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DTA Report 425
NR 1715

Impulse Noise Measurement and Assessment in the New Zealand Army: A Scoping Study

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ABSTRACT

The New Zealand Army Landworthiness Authority has recently considered the risk of hearing damage in the NZDF due to impulse noise exposure. The need for a consistent noise database of all in-service weapons was identified, with a view to informing a hearing protection program. This report considers the problem of impulse noise measurement and assessment of noise exposure, with the aim of meeting the requirements of the Health and Safety at Work Act. Existing standards and guidelines relating to impulse noise are reviewed, and a measurement system capable of capturing the necessary acoustic data is proposed. Finally, areas where scientific uncertainties remain are identified and mitigation approaches suggested.

DTA Report 425
ISSN 1175-6594 (Print)
ISSN 2253-4849 (Online)

Published by
Defence Technology Agency
Private Bag 32901
Devonport
Auckland 0744
New Zealand

EXECUTIVE SUMMARY

BACKGROUND

Following a subject matter review in March 2017, the New Zealand Army Landworthiness Authority has determined a number of requirements to mitigate the risk of hearing damage due to impulse noise. One of these is the collection of a comprehensive and consistent impulse noise database from all ammunition, explosives and pyrotechnics in NZDF service.

AIM

The aims of this study were: to survey existing standards and guidelines relating to impulse noise measurement; to propose a noise measurement system; to review scientific literature regarding impulse noise hearing damage; to identify areas where scientific uncertainties remain and suggest possible mitigation strategies.

RESULTS

The problem of impulse noise measurement, and assessment of noise exposure, has been considered with the aim of satisfying the requirements of the Health and Safety at Work Act 2015. Existing standards and guidelines relating to impulse noise were reviewed, and a number of areas identified where there are uncertainties in the interpretation of existing data. The key findings and recommendations are listed below.

- Due to the high directivity of muzzle blast noise, a multichannel high-pressure acoustic measurement system is required to capture the angular variation of the sound level. The preferred option would have a nine channel capability.
- Microphones should be placed in a semicircle 3 m from the muzzle, covering angles from 5 degrees to 180 degrees in equal increments, at 1.6 m height. An additional microphone should also be placed near the most exposed ear of the firer.
- An acoustic propagation model is required which must extrapolate from measurement positions to estimate acoustic pressure at arbitrary receiver points. This may require a small number of dedicated measurements to confirm model performance, particularly in the near-field of the source.
- A program of experimentation using an artificial head is recommended covering those hearing protection options likely to be used by the NZDF.
- A methodology is needed to estimate average noise dose in different training environments, under static and moving conditions, and with multiple impulse sources present.
- The Auditory Hazard Assessment Algorithm for Humans (AHAAH) has been reviewed regarding suitability for impulse noise risk assessment. While promising, a number of concerns with the model have been raised by an independent review panel. AHAAH should not be proposed for use in New Zealand until those issues have been addressed.

- The impulse noise exposure limits recommended by the NATO RSG-029 panel should replace Regulation 11 of the Health and Safety at Work Act for the NZDF. The current limits are excessively restrictive for low frequency impulse noise exposure, and too permissive for high frequency impulse noise.

SPONSOR

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SYMBOLS AND ABBREVIATIONS

AHAAH	Auditory Hazard Assessment Algorithm for Humans
B&K	Brüel & Kjaer
DoD	Department of Defence
DRC	damage risk criterion
DSA	dynamic signal acquisition
HRTF	head-related transfer function
HSEA	Health and Safety in Employment Act
HSWA	Health and Safety at Work Act
IL	insertion loss
MAT	MATLAB binary data file format
NATO	North Atlantic Treaty Organisation
NI	National Instruments
NIOSH	National Institute for Occupational Safety and Health
NR	noise reduction
NZDF	New Zealand Defence Force
PTS	permanent threshold shift
REAT	real ear attenuation at threshold
SEL	sound exposure level
SNR	signal-to-noise ratio
SPL	sound pressure level
TTS	temporary threshold shift
WAV	waveform audio file format

CONTENTS

1 INTRODUCTION

Impulse noise is characterized by a rapid rise in acoustic pressure followed by an exponential decay. Muzzle blast from guns and noise from explosive charges are sources of impulse noise that are commonly encountered in military service. The acoustic energy from these events is concentrated into a few milliseconds or less, and can be very damaging to the unprotected ear.

The New Zealand Army has a program to replace its hearing protectors with devices that are compatible with individual protection and communications equipment. It is likely that the outcomes of this program will influence Navy and Air Force in future hearing protector acquisition. The hearing protector solution must be compliant with New Zealand's health and safety legislation, and include guidance regarding the maximum number of exposures per day.

Following a subject matter review in March 2017, the New Zealand Army Landworthiness Authority has determined a number of requirements to mitigate the risk of hearing damage due to impulse noise [1]. One of these is the collection of data to produce a "comprehensive and consistent impulse noise database from all ammunition, explosives and pyrotechnics in NZDF service".

A working group, including Army and DTA representatives, has been established to undertake this task. The working group must propose:

- how acoustic measurements should be made - equipment, measurement positions, and data management;
- a time line for measurement activities;
- a methodology to predict hearing protector effectiveness and noise exposure;
- a process for external review.

The proposal must be costed and funding options explored. Due to the scope of this task, industry support will be required. DTA will make recommendations regarding measurement equipment and methodology, noise exposure assessment, and the appropriate use of external consultants.

2 LEGISLATIVE REQUIREMENTS ON NOISE EXPOSURE

Under the 2015 Health and Safety at Work Act (HSWA), existing health and safety regulations remain in force unless amended. Hence, at present, Regulation 11 of the 1995 Health and Safety in Employment Act (HSEA) is still the legal requirement for workplace noise management. Regulation 11 states that

> "Every employer must, so far as is reasonably practicable, ensure, in relation to every workplace under the control of that employer, that no employee is exposed to noise above the following levels:
>
> (a) a noise exposure level, LAeq,8h, of 85 dB(A); and
>
> (b) a peak noise level, Lpeak, of 140 dB,-
>
> whether or not the employee is wearing a personal hearing protection device."

Part (2)(c) of Regulation 11 requires workplace noise to be assessed in accordance with the AS 1269:1989 standard. This standard defines measurement procedures, equipment that should be used to perform measurements, and how the effect of hearing protectors can be assessed. It has been revised since the HSEA was written, and the latest version is AS/NZS 1269:2005. The implications of this standard for impulse noise measurement are discussed in Section 6.

The HSWA takes a proactive view of health and safety, rather than a reactive view. It is expected that organizations seek out potential hazards before they occur and mitigate them, rather than fix problems after an incident. This suggests there is some obligation on the NZDF to also investigate the suitability of Regulation 11 as a metric of impulse noise hazard.

The limits in Regulation 11 are commonly applied to workplace steady-state noise and were not intended to cover the situation of highly impulsive sound sources. Over several decades a substantial body of research on the effects of impulse noise has accumulated, but this is not currently reflected in the legislation. A number of damage risk criteria specific to impulse noise have been proposed and these are presented in Section 3.

3 HEARING DAMAGE RISK CRITERIA FOR IMPULSE NOISE

This section provides a short review of impulse noise damage risk criteria that have been proposed or are in use today. A comprehensive account was given by McBride in a 2010 paper written for New Zealand's Accident Compensation Commission [2], which discusses in more detail how the temporary threshold shift has been used to assess risk of hearing damage. Here the main outcomes of the research are given, and tools and techniques for assessing impulse noise hazard are discussed.

