuppressed	177

*Microphone was taped to the ballistic eyewear worn by the shooter.

The Metrics were used to calculate the allowed number of exposures (ANE) within a 24-hour period for the unsuppressed weapons (Table A.2). The exposure limit is 85 dBA (decibels, A-weighted) for both the L_{Aeq8hr} and $L_{IAeq100ms}$ Metrics, and 500 ARU for the AHAAH. The use of a hearing protection device (HPD) can be included in the calculation of the ANE if its noise attenuation value, called the impulse peak insertion loss (IPIL), is known. IPIL values for several types of HPDs were measured in a previous study [9]. Since the IPIL that is achieved by a user is largely dependent on how well it fits, we used the IPIL for different types of HPDs rather than specific manufacturer models; these types are specified in Table A.2. HPD users are encouraged to determine the type of HPD that provides the appropriate amount of protection, and then select the device within that category that fits them the best.

Table A.2: *Allowed number of exposures (ANE) for unsuppressed weapons at the firing point. The ANE were calculated using the highest peak levels for each measurement, indicating the worst case scenario and therefore the most conservative result.*

Type of Hearing Protection Device	L_{Aeq8hr}	AHAAH[1]	$L_{IAeq100ms}$
C7			
Unprotected	1	2	3
Earplug, passive level-independent (IPIL 28)	977	237	1622
Earmuff, passive level-independent (IPIL 22)	245	313	406
Earplug, passive non-linear (IPIL 10)	15	24	25
Earplug and earmuff, passive level-independent (IPIL 39)	12300	495	20600
C8			
Unprotected	2	4	3
Earplug, passive level-independent (IPIL 28)	1737	456	2052
Earmuff, passive level-independent (IPIL 22)	436	750	513
Earplug, passive non-linear (IPIL 10)	27	95	32
Earplug and earmuff, passive level-independent (IPIL 39)	21800	1100	26000
C14			
Unprotected	0	2	2
Earplug, passive level-independent (IPIL 28)	323	125	950
Earmuff, passive level-independent (IPIL 22)	81	320	238
Earplug, passive non-linear (IPIL 10)	5	29	5
Earplug and earmuff, passive level-independent (IPIL 39)	4073	497	12000
C15			
Unprotected	0	2	1
Earplug, passive level-independent (IPIL 28)	95	141	1042
Earmuff, passive level-independent (IPIL 22)	23	108	113
Earplug, passive non-linear (IPIL 10)	1	18	7
Earplug and earmuff, passive level-independent (IPIL 39)	1202	279	5747
9mm Pistol			
Unprotected	6	10	20
Earplug, passive level-independent (IPIL 28)	3981	1574	13400
Earmuff, passive level-independent (IPIL 22)	1000	1910	3355
Earplug, passive non-linear (IPIL 10)	63	90	210
Earplug and earmuff, passive level-independent (IPIL 39)	50000	3340	170000

[1]AHAAH calculation for unprotected used microphone placement 1 (free-field). Protected exposures were for default settings (microphone placement 3 [at eardrum], normal incidence).

Statement of discussion

The L_{Aeq8hr} is an energy-based Metric that was easily implemented with a program written in Matlab (The Mathworks, Inc, R2013b, Natick, MA). The ANE results listed in Table A.2 for the different HPD types were consistent with their respective IPIL values; that is, the ANE were higher for HPD types with a higher IPIL. The L_{Aeq8hr} has been recommended in the literature by two independent groups [5,6]. The ease of implementation and positive reviews from the literature make the L_{Aeq8hr} Metric feasible for use by the CAF.

The AHAAH software was downloaded from the US Army Research Laboratory website [10]. The software is a graphical user interface and does not provide the user with visibility of the calculations. It is not user-friendly in its current state of development. In particular, there are options in the model for microphone placement, choice of HPD and angle of sound arrival at the ear that may be difficult for inexperienced users to understand. The AHAAH software has built-in functions for applying HPDs that sometimes produced unexpected results. For example, the ANE that were calculated for double protection (earplug and earmuff worn together) were much lower than expected based on the L_{Aeq8hr} results. Several independent reviews from the literature have indicated that the AHAAH model has significant scientific flaws [4,5,6]. Given the difficulties experienced with using the software and the critical reviews from the literature, the AHAAH Metric is not recommended for CAF use.