3.1 The 1968 CHABA criteria

The earliest systematic attempt to devise a damage risk criterion (DRC) for impulse noise was undertaken by the U.S. National Academy of Sciences Committee on Hearing, Bioacoustics, and Biomechanics (CHABA). The resulting 1968 CHABA DRC was based on experimental measurements of temporary threshold shift (TTS) in subjects exposed to gunshots, without the use of hearing protection [2–4].

Using these measurements, the committee proposed limits on the TTS measured two minutes after exposure, TTS_2, that could be allowed without risking permanent hearing loss. The proposed limit on TTS_2 was 10 dB at or below 1 kHz, 15 dB at 2 kHz, and 20 dB at 3 kHz and above [5].

Based on data available at the time the CHABA working group proposed an impulse noise exposure limit of

$$L_{\text{pk}} + 6.67\log_{10} T_B + 5\log_{10} N \leq 163.4 \tag{1}$$

to satisfy the TTS_2 limit criteria for 95% of the population [5, p4]. Here, L_{pk} is the peak pressure level, T_B is the B-duration of the impulse (the total time that the acoustic pressure envelope is within 20 dB of the peak) in milliseconds, and N is the number of impulses. T_B should be limited to a maximum of 200 ms. For example, the M14 rifle produces peak SPL of around 160 dB, and has a B-duration of about 5 ms. In this case the 1968 CHABA DRC would allow only one unprotected shot [2].

Other researchers have reinvestigated this problem as more experimental TTS data have become available. Pfander et al. developed a damage risk criterion (DRC) using audiometric data from soldiers exposed to rifle fire without hearing protection [6]. It was based on the total energy in a series of impulses, using slightly different allowed TTS criteria to the CHABA recommendations. In 1982, Smoorenburg took a similar approach, but using measurements from 11 different impulse noise TTS studies [7].

The CHABA risk criterion, and the later criteria of Pfander and Smoorenburg, all assume that longer impulse waveforms are more damaging than shorter waveforms, and ignore the spectral properties of the impulse.

However, experiments have shown that impulses with a reduced A-duration[1] but the same peak level produce increased hearing loss, despite having less total acoustic energy [5, p5]. This can only be explained if the human hearing system has a sensitivity to high frequency noise that is not accounted for by the A-weighting function [5, p13].

Moreover, there is strong evidence that an impulse noise damage model should include a non-linear mechanism that can account for the reduction in damage observed when low-frequency energy content increases [8, 1.7].

3.2 MIL-STD-1474D

The U.S. Department of Defense impulse noise exposure standard prior to 2015 was defined in MIL-STD 1474D, and was based on the 1968 CHABA criterion (Section 3.1). MIL-STD 1474D stipulates an allowable number of impulses in one day to avert the risk of hearing loss. The allowable number is a function of hearing protection (single or double), peak sound level, and the B-duration of the impulse waveform [9]. The B-duration is the length of time that pressure fluctuations are within 20 dB of the peak level.

When the peak pressure level of an impulse is below 140 dB the MIL-STD 1474D does not require hearing protection, and the number of exposures is unlimited [9, Table 4-1]. When the peak pressure exceeds 140 dB either single or double hearing protection must be used. The number of allowable exposures per day is given below in Table 1. The standard does not account explicitly for the spectral content, or for combined exposure to continuous and impulsive noise. Additionally, it does not account for the protection provided by the non-linear acoustic reflex and the peak clipping that occurs in the middle ear [5].

	Max. impulses per day
No protection	0
Single protection	$N_1 = 10^{L/5}$
Double protection	$N_2 = 20N_1$

Table 1: The MIL-STD-1474D number of allowable impulse exposures per day as a function of hearing protection for impulses with a peak pressure exceeding 140 dB. The level L is defined by $L = 177 - L_{\text{pk}} + 6.64 \log_{10}(200/T_B)$, where L_{pk} is the peak pressure level in decibels and T_B is the B-duration of a single impulse in milliseconds.

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[1] A-duration is the time interval between the impulse onset and return to zero overpressure.

3.3 Pfander criterion

Pfander et al. proposed a variant of the 1968 CHABA criteria utilizing different measures of impulse duration and accumulation of risk due to multiple impulses [6]. From a paper by Chan et al., the Pfander criterion can be expressed as [10]

$$L_P = L_{\text{pk}} + 10\log_{10} T_c + 10\log_{10} N \leq 164.6 \tag{2}$$

where L_{pk} is the peak pressure in decibels, and T_c is the C-duration in milliseconds (the integrated time where the absolute amplitude of the waveform is within 10 dB of the peak pressure) in milliseconds and N is the number of impulses [10]. The effect of hearing protection can be incorporated by adding the peak attenuation to the allowable exposure level. For example, if the peak attenuation of a hearing protector was 25 dB then the maximum exposure level would increase to 189.6 dB. The Pfander criterion was adopted for military use by the Federal Republic of Germany.

3.4 Smoorenburg criterion

Smoorenburg proposed an exposure limit with a nearly identical form to Pfander [7], which can be expressed in the form

$$L_S = L_{\text{pk}} + 10\log_{10} T_d + 10\log_{10} N \leq 166.2 \tag{3}$$

where again L_{pk} is the peak pressure, and N is the number of impulses [10]. However, the definition of impulse duration is different: here, T_d is the time in milliseconds during which the envelope of the waveform remains within 10 dB of the peak pressure, which is called the D-duration [10]. Again, the effect of hearing protection is included by adding the peak attenuation to the maximum allowable exposure level.

3.5 Auditory Hazard Assessment Algorithm for Humans

The Auditory Hazard Assessment Algorithm for Humans (AHAAH) model is an electro-acoustic model of the ear developed by the U.S. Army Research Laboratory. It is designed to model the transfer function from free-field acoustic pressure to basilar membrane displacement [11]. The model assumes that auditory damage is related to the sum of peak, squared upward displacements of the basilar membrane during an impulse noise exposure.

The AHAAH model attempts to account for protective non-linearities of the middle and inner ear and explains why short impulses can cause more hearing damage than longer impulses, even if they contain less acoustic energy [12].

Based on the prediction of basilar membrane displacement an impulse noise damage risk measured in “Auditory Risk Units” (ARUs) is calculated. For a single impulse a maximum of 500 ARUs is allowed; if this limit is exceeded permanent hearing loss may occur. Exposure is cumulative if the subject is exposed to repeated impulses. Other researchers have recommended reducing this limit to 200 ARUs for regular occupational exposures [13].

The model now includes a module for predicting the effects of generic earmuffs and earplugs, covering a total of eleven hearing protection configurations. The hearing protection module models all hearing protectors as passive level independent devices. The module also provides models for several level dependent non-linear protectors, but these are treated as linear devices using octave band attenuation measurements [13–15].

The AHAAH model was reviewed by the NATO RSG-029 panel in 2003, as part of a comprehensive study of auditory damage risk due to impulse noise. The review panel concluded: “[AHAAH] is promising in that it accounts for a decrease in risk of hearing damage with increasing low-frequency energy in the impulse sounds. However, with respect to its compressive properties[2] and the level-number trade-off function it has to be further developed”.

In a 2009 paper, Murphy et al. compared the performance of AHAAH with the MIL-STD-1474D and $L_{A\mathrm{eq,8h}}$ risk criteria using the U.S. Army Albuquerque Blast Overpressure study hearing loss data [16]. The paper describes in detail the controversy surrounding the interpretation of this very significant data set. The study concluded that $L_{A\mathrm{eq,8h}}$ was the best metric in predicting temporary threshold shift in response to blast overpressure.

A 2012 U.S. National Institute for Occupational Safety and Health (NIOSH) report by Murphy et al. discusses in more detail the various features of the AHAAH model, including its treatment of the middle ear muscle reflex, which can attenuate impulse noise [17]. In this report the authors highlight that disagreements surrounding model performance are related to interpretation of existing limited data sets [17, 3.3]. They suggest that new audiometric studies with impulse noise dosimetry are needed to allow the community to reach a consensus. The report recommended that the MIL-STD-1474D impulse noise risk criteria be replaced by the $L_{A\mathrm{eq,8h}}$ metric.

A review of AHAAH by Wightman et al. in 2010, for the American Institute of Biological Sciences (AIBS), also highlighted a number of perceived deficiencies, including some of those mentioned by other authors [18]. The review panel recommended that in the interim the $L_{A\mathrm{eq,8h}}$ metric replace the MIL-STD-1474D, and when the identified problems with the AHAAH model were rectified it would become the new standard.

The latest version of the standard, MIL-STD-1474E, was released in 2015, and AHAAH has been provisionally accepted for use as part of this standard [19]. The revised standard actually presents two alternative metrics for assessing impulse noise hazard: $L_{IA\mathrm{eq,100ms}}$ (used to assess noise exposure from a combination of impulsive and continuous noise sources) and the AHAAH model [13].

The standard acknowledges the conclusions of the AIBS panel review of AHAAH, that several critical assumptions in the model need further research [19, Table B-II]. In partial justification for its inclusion, MIL-STD-1474E points out that AHAAH is being used by “at least one other nation”, and that the car industry uses it to evaluate hearing hazard from airbag deployments.

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[2] The protective effect of the low-frequency part of the spectrum in impulse noise.

3.6 NATO RSG-029 criteria

Research by the North Atlantic Treaty Organisation (NATO) into the effects of impulse noise on hearing began in 1979 with the establishment of the research study group RSG-6 [8]. The group concluded that noise exposure limits in use at the time were probably overprotective for large calibre weapons, but the existing data did not permit a definitive conclusion. Therefore, new experiments were proposed to measure temporary threshold shift in response to blasts with varying duration and intensity.

By 1994, new impulse noise threshold shift data was available from the U.S., France and Germany. A new NATO study group, RSG-029, was formed to reconsider the effects of impulse noise on hearing. Using the new threshold shift data, RSG-029 published a report in 2003 with consensus recommendations on safe exposure limits for impulse noise [8]. A number of different metrics were considered in the course of this study, including the AHAAH model.

On the basis of the available data, RSG-029 divided impulse sources into two categories, based on the blast duration: short impulses, with A-durations of 0.2 ms to 0.3 ms typical of rifle shots; long impulses with A-durations in the range 0.9 ms to 3 ms characteristic of blasts from heavy calibre weapons and explosives. The A-duration is defined as the length of the initial positive phase of a blast pressure wave.

RSG-029 recommended a single impulse exposure limit based on the sound exposure level (SEL) with A-weighting[3], instead of the peak sound pressure level (SPL). There is a critical level that should not be exceeded for a single impulse: for short impulses the limit is 116 dB SEL(A); for long impulses the limit increases to 135 dB SEL(A). For multiple blasts, the daily noise exposure $L_{A\mathrm{eq,8h}}$ should not exceed 80 dB for short impulses and 98 dB for long impulses.

The daily exposure limit of 80 dB on $L_{A\mathrm{eq,8h}}$ for short duration impulses is more restrictive than the current New Zealand limit of 85 dB. However, the 98 dB limit on long duration blast noise is significantly more permissive: 20 times as many blasts per day are permitted compared with an 85 dB limit. The RSG-029 impulse noise exposure limits are summarized below in Table 2 [8, 1.7.4].

Source	A-duration (ms)	SEL(A) limit	$L_{A\mathrm{eq,8h}}$ limit
Small arms	0.2–0.3	116	80
Blasts	0.9–3	135	98

Table 2: Impulse noise exposure limits on SEL(A) and $L_{A\mathrm{eq,8h}}$ recommended by NATO RSG-029 in 2003 [8]. The “Blasts” category includes muzzle blast from heavy calibre weapons and noise from explosive charges.

3.7 The 140 dB limit on peak pressure

The 140 dB limit recommended for the peak SPL is traceable to the 1968 report from the U.S. National Research Council Committee on Hearing, Bioacoustics (CHABA) on impulse noise hazard [3, 20]. The limit for impulse noise originally recommended in the

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[3] The A-weighted SEL is usually written SEL(A) or L_{AE}.

1968 CHABA report was defined in terms of peak pressure and impulse duration. The shorter the impulse, the higher the permitted peak pressure [21, p141].

However, subsequent U.S. Army standards limiting impulse noise exposure simplified the recommendations by setting a limit of 140 dB on the peak pressure irrespective of impulse duration [20] - this may have been motivated by the difficulty in measuring impulse duration with equipment available at the time.

The 140 dB limit is now common in civilian noise exposure legislation. However, it is well known that peak pressure alone is not sufficient to predict hearing damage. The duration, frequency content and energy are all important elements in determining auditory hazard [20]. The 140 dB peak pressure limit is difficult to meet for gunshot and explosive noise, and may often lead to double hearing protection even when it is unnecessary [22].

3.8 Comment

The NZDF is required to be compliant with the noise regulations in the HSWA during training activities, as far as is practicable. This limits peak pressure exposure to 140 dB and the daily noise dose to 85 dB $L_{A\text{eq,8h}}$ (Section 2). Although it is common to impose a limit on the peak pressure level for workplace noise control, this is not a useful measure of impulse noise hazard. Accordingly, the 140 dB limit should be replaced with a more appropriate metric specific for explosive blast noise.

The AHAAH model is a promising approach for impulse noise hazard prediction. The latest version also includes a module for assessing the effectiveness of a number of hearing protection combinations. However, the issues identified by the 2010 AIBS review panel should be addressed before this model is adopted in New Zealand [18].

Based on a recent literature review, the best validated exposure limits for impulse noise hazard are the 2003 RSG-029 recommendations [8]. These impose limits on the SEL(A) and the $L_{\text{A eq,8h}}$, and make a distinction between the noise from small and large calibre weapons. It is important to distinguish impulse duration as the existing standards are overprotective for long impulses, but are likely under-protective for short.

Until a better model becomes available, DTA recommends that the RSG-029 criteria be used instead of Regulation 11 of the HSEA for blast noise risk assessment.

4 ACOUSTIC CHARACTERISTICS OF GUNSHOT NOISE

Firearms typically use an explosive charge to propel a projectile out of the gun barrel. The shock wave due to expanding propellant gases escaping from the muzzle is known as the muzzle blast. The duration of the blast ranges from 0.2 ms for small calibre weapons, and up to 5 ms for heavy weapons [8]. It is characterized by a very rapid increase in pressure, followed by a decay to a partial vacuum, before returning to ambient pressure.

The muzzle blast propagates through the air at the speed of sound. It is reflected by the ground and other objects. It is also affected by wind and temperature gradients in the air, and weakens due to spreading losses and atmospheric absorption. The blast is emitted in all directions, but most of the energy is expelled in the forward direction.

The acoustic pressure due to a 5.56 mm rifle shot recorded by DTA is shown in Fig. 1. The microphone was located 5 m from the muzzle, at an angle of 45 degrees to the line of fire. The first impulse in the acoustic pressure (starting just after $t = 0.5$ ms) is the shockwave due to the supersonic bullet speed.

The second impulse, starting just before $t = 2$ ms, is the muzzle blast. This consists of a positive going impulse with a peak of about 1 kPa, followed by a partial vacuum; the total muzzle blast waveform duration is less than 2 ms. The final impulse in the plot has a peak at about $t = 5$ ms, and resembles an attenuated version of the muzzle blast waveform. This is a reflection of the muzzle blast from the ground.