The $L_{IAeq100ms}$ energy-based metric like the L_{Aeq8hr}, and it was easily implemented with a similar Matlab program. Protected exposures were calculated using IPIL values. The $L_{IAeq100ms}$ differs from the L_{Aeq8hr} in that it uses a correction factor that accounts for the duration of the impulse (A-duration; see Figure A.1). The correction factor reduces the overprediction of noise dose for longer impulses (e.g., large calibre weapons and blasts). Some difficulties were encountered in using the A-duration correction. This is illustrated by Figure A.2, which shows the noise signal from a C8 suppressed weapon measured at the firing point. The reflections of the noise signal from the ground surface and the shooter’s body make it difficult to extract the A-duration according to its definition. The A-duration correction clearly changes the noise dose calculation as shown in Table A.2. The ANE values calculated with the $L_{IAeq100ms}$ Metric are larger than those calculated with the L_{Aeq8hr} Metric. It is stated in MIL-STD 1474E that the $L_{IAeq100ms}$ Metric has not been systematically validated or peer-reviewed [8]. Given the uncertainty associated with the correct measurement of the A-duration and lack of supporting literature, the $L_{IAeq100ms}$ Metric is not recommended for CAF use.

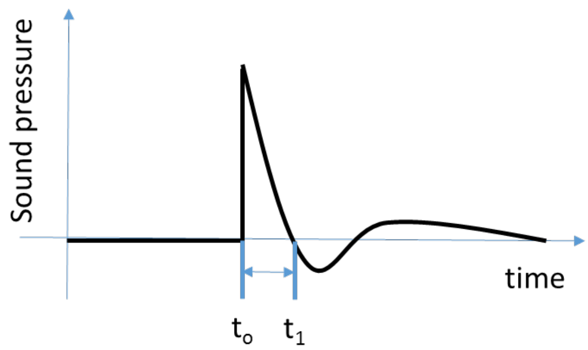


Figure A.1: *Idealized impulsive signal in the free-field with A-duration equal to t1-t0.*

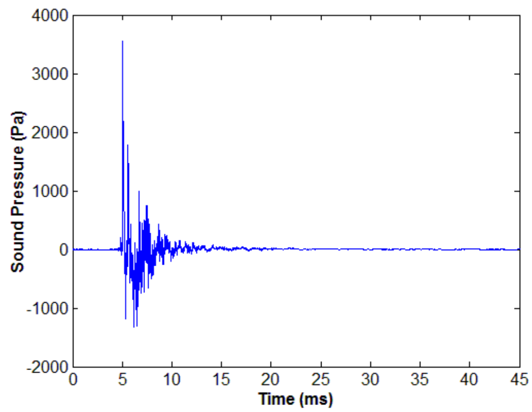


Figure A.2: *Pressure-time signal of the C8 (unsuppressed) measured at the firing point.*

Recommendations

Based on the literature review and validation of the metrics using CAF-relevant data, DRDC recommends that:

1. The L_{Aeq8hr} Metric be used for the assessment of noise exposure for small calibre weapons;
2. The exposure limit be 85 dBA (decibels, A-weighted) within a 24-hour sliding window; and
3. Hearing protection be accounted for in the assessment of noise exposure using the IPIL.

Data from large calibre weapons and blasts were not available for the current analysis and should be investigated further.

Prepared by: Ann Nakashima, M.A.Sc., Defence Research and Development Canada, Toronto Research Centre.

References

[1] Department of National Defence. (2004). Training Safety. B-GL-381-001/TS-000.

[2] Nakashima, A. (2011). Review of hearing conservation guidelines (impulse noise) in training safety manual B-GL-381-011/TS-000. Defence Research and Development Canada, Letter Report 3771-1.

[3] Nakashima, A. (2015). A comparison of metrics for impulse noise exposure: Analysis of Noise Data from Small Calibre Weapons. Defence Research and Development Canada, Scientific Report DRDC-RDDC-2015-R243.

[4] NATO Research and Technology Organisation. (2003). Reconsideration of the effects of impulse noise. RTO Technical Report TR-017.