The arrival time of the ground reflection at the microphone can be predicted from the measurement geometry. Assuming the muzzle and microphone are both at a height h, the microphone is a distance R from the muzzle, and the blast wave speed is c, the time difference of arrival between the ground reflection and the direct blast, Δt, is given by

$$\Delta t = t_{\text{GR}} - t_{\text{DB}} = \left(\sqrt{R^2 + 4h^2} - R\right)/c \tag{4}$$

noting that $\Delta t > 0$ since the direct blast always arrives first. For clean muzzle blast measurement, the direct blast wave must be separated from the ground reflection. From (4), the time difference of arrival can be stretched by increasing h and/or reducing R.

The ground reflection can contain significant acoustic energy, particularly when the ground is hard and highly reflective, and add significantly to total noise exposure. A workplace impulse noise assessment should consider the contribution of reflections, and reverberation, to the daily noise dose.

Figure 2 shows the muzzle blast waveform and associated spectrum. The direct path muzzle blast waveform must be windowed to isolate it from the ground reflection, or the reflected waveform will have a comb filter effect on the spectrum. The cumulative energy in the top plot of Fig. 2 shows that most of the energy is contained inside the time interval 1.5 ms to 3.5 ms.

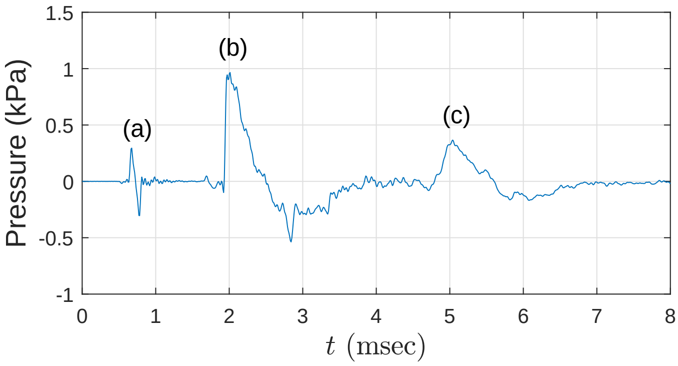

Figure 1: The acoustic pressure due to a 5.56x45 mm calibre rifle shot. The microphone was located 5 metres from the muzzle, at an angle of 45 degrees to the line of fire. Marked features are: (a) bullet shockwave (or N-wave); (b) muzzle blast; (c) ground reflection of the muzzle blast.

To assess exposure to blast noise, measurements are made at a number of positions, and levels at other locations must be predicted using interpolation and extrapolation.

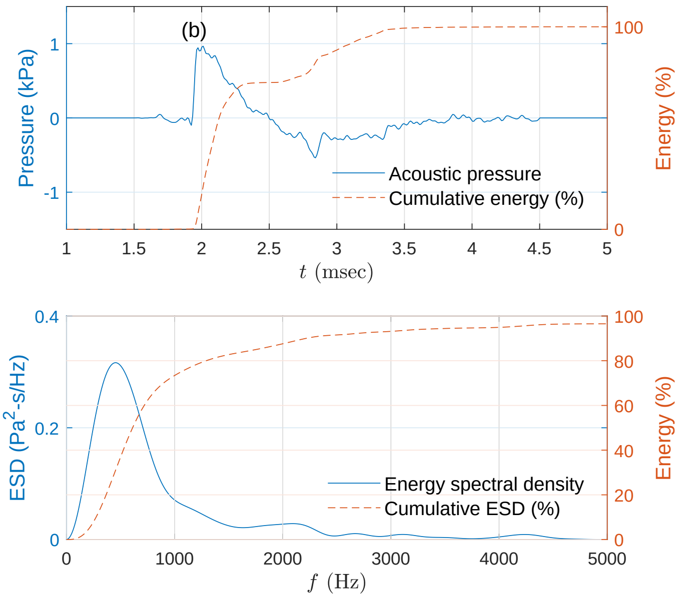

Figure 2: Top: the acoustic pressure due to the muzzle blast waveform alone. Bottom: the energy spectral density (ESD) of the muzzle blast.

Prediction of the peak level at different ranges in the near-field can be obtained from the relation

$$\bar{p} = 2.4 \left(R/l'\right)^{-1.1}, \tag{5}$$

which is the result of fitting a scaling law to near-field (a few metres from the muzzle) experimental data [23, p171]. Here, R is the range from the muzzle, and l' is a characteristic length that must be measured experimentally. Beyond the near-field the decay should reduce to a pure geometric loss, i.e. R^{-1}.

Some experimentation to measure blast decay with distance could be included as part of the measurement project, to provide additional support for the use of (5) in the near-field. Additional factors that will need consideration are ground reflections, shadowing due to terrain and foliage, and reverberation in indoor environments. These could significantly alter the daily noise dose and need to be accounted for in exposure assessments.

5 STANDARDS AND GUIDELINES FOR IMPULSE NOISE MEASUREMENT

A literature review of standards, protocols, and guidelines relating to impulse noise measurement was completed by DTA. The most relevant that were found were: ISO Standard 17201-1:2005, which has been used in New Zealand to assess noise from shooting ranges; the US Army TOP 01-2-608A; and the NATO Standard AEP-4785 for noise measurement of suppressed small arms. The NATO standard is now used in the UK for the measurement of noise from all small arms, suppressed and unsuppressed. These standards are briefly summarized below.

5.1 ISO 17201, Acoustics - Noise from shooting ranges

ISO 17201 provides guidelines for calculating noise levels in the vicinity of shooting ranges. It specifies methods for measurement of the muzzle blast for calibres of less than 20 mm, or explosive charges of less than 50 g TNT equivalent. It is applicable at distances where peak pressures less than 1 kPa (154 dB) are observed. The limit on the peak pressure for measurements is to ensure that non-linear effects, which set in at high acoustic pressure levels, are reduced. The source energy, directivity, and spectrum structure determined by these methods are intended for use as input data to acoustic propagation models.

There are currently five parts in ISO 17201. A description of each part of the standard is given in Section 4 of Ref. [24]. A sixth part has been proposed which will deal with occupational noise exposure from impulse noise at close range to the source [24].

5.1.1 Instrumentation

ISO 17201-1 specifies that measurement instrumentation shall comply with the requirements for a Type 1 instrument as in IEC 61672-1:2002 [25, 7.4], and recommends compliance with the additional requirements in the IEC standard for impulse noise. It adds that the measurement system "shall be suitable for the measurement of high peak sound pressures", and "shall have adequate bandwidth and dynamic range". It does not mandate specific sensor types, signal conditioning or recording equipment.

5.1.2 Measurement geometry

For measurements ISO 17201-1 specifies that

- the gun barrel should be horizontal and at least 1.5 m above the ground;
- microphones should be arranged in a circular or semicircular pattern, at equal angular increments of no more than 45 degrees (for a symmetric muzzle blast at least five microphones would be required);
- at least five measurements should be made at each microphone position;
- microphones should be placed at a distance 10 m to 50 m from the muzzle, to ensure the peak pressure does not exceed 1 kPa (154 dB).

In certain directions, the bullet shockwave and the muzzle blast can be separated by windowing. For directions where this is not possible, the standard advises correcting for ground reflection when calculating the angular energy distribution, using the method of ISO 9613-2 [26]. This involves estimating the ground impedance at the measurement site, and subtracting out the contribution to the acoustic energy from the ground reflection.

5.1.3 Comment

ISO 17201 is concerned with prediction of noise levels at relatively long ranges, for environmental noise assessment. The introduction to ISO 17201-1:2005(E) states that the methods are intended for the linear acoustic regime, which is defined as those regions for which the peak pressure has decayed below 154 dB. For gunshot noise, this will dictate pressure measurements in the range of 10 m to 50 m from the weapon.

However, for noise exposure assessment near-field measurements (less than 10 m) are required, and ISO 17201 is not directly applicable. Another difficulty with the recommended measurement ranges is the reduction in time delay between direct and ground reflected waveforms, which may make it impossible to separate the two.

Isolation of the direct path waveform is necessary to predict reflections from different types of terrain. It would be preferable to use a sensor with a greater peak pressure capability, and bring the microphones closer to the source, to enable the ground reflection to be gated out.

Decay of the peak pressure in the near-field of a muzzle blast has been found to fit a $R^{-1.1}$ law from experimental data [23, p171]. Waveform distortion due to non-linearities is not easy to model, but for noise exposure estimation is likely to be a second order effect when compared to other uncertainties.

5.2 U.S. Army Test Operations Procedure for noise measurements

The U.S. Army Test Operations Procedure TOP 01-2-608A describes procedures for measuring the sound levels of continuous and impulse noise sources [27].

5.2.1 Measurement geometry

For measurements of shoulder-fired and hand-held weapons, TOP 01-2-608A requires the barrel to be 1.6 m above and parallel to the ground. The transducers are to be located at the centre of the probable head location of the operators or crew. For other weapons the transducer is to be located 1.6 m above the ground, 15 cm from the operator's ear that is closest to the noise source, on a line connecting the ear and the source [27, 4.2.1(b)].

Measurements should be made with no reflecting surfaces, including people, within 10 m of both the source and transducers. For weapons that must be supported, a stand with minimal reflecting surfaces or obstructions shall be used. The acoustic path from the noise source to the ground and then to the transducers must be unobstructed.

For impulse noise measurements above 171 dB this standard specifies either piezoresistive or piezoelectric transducers. Below this, condenser microphones may be used [27, 2.2].

5.2.2 Sound level metrics

At least three rounds are fired for each measurement. If the extreme spread in the peak pressure exceeds 3 dB, additional rounds are to be fired until the number of rounds equals or exceeds the extreme spread in decibels [27, 4.2.1(c)]. The mean peak sound pressure, the A- and B-durations of the waveform are calculated, according to the definitions given in MIL-STD 1474D [9].

5.2.3 Assessment of 140 dB noise contour

For impulse noise sources the distances and directions where the peak sound pressure level is 140 dB are determined; the locus of these points forms the 140 dB noise contour. Measurements are to be made at angular increments of 45 degrees or less. The contour can also be obtained by extrapolation from distances where the sound level is 150 dB or less. Sound pressure levels at greater distances are to be inferred using the spherical spreading rule (a 6 dB reduction in level for a doubling of distance).

5.2.4 Comment

The requirement of piezoresistive or piezoelectric transducers for impulses over 171 dB is unnecessary. There are a number of condenser microphones[4] on the market specifically designed for use in high sound pressure environments. For example, the B&K Type 4941 which has an upper limit of 184 dB, and the GRAS 40DP for levels up to 174 dB. The use of these microphones is common in industry, and acoustic calibrators are readily available. Both DTA and local industry use the Type 4941 microphone.

The requirement that measurements are made at field points where the peak pressure is 150 dB or less is presumably to avoid the non-linear region of the blast wave. An $R^{-1.1}$ scaling law has been found to fit peak pressure data in the near-field (Section 4) of the gun muzzle. This law could be used to extrapolate the peak pressure between points in the near-field region, and from the near- to the far-field. However, it does not describe waveform distortion caused by non-linearities due to high peak pressures.

5.3 NATO protocol for acoustic measurement of suppressed firearms

The recent NATO Standard AEP-4785 provides an acoustic measurement and analysis procedure for radiated noise from suppressed firearms [28]. This standard is currently used in the UK for small arms noise measurement.

5.3.1 Instrumentation

The AEP-4785 instrumentation requirements are [28, 2.3]:

- a maximum SPL of 164 dB or higher (about 3.2 kPa);
- minimum of 90 dB dynamic range;
- minimum bandwidth of 10 Hz to 20 kHz;
- the frequency response over the bandwidth must be flat within 3 dB;
- the minimum sampling rate is about 2.5 times the upper value of the frequency range of interest; e.g. 50 ks/s for 20 kHz.

5.3.2 Measurement geometry

The standard recommends that the firearm to be tested and sensors are to be elevated to a minimum of 4 m from the ground, with a horizontal separation of 5 m between the muzzle and all sensors. This ensures that the delay between the direct path signal and the ground reflection is at least 12.5 ms. This time interval was selected as it was believed to contain 95 % of the acoustic energy of a muzzle blast from a suppressed weapon.

AEP-4785 calls for at least eight pressure sensors (microphones or transducers), arranged in a semi-circle, with a radius of (5.0 ± 0.1) m, centred on the muzzle. The first sensor is placed 5° from the line of fire, and the remaining sensors at 25° increments at 30°, 55°, 80°, 105°, 130°, 155°, and 180° [28, Fig. 4].

After placement and calibration, the sensor positions must be measured relative to the bore axis to an accuracy of ±1 cm. The standard recommends the use of a Total Station

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[4] A condenser microphone is essentially a capacitor. The distance between the plates varies in response to an incident sound wave, and this results in a changing voltage proportional to the acoustic pressure field.

Theodolite for positional measurements, but notes there may be other devices that may have the required accuracy.

5.3.3 Environmental data

AEP-4785 requires the following environmental data to be collected [28, 2.2]:

- ambient temperature at muzzle height;
- wind speed at muzzle height;
- wind direction relative to the axis of the bore;
- relative humidity;
- ambient air pressure (at the beginning of a measurement series).

5.3.4 Sample size

The number of shots in each configuration should be chosen so that the standard deviation of the sound exposure level is less than 0.5 dB, with a one second interval between shots. Ten shots per configuration is suggested [28, 2.4-1].

5.3.5 Comment

For unsuppressed 5.56 mm firearms, over 99 % of the acoustic energy is contained in a 4 ms window (Section 4), and so the ground separation requirements are reduced compared to suppressed fire. Since unsuppressed weapons are the major contributor to acoustic hazard a lower ground clearance can be tolerated and 1.6 m (approximate standing height) is suggested. This can be achieved by firing from a standing position and supporting the weapon on a tripod for stability.

6 THE AS/NZS 1269 STANDARD FOR WORKPLACE NOISE MANAGEMENT

In New Zealand, Regulation 11 of the Health and Safety in Employment Act (HSEA) is still the legal requirement for workplace noise management under the Health and Safety at Work Act. Regulation 11(2)(c) requires workplace noise to be assessed in accordance with the AS 1269:1989 standard. Note that this standard has since been revised and the latest version is now AS/NZS 1269:2005. The AS/NZS 1269:2005 standard specifies measurement equipment, microphone locations and methods for selection of hearing protectors.

6.1 Measurement equipment

Section 7 of 1269.1 states that Type 1/Class 1 sound level meters are recommended for noise measurements. The standard allows a personnel sound exposure meter (PSEM), but a hand-held sound level meter is preferred. Furthermore, the instrument should be capable of accurately measuring the peak sound pressure levels expected in testing.

6.2 Microphone locations

Microphone locations are specified as follows (Section 8.3.5):

- with the person in their work location, the microphone should be located, whenever practicable, approximately 0.1 m, but not more than 0.2 m horizontally from the entrance of the external ear canal receiving the higher noise level;

- for convenience, a microphone worn on a person may be mounted on the top of the shoulder.

6.3 Hearing protector selection in continuous noise

Selection of hearing protectors is covered in AS/NZS 1269.3 [29]. Possible selection methods include the classification method, the octave band method, the SLC$_{80}$, and the HML method [29, Appendix A]. However, if $L_{A\text{eq,8h}}$ > 110 dB the octave band method must be used.