[5] AIBS. (2010). Peer review of injury presenting and reduction, Research Task Area, Impulse noise injury models. 2010.

[6] NIOSH (2012). A case for using A-weighted equivalent energy as a damage risk criterion. EPHB Report No. 350-11a.

[7] Ministere de la Defense, Groupe de coordination technique (1983). Recommendation on evaluating the possible harmful effects of noise on hearing, DTAT Traduction AT-83/27/28.

[8] MIL-STD-1474E. (2015). Department of Defence Design Criteria Standard, Noise Limits.

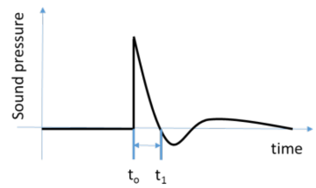
[9] Nakashima, A. (2015). A comparison of different types of hearing protection devices for use during weapons firing. Journal of Military, Veterans and Family Health, 1(2):43–51.

[10] United States Army Research Laboratory, Auditory Hazard Assessment Algortihm for Humans (AHAAH). http://www.arl.army.mil/www/default.cfm?page=343, (Access date: 4 November 2015).

This page intentionally left blank.

Annex B Acoustical terminology, equations and acronyms

Table B.1: *Acoustic definitions and acronyms.*

Name	Description	Equation/definition
A-duration	The time interval between the impulse onset and the first crossing with the baseline.	A-duration = t_1-t_0 
AHAAH	Auditory Hazard Assessment Algorithm for Humans	
AIBS	American Institute of Biological Sciences	
ANE	Allowed Number of Exposures	
ANSI	American National Standards Institute	
ARL	Army Research Laboratory	
ARU	Auditory Risk Units	
CAF	Canadian Armed Forces	
CFB	Canadian Forces Base	
CHABA	Committee on Hearing, Bioacoustics and Biomechanics of the National Research Council	
Decibel (dB)	Unit of sound pressure level	The ratio sound energy relative to a reference value, usually the average human hearing threshold (20µPa).
dBA	A-weighted sound pressure level	Weighted sound pressure level to account for the frequency sensitivity of the human auditory system (see Figure B1).
dB SPL	Unweighted sound pressure level	Used to distinguish unweighted sound pressure levels from A-weighted.
D_I(%)	Impulsive noise dose for a single impulse, calculated with $L_{IAeq8hr}$ (MIL-STD 1474E)	$D_I(\%) = \frac{100}{2^{(85-L_{IAeq8hr})/3}}$
DND	Department of National Defence	
DoD	Department of Defence	
DTAT	Direction Terrestre des Armements Terrestres	
EU	European Union	
HPD	Hearing Protection Device	
ISO	International Organisation for	

	Standardization	
L_p	Sound pressure level, in decibels, referenced to $p_o = 2x10^{-5}$ Pa	$L_p = 10Log10\left(\frac{p^2}{p_o^2}\right)$ $p_o = 2x10^{-5}$
L_{peak}	Peak sound pressure level, in decibels	$Max\|L_p\|$
$L_{Aeq,T}$	Equivalent continuous A-weighted sound pressure level	$L_{Aeq,T} = 10log\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_o^2}dt\right]$
L_{Aeq8hr}	Equivalent noise exposure level normalized to a nominal 8 hour working day.	$L_{Aeq8hr} = L_{Aeq,T} + 10log\left(\frac{t_2 - t_1}{T_o}\right) + 10logN$
$L_{EX,8hr}$		$L_{EX,8hr} = L_{Aeq,Te} - 10log\left(\frac{T_e}{T_o}\right)$
$L_{IAeq100ms}$	Equal energy equivalent averaged over 100ms intervals (MIL-STD 1474E)	$L_{IAeq100ms} = 10log\left\{\frac{1}{T}\sum_{i=1}^{n}10log^{-1}\left[\frac{L_{Ai}}{10}\right] \times \Delta t_i\right\}$
$L_{IAeq8hr}$	Equivalent noise exposure level normalized to a nominal 8 hour working day, calculated with $L_{IAeq100ms}$ (MIL-STD 1474E)	$L_{IAeq8hr} = L_{LIeq100ms} - 54.6 - 1.5 * 10 * log\left(\frac{\text{A} - \text{duration}}{0.2}\right)$ $L_{IAeq8hr} = L_{LIeq100ms} - 71.0$
MDE	Maximum Daily Exposure	
MEM	Middle Ear Muscle	
MIL-STD	Military Standard	
P_{peak}	Peak sound pressure (Pa)	$Max\|p\|$
Pa	Pascals, unit of sound pressure	
TCAPS	Tactical Communication and Protection Systems	
TTS	Temporary Threshold Shift	