6.4 Hearing protector selection in impulse noise

AS/NZS 1269.3 also contains specific hearing protector selection rules for impulse noise, although it begins by stating that "there is no standard method for quantifying the attenuation of hearing protectors to impulse sound" [29, Appendix B]. Until a suitable method becomes available, the standard advises:

- for small calibre weapons Class 5 protectors should be used;
- for large calibre weapons well-fitted earplugs having a classification of at least 3 in combination with earmuffs of any classification, shall be worn.

In the past, both DTA and external consultants have attempted to apply the octave band method to free-field impulse noise measurements. The consultants' approach was to extract octave band levels from impulse noise recordings, and apply octave band attenuations to estimate the acoustic energy and $L_{A\text{eq,8h}}$ under the protector. This can be used to predict the number of allowable shots per day, given that the daily acoustic energy exposure limit is 3600 Pa^{2}s (equivalent to 85 dB $L_{A\text{eq,8h}}$).

7 IMPULSE NOISE MEASUREMENT SYSTEMS

7.1 The Brüel & Kjaer LAN-XI data acquisition system

Brüel & Kjaer (B&K) provide data acquisition systems based around a LAN-XI frame containing a number of data acquisition modules. The 3052-A-030 module has three input channels each sampled at 262 kHz, providing a usable measurement bandwidth of about 100 kHz. This is more than sufficient for impulse noise measurement. Additionally, the module uses a 24-bit ADC and the manufacturer claims a 160 dB signal-to-noise (SNR) ratio. The high SNR obviates the need for variable gain control, a considerable simplification for field use.

To record from more than three channels simultaneously a number of these modules can be mounted in a LAN-XI frame, which provides power and Ethernet connectivity. The frame is connected to control and recording software on a PC via an Ethernet connection. The LAN-XI data acquisition system is plug-and-play compatible with a number of B&K acoustic and vibration sensors, including the 4941 high pressure microphone. The 4941 must be used in conjunction with a 2670 preamplifier to connect to the LAN-XI modules.

The simplest software interface to a LAN-XI data acquisition system is the Pulse time-data recorder. This provides multi-channel recording capability, with time and frequency visualization on a single channel. Other controller software available from B&K provides multi-channel visualization and post-processing options, but at higher cost. This software saves acoustic data to disk in a proprietary format, but it can be exported in WAV or MAT formats for analysis.

7.2 National Instruments / G.R.A.S.

National Instruments (NI) has partnered with G.R.A.S. Sound & Vibration of Denmark to provide integration between NI data acquisition cards and G.R.A.S. microphones. There are a number of G.R.A.S. microphones which contain a Transducer Electronic Data Sheet (TEDS) chip and can be directly connected to NI data acquisition cards that support TEDS.

The disadvantage of this approach is that the user must write their own data acquisition software. DTA has written dual channel acoustic data recording software for the NI PCI-4462 DSA card to interface to a high pressure microphone and a piezoelectric transducer. Extending this software to handle nine channels would involve some redesign work, particularly in the user interface.

A G.R.A.S. microphone measurement system would require three PXI-4462 DSA cards or equivalent (providing four channels each), a PXIe-1082 chassis to mount the cards, and a number of 46BD 1/4" pressure microphones. However, the 46BD microphone has an upper limit on SPL of 166 dB and it is necessary to measure higher sound pressure levels. For example, the peak SPL of the L119 105 mm gun was 176 dB at a distance of about three metres, and the 81 mm mortar has comparable levels at the gun crew location. The B&K 4941 microphone is preferred since it has an upper SPL limit of 184 dB.

8 MEASUREMENT SYSTEM AND DATA HANDLING

DTA has been involved in impulse noise measurement and hearing protector performance assessment in the NZDF since 2010. Noise emissions from a large number of impulse sources have been recorded, using a variety of sensors and data acquisition devices. DTA has also assisted external contractors in impulse noise measurement tasks, and provided reviews of their work. The following recommendations are based on that experience, and a review of the standards and regulations applicable to impulse noise measurement in New Zealand.

8.1 Impulse noise measurements

8.1.1 Microphone/transducer type

Measurement of impulse noise from weapons and explosives requires the use of specialized high-pressure microphones or piezo-ceramic transducers. DTA has used the B&K Type 4941 microphone since 2011, which has an upper limit on SPL of 184 dB. This is sufficient to measure every impulse noise source in the NZDF inventory, including the 105 mm gun and the 81 mm mortar.

8.1.2 Microphone mounting and impact noise

When measuring blast noise some shock insulation must be provided for the microphone[5]. DTA has made a custom mount for the 4941 using a PVC tube into which the microphone and pre-amplifier assembly is inserted after wrapping with sound absorbing foam. This arrangement has provided adequate shock insulation.

In addition, the experimenter must be careful to ensure the microphone, tripod, and cables are not impacted during measurement as the vibration will produce a high-level microphone response. Impact noise can be distinguished from the very distinctive muzzle blast signature in audio editing software, but if it occurs in the same time window it may corrupt the measurement.

Ejected cartridge cases can cause significant impact noise if they strike the tripod or microphone. If possible, microphones should be positioned on the opposite side of the weapon to the ejection port.

8.1.3 Microphone placement

There are two requirements for impulse noise exposure assessment that dictate microphone positioning:

- estimation of the 140 dB noise contour for an impulse source;
- assessment of worker noise exposure in their normal positions.

Guns are highly directive noise sources. Peak pressure can vary with angle by 15 dB to 20 dB [30, 31]. The assessment of noise contours will require microphones placed circumferentially around the weapon to capture the directivity of the muzzle blast. These measurements can be used to predict the range at which the level has dropped to 140 dB, or any other designated level.

Microphones should be placed so that the direct path muzzle blast is separated from the ground reflection as much as possible, by increasing the muzzle height and reducing the microphone-to-muzzle distance. In a portable measurement system the weapon can be fired offhand in the standing position, or preferably mounted on a tripod for stability. Weapons can be fired from raised platforms, but this greatly increases cost and complexity, and the system is no longer portable.

The time separation between the direct muzzle blast waveform and the ground reflection was given in Eq. (4). Setting $h = 1.6$ m (approximate height of the muzzle for a standing firer) and taking $R = 3$ m gives $\Delta t = 4$ ms. This is sufficient to capture the muzzle blast waveform for small arms without significant interference from ground reflections (see Fig. 2).

Measurement repeatability can be achieved by mounting and firing the weapon on a tripod. Some care will be needed to ensure that the weapon does not move appreciably due to recoil while measurements are taken. A one second interval between shots is recommended.

A theodolite or other suitable surveying tool may be needed to determine microphone positions relative to the gun muzzle when mounted on the tripod. An accuracy of ±2 cm should be achievable. Note that a 2 cm distance error corresponds to 0.2 dB at one

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[5] This issue is not addressed in the AS/NZS 1269.1 standard.

metre range. This is well inside the expected accuracy of the acoustic measurement system (±0.5 dB).

8.2 Data acquisition

Generally, a number of shots are recorded in a single measurement, to enable statistical variation between rounds to be captured. The recordings are saved to permanent storage, usually in the form of a WAV file. This file format contains a header which specifies the sample rate, sample format, number of channels, and type of compression used (if any), followed by a segment containing the sample data.

All data acquisition devices record digitized values of the acoustic signal which must be converted to units of pressure in post-processing [6]. This is achieved by recording a precisely known signal obtained from an acoustic calibrator. DTA uses a 124 dB, 250 Hz piston-phone to calibrate high pressure microphones.

8.3 Waveform extraction and storage

Short time windows containing the impulse signals of interest should be extracted from raw audio data, to speed up analysis. As indicated in Figs. 1 and 2, impulse signals from gunshot noise are typically milliseconds long, compared to several seconds for the total recording duration.

The measurement geometry should be constructed to enable separation of the shockwave and ground reflected waveforms. Analysis software will be needed to identify, validate and extract the muzzle blast waveform. For small arms, an impulse time window of 4 ms to 5 ms should be sufficient. This is made up of a 0.5 ms pre-recording interval before the pressure peak, followed by a 3.5 ms to 4.5 ms post-peak window. As shown in Fig. 2 this is sufficient to capture a majority of the energy in an unsuppressed gunshot acoustic pressure waveform, excluding the ground reflection and the bullet shockwave (if present).

Impulse waveforms should be stored in the original sample format (usually 24-bit signed integer), and converted to units of acoustic pressure using a recording of the calibration signal as required. Samples in units of acoustic pressure could additionally be stored in MAT format, which might aid analysis in MATLAB.

If all microphones were the same distance from the muzzle the blast wave would arrive at the same time on each channel. Extracting individual shots in a multi-channel recording would then be straightforward as they all line up in the same time window. But if the microphones are not all at the same distance the waveforms will arrive at different times. This will be the case, for instance, if one microphone is placed at the shooter's ear location.

When impulse arrival times are different, and the relative arrival time is unimportant, it may be preferable to extract the shots from a multichannel recording into separate files. Multiple shots (each with the same number of samples) could be concatenated in a single channel, or stored as separate channels.

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[6] B&K inserts this calibration data into a custom chunk in a WAV file recordings.

8.4 File naming conventions

A gun and ammunition combination (or configuration) is principally characterized by barrel length, diameter, and cartridge type. Additionally, many small arms use barrel attachments such as sound suppressors and muzzle brakes. Ideally, files containing gunshot acoustic data would be named in a way that enabled the user to identify the type of gun, the projectile type, barrel attachment, and even measurement position relative to the muzzle.

In practice, there is so much metadata that could potentially be recorded the file name would become excessively long. In the Windows operating system file names are limited to 255 characters, and the path length is limited to 260 characters.

Two options for data file naming are given below. The first specifies a detailed file name containing the most important metadata, but well within the operating system limitation on path length. The second offers a file name code and relies on database or spreadsheet lookup to retrieve metadata, using the file name as a key. The advantage of associating the file to a database is that the quantity of metadata that can be stored is unlimited.

8.4.1 Option 1: Descriptive file names

A file name containing impulse source metadata would need descriptors for weapon type, barrel length and attachment used, cartridge fired, muzzle height above ground, and the range, angle and height of the microphone from the muzzle. Usually, the microphone and muzzle heights from the ground will be the same, and the waveform will be windowed to remove the ground reflection. In this case it is not necessary to record microphone and muzzle heights in the file name.

Variable length descriptors in the file name can be separated by underscore characters, prefixed by a single character to denote the descriptor type: **b** for barrel length; **s** for suppressor; **c** for cartridge; **r** for microphone range; and **a** for microphone angle from line of fire. The prefixes make it easier for software to read and extract the descriptors.

For example, consider an M4 rifle with a 14.5 in barrel, using a SureFire Genesis 762 sound suppressor, firing an SS109 NATO cartridge, with a microphone positioned two metres from the muzzle at an angle of 45 degrees. Using this naming scheme the WAV file with acoustic pressure samples would be named

M4_b14.5in_sGenesis762_cSS109_r2m_a135d.WAV

In another example, a DMW rifle with a 20 in barrel, unsuppressed, firing a .308 Winchester round, with the microphone placed at five metres and 90 degrees, would be named

DMW_b20in_c308Winchester_r5m_a90d.WAV

Abbreviations for the weapon type, barrel attachment (brake or suppressor), and cartridge type could be used to reduce the file name length.

8.4.2 Option 2: Simple file names

Alternatively, the metadata for each firing could be stored entirely separately, in a spreadsheet, database or simple text file. Each acoustic pressure file could be named using a short alphanumeric character string to designate the measurement set, followed by a ddmmyyyy date format, and finally a recording number. For example, the 52nd recording on June 2, 2017 of measurement set A could be stored in a file named

A_02062017_52.WAV

The metadata for this recording would be retrieved by table lookup inside a spreadsheet or text file, using the file name as a key.

8.5 Metadata storage

The most simple method is to keep metadata in a spreadsheet or text file in the same location as the acoustic data. Metadata cannot be included directly in the acoustic data file as it is not guaranteed to be preserved by audio editing software.

In a more sophisticated approach a searchable database would link acoustic data with measurement information. DTA has constructed a prototype Python/Django web application using SQLite, which can upload and store acoustic data. An advantage of this approach is that multiple users can access the data concurrently. However, a considerable amount of work would be required for further development and maintenance of a web hosted database.

Instead of a web application, MATLAB can be used as an interface to a SQL database. In this case access is limited to computers on a LAN and MATLAB licenses and programming knowledge is required.

9 INDUSTRY SUPPORT

DTA does not have the capacity to undertake all the work needed to complete this task. A local consulting firm was approached to provide cost estimates for performing field measurements and initial data handling and extraction. The estimate was $2200 per day (assuming two people). There would be additional costs for assessments of acoustic dose, effectiveness of hearing protection, and report writing.

The Australian Defence Force has also utilized industry experts in a blast noise assessment program. The consultants performed measurements using very similar equipment available to DTA, and made an assessment of noise dose and allowable shots per day using the AHAAH model (discussed in Section 3.5). The services of this company are also available to the New Zealand Defence Force. But note that, for reasons discussed in Section 3.5, the use of AHAAH is not yet recommended for noise exposure assessment.

10 MODELLING HEARING PROTECTOR ATTENUATION IN IMPULSE NOISE

There is at present no generally accepted model of hearing protector attenuation in impulse noise. The octave band method [32, p208], recommended for use in New Zealand for continuous noise sources, cannot be applied directly to impulsive or transient sound. Complicating factors in developing such a model are the difficulty in performing measurements with human subjects due to risk of hearing loss, and the non-linearity of protectors in high acoustic pressure levels [8, 33, 34].

Hearing protector attenuation is usually measured using a procedure known as Real Ear Attenuation at Threshold (REAT). The method measures a quantity known as insertion loss (IL), which is the difference in noise level at the eardrum location between unprotected and protected states. The REAT method determines the IL in octave bands by measuring hearing thresholds under unprotected and protected conditions across a sample of test subjects.

The attenuation used for practical noise assessments is the mean attenuation minus one standard deviation, which is called the assumed protective value (APV). This results in a value of attenuation that should be achieved for 84% of users [35].

10.1 Physical models of hearing protectors

Manufacturers measure only the amplitude response of hearing protectors in octave bands, since this is sufficient to assess the protective effect on continuous noise. However, to model the effect of hearing protection on impulse noise waveforms both amplitude and phase response measurements are required. The phase response must either be directly measured or inferred through a physical model. A literature review revealed two approaches previously proposed for this problem.

The U.S. Army Research Laboratory has proposed a model for predicting impulse noise inside a protector based on free-field measurements of the acoustic pressure [14, 15]. The method works by fitting a physical model, which includes the phase response, to octave band attenuations assessed using the REAT method. Since 2013 it has been available as part of the AHAAH model (Section 3.5).

An alternative approach is a hearing protector model based on physical characteristics of the device, e.g. mass, stiffness, rather than on REAT attenuation measurements. A physical model of an earmuff was proposed by Shaw in the early 1980s [36], and a recent test of this model on impulse noise was conducted by Mlynski et al. [37]. The Shaw earmuff model requires laboratory measurement of earmuff properties including surface area, enclosed volume, mechanical resistance and cup stiffness. Applying this model to 9 mm pistol shot data the authors obtained fitting errors in peak SPL from 0.1 dB to 7 dB over the ten protectors that were tested.