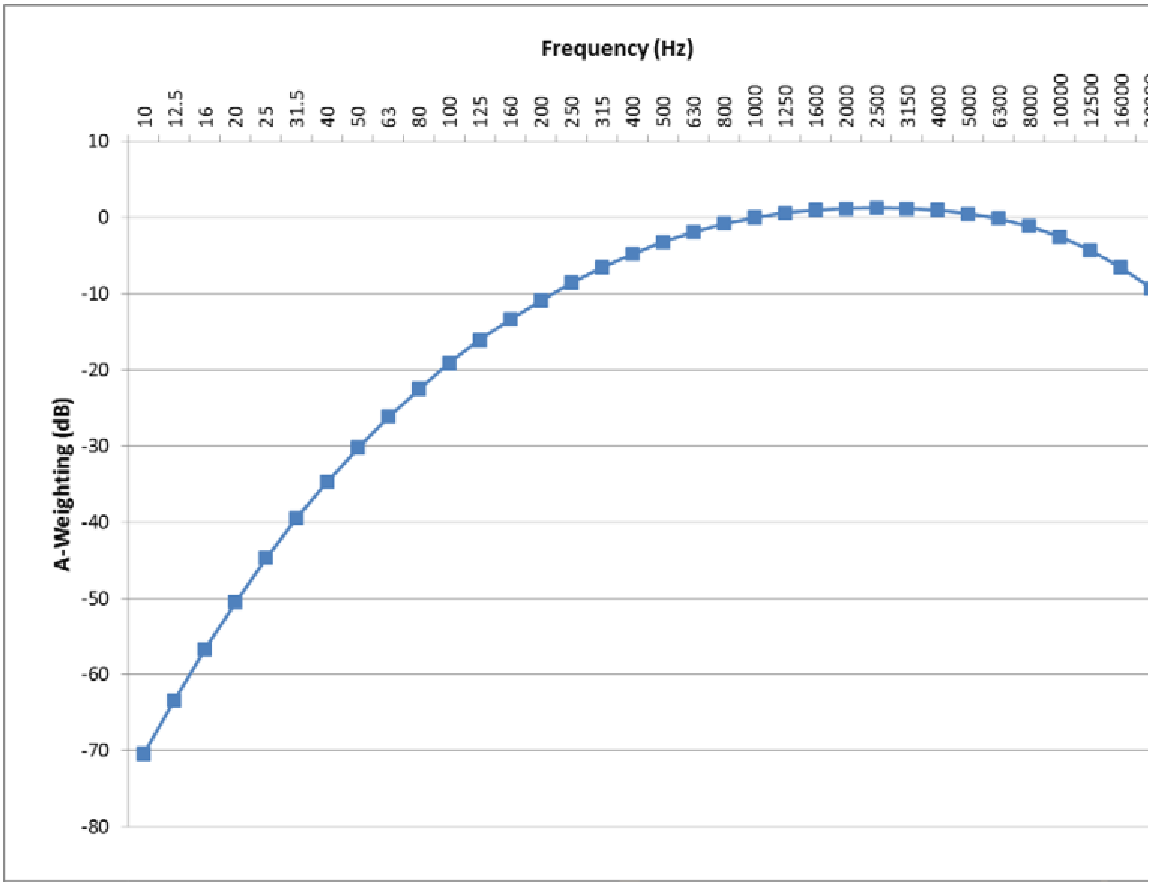


Figure B.1: *A-weighting scale, reproduced from ANSI/ASA S1.4:1983(R2006).*

This page intentionally left blank.

Annex C Description of hearing protection devices

Table C.1: *Descriptions and examples of hearing protection devices. Note that this list is not exhaustive, as some devices incorporate multiple technologies.*

Type	Description	Example
Earplug, passive, level-independent	In-ear, non-electronic device. Attenuation does not change with noise level.	E-A-R™ Classic™ (3M, St. Paul, MN)
Earmuff, passive, level-independent	Circumaural, non-electronic device. Attenuation does not change with noise level.	Peltor™ H10A (3M, St. Paul, MN)
Earplug, passive, non-linear	In-ear, non-electronic device. Usually, low attenuation for noise below 110 dB, and higher attenuation for noise above 110 dB	Combat Arms™ (3M, St. Paul, MN)
Earmuff, active, limited amplification	Electronic device with microphone on the outside of the earcup. Limited amplification of ambient sounds (such as speech) to the ear, usually to 82 dBA.	Impact™ (Howard Leight by Honeywell, Smithfield, RI)
Active Noise Reduction (ANR)	Electronic device with active noise cancellation. Can be in-ear or circumaural.	Racal Slimguard (Racal Acoustics by Esterline, Harrow, UK)
Tactical Communication and Protection System (TCAPS)	Electronic integrated radio communication and hearing protection device. Can be in-ear or circumaural. Can include ANR and/or limited amplification.	QP400 (Honeywell Safety, Smithfield, RI)
Double protection	Any combination of earplug and earmuff worn together	

This page intentionally left blank.

Annex D Peak noise levels

Table D.1: *C7 peak noise levels.*

Distance (m)	Peak Level				
	0º (left of shooter)	**45º**	**90º (behind shooter)**	**135º**	**180º (right of shooter)**
4			140.2		151
8			136.9		145.2
12			130		141.2
16			133.1		139.9
20			126.3		138.2
	Left Ear		**Right Ear**		
At shooter	159.7		161.8		
At range safety officer	150.1		151.2		

Table D.2: *C8 Unsuppressed peak noise levels.*

Distance (m)	Peak Level				
	0º (left of shooter)	**45º**	**90º (behind shooter)**	**135º**	**180º (right of shooter)**
4	155.2	149.5	141.9	144.2	148.7
8	151.7	145.1	134.7	137.5	145.2
12	141.6	136.8	130.3	130.6	135.6
16	140.7	134	127.9	128	133.2
	Left Ear		**Right Ear**		
0.5	165.0		161.2		

Table D.3: *C8 Suppressed peak noise levels.*

Distance (m)	**Peak Level**				
	0^{o} (left of shooter)	**45^{o}**	**90^{o} (behind shooter)**	**135^{o}**	**180^{o} (right of shooter)**
4	135.3	129	121.2	129.1	129.7
8	135.9	124.7	115.7	122.3	124.4
12	123.3	114.3	111.9	114.9	116.4
16	121.1	111.7	109.5	112.2	113.1
	Left Ear		**Right Ear**		
0.5	143.3		142.4		

Table D.4: *C14 Unsuppressed peak noise levels. The cells containing >140 indicate that the microphones overloaded[1].*

Distance (m)	**Peak Level**				
	0^{o} (left of shooter)	**45^{o}**	**90^{o} (behind shooter)**	**135^{o}**	**180^{o} (right of shooter)**
4	162.3	159.5	156.6	157.5	162.9
8	156.1	154.7	152	152.6	155
12	> 140	> 140	> 140	> 140	> 140
16	> 140	> 140	> 140	> 140	> 140
	Left Ear		**Right Ear**		
0.5	171.5		170.3		

[1]Dynamic ranges of the microphones placed at 12 and 16 m were lower than the microphones placed closer to the weapon.

Table D.5: *C14 Suppressed peak noise levels.*

Distance (m)	Peak Level				
	0° (left of shooter)	**45°**	**90° (behind shooter)**	**135°**	**180° (right of shooter)**
4	137.5	131.5	123.6	135.8	132.1
8	137.9	129.5	116.1	133.8	119.6
12	130.1	117.6	112.1	123.1	115.2
16	126	115.3	109.6	121.4	112.9
	Left Ear		**Right Ear**		
0.5	143.6		142.1		

Table D.6: *C15 Unsuppressed peak noise levels*[1]*.*

Distance (m)	Peak Level				
	0° (left of shooter)	**45°**	**90° (behind shooter)**	**135°**	**180° (right of shooter)**
4	165.6	163.1	162.4	164.1	164.7
8	157.2	155.6	154.4	155.3	158.4
12	> 140	> 140	> 140	> 140	> 140
16	> 140	> 140	> 140	> 140	> 140
	Left Ear		**Right Ear**		
0.5	175.3		176.9		

1 Dynamic ranges of the microphones placed at 12 and 16 m were lower than the microphones placed closer to the weapon.

__Table D.7:__ C15 Suppressed peak noise levels.

Distance (m)	**Peak Level**				
	0^o (left of shooter)	**45^o**	**90^o (behind shooter)**	**135^o**	**180^o (right of shooter)**
4	139.8	131.7	127	132.8	138
8	135.4	124.9	122.2	130.2	136.4
12	129.9	120.6	118	122	128
16	127.9	118.4	116.3	119.2	125.2
	Left Ear		**Right Ear**		
0.5	146.1		144.1		

__Table D.8:__ C16 grenade launcher peak noise levels.

Distance (m)	**Peak Level**				
	0^o (left of shooter)	**45^o**	**90^o (behind shooter)**	**135^o**	**180^o (right of shooter)**
4	150.7	145.6	136.4	136.6	144
8	147.2	140.4	131	133.5	141.1
12	140.9	134.1	123.9	128.1	136
16	140.2	132.5	120.9	126	135.2
	Left Ear		**Right Ear**		
0.5	148.1		151.3		

DOCUMENT CONTROL DATA

(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Designated)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g., Centre sponsoring a contractor's report, or tasking agency, are entered in Section 8.) DRDC – Toronto Research Centre Defence Research and Development Canada 1133 Sheppard Avenue West P.O. Box 2000 Toronto, Ontario M3M 3B9 Canada	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) UNCLASSIFIED 2b. CONTROLLED GOODS (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC DECEMBER 2013

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

A comparison of metrics for impulse noise exposure : Analysis of noise data from small calibre weapons

4. AUTHORS (last name, followed by initials – ranks, titles, etc., not to be used)

Nakashima, A.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
November 2015	52	32

7. DESCRIPTIVE NOTES (The category of the document, e.g., technical report, technical note or memorandum. If appropriate, enter the type of report, e.g., interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Scientific Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

DRDC – Toronto Research Centre
Defence Research and Development Canada
1133 Sheppard Avenue West
P.O. Box 2000
Toronto, Ontario M3M 3B9
Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR’S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
DRDC-RDDC-2015-R243	

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

A previous analysis of the Department of National Defence (DND) training safety document concluded that the recommendations for hearing conservation during weapons training are outdated. Current impulse noise metrics being used by the United States (MIL-STD 1474E) and France (DTAT, 1983) were analyzed by way of literature review and feasibility assessment using weapon noise recordings from in-service weapons. The noise exposures for the shooter and potential observers, with and without the use of hearing protection devices, were considered in the analysis. Based on the critical reviews of the metrics from the literature and the current feasibility assessment, it is recommended that an equivalent energy approach (L_{Aeq8hr}) be implemented for the assessment of noise exposure from small calibre weapons. Large calibre weapons and blasts were not considered in the current analysis and should be further investigated.

Dans le cadre d’une analyse précédente du document du ministère de la Défense nationale (MDN) sur la sécurité de l’entraînement, on avait conclu que les recommandations concernant la protection de l’ouïe pendant l’entraînement au tir étaient désuètes. Les mesures actuelles du bruit impulsif, utilisées par les États-Unis (MIL-STD 1474E) et la France (DTAT, 1983), ont été analysées dans une revue documentaire et une étude de faisabilité à l’aide d’enregistrements de bruits provenant d’armes de service. Dans cette analyse, on a tenu compte de l’exposition au bruit pour le tireur et les observateurs potentiels, avec ou sans dispositif de protection de l’ouïe. Selon un examen critique des mesures tirées de la revue documentaire et de la présente étude de faisabilité, on recommande de mettre en œuvre une méthode d’énergie équivalente (L_{Aeq8hr}) pour évaluer l’exposition au bruit des armes de petit calibre. On n’a pas tenu compte des armes de gros calibre et des explosions dans la présente analyse. Celles-ci devraient faire l’objet d’une autre recherche.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g., Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

impulse noise; hearing conservation