DTA has experimented with both of these approaches, but has been unable to obtain a satisfactory fit between these models with attenuation data for hearing protectors of interest. Also, the Shaw model is applicable only to earmuffs. As an alternative, we have experimented with interpolated octave band attenuation data supplemented with a nominal phase response. A trial of this method with 9 mm pistol shot data is promising, but more experimental work for adjustment and validation is needed.

10.2 Measurements of attenuation in impulse noise

Some measurements of hearing protector attenuation in impulse noise are available in the literature. A 2009 paper by Buck et al. reported attenuation measurements for impulses up to 190 dB peak SPL [33]. A 2012 paper by Murphy et al. reported measurements for impulses at 130, 150 and 170 peak SPL [17]. The impulsive source in the Murphy paper was an AR15 rifle, and hence the attenuations reported are indicative of small arms fire. The results of both studies were summarized in DTA Report 391 [38].

10.3 Previously used approaches

10.3.1 DTA attenuation model

For the L119 light gun noise assessment DTA modelled hearing protector attenuation using an FIR filter with a frequency response obtained by interpolating the octave band attenuation data, with the assumption that the phase is linear [38]. This filter was applied to the free-field acoustic pressure measured by a microphone to yield an estimate of the ear canal pressure when a hearing protector is worn.

10.3.2 The Noise Reduction Rating

During the design of the Battle Training Facility, intended for indoors live fire exercises, a full acoustic assessment was performed by a consultant aimed at predicting:

- reverberation levels of the two main firing halls;
- noise exposure to personnel during training exercises;
- noise transmission to adjacent spaces.

To model the effect of hearing protection on received noise dose the consultant used the noise reduction rating (NRR), although this system is used in the United States and is not approved for use in New Zealand.

10.3.3 AHAAH hearing protector module

The AHAAH auditory hazard assessment program contains a module for predicting the effects of generic earmuffs and earplugs. The hearing protection module treats all hearing protectors as passive level independent devices. The module also provides models for several level dependent non-linear devices. All hearing protectors are modelled as linear systems based on attenuation measurements in seven octave bands from 0.125 kHz to 8.0 kHz [13]. A mathematical description of the AHAAH hearing protector model has been published by Kalb [14, 15].

10.4 Non-linear hearing protector behaviour

Hearing protection devices are known to behave in a non-linear way in very high levels of impulse noise. For earmuffs, the effect is to reduce the levels of protection. For some earplugs, the effect can be to increase the protection. It was suggested by Buck et al. that earmuff non-linearity could be modelled as a reduction in attenuation by 5 dB for every 10 dB of peak pressure beyond 170 dB [22, Fig. 6].

Standard (i.e. linear) earplugs, at least in the range 150 dB to 190 dB peak pressure, exhibit much less non-linear behaviour than earmuffs [22, 33]. These conclusions are in agreement with experiments on a selection of earplugs, and one earmuff, for peak levels of 130 dB to 170 dB [17].

Significant non-linearity complicates the modelling problem, and all current hearing protection models assume a linear response to acoustic pressure. However, typical small arms exposure levels are less than 170 dB peak, and hence one expects the effect of non-linearity to be negligible. For heavy calibre weapons it is possible the peak pressure may exceed this. Levels of 176 dB were measured by DTA for the 105 mm gun, although the measurement position was more exposed to muzzle blast than the gun crew.

It is likely for most impulse noise exposures the peak pressures will be around 170 dB or less. Hence, corrections for non-linear hearing protector behaviour are expected to be no more significant than inter-subject differences in attenuation.

10.5 Transfer function of the open ear correction

In practical noise exposure assessments a measurement of the sound field is made with the listener absent. The pressure measurement is passed through an A-weighting filter to account for human loudness perception, and hearing protector attenuations applied to estimate the protected sound pressure level in the ear canal.

The difference in sound level between two compartments, or inside and outside of a structure, is termed the noise reduction (NR). However, in laboratory assessments of hearing protectors the attenuation is measured as the difference between unprotected and protected sound levels in the ear canal, and this type of attenuation is an insertion loss (IL). The IL of a hearing protector is not equal to the NR (the difference in level outside the device and in the ear canal), although IL is generally used as a proxy for NR in practice. The NR and the IL are related by

$$\mathrm{NR} = \mathrm{IL} - \mathrm{TFOE} \tag{6}$$

where TFOE (transfer function of the open ear) is the amplification relative to the undisturbed sound field caused by the head, pinna and ear canal shape [35]. If the unprotected ear-canal pressure cannot be directly measured, then an estimate can be obtained by filtering the free-field acoustic waveform with a TFOE.

The potential importance of a TFOE correction can be seen in Fig. 3. This shows the energy spectral density of a 5.56 mm rifle shot, recorded in the free field, compared with a grazing incidence TFOE given by Shaw [39]. The bulk of the acoustic energy in the shot is contained between 100 Hz to 1000 Hz. The amplification due to the TFOE ranges from 2 dB to 3 dB up to over 10 dB in this frequency range.

As part of the impulse noise assessment project the inclusion of a TFOE correction should be considered, to more accurately model the effect of hearing protector attenuation on impulse noise. Since the TFOE is amplifying at higher frequencies, the effect of its inclusion would be a reduction in permitted exposure.

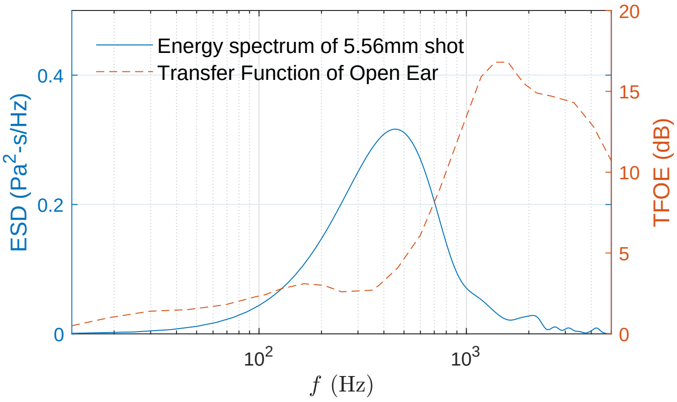

Figure 3: A comparison of the energy spectral density of a 5.56 mm rifle shot with a transfer function of the open ear (TFOE) at grazing incidence (listener facing source).

11 RECOMMENDATIONS

The problem of impulse noise measurement, and assessment of noise exposure, has been considered with the aim of satisfying the requirements of the Health and Safety at Work Act 2015. Existing standards and guidelines relating to impulse noise were reviewed, and a number of areas identified where there are uncertainties in the interpretation of existing data. The key findings and recommendations are listed below.

- Due to the high directivity of muzzle blast noise, a multichannel high-pressure acoustic measurement system is required to capture the angular variation of the sound level. The preferred option would have a nine channel capability.
- Microphones should be placed in a semicircle 3 m from the muzzle, covering angles from 5 degrees to 180 degrees in equal increments, at 1.6 m height. An additional microphone should also be placed near the most exposed ear of the firer.
- An acoustic propagation model is required which must extrapolate from measurement positions to estimate acoustic pressure at arbitrary receiver points. This may require a small number of dedicated measurements to confirm model performance, particularly in the near-field of the source.
- A program of experimentation using an artificial head is recommended covering those hearing protection options likely to be used by the NZDF.
- A methodology is needed to estimate average noise dose in different training environments, under static and moving conditions, and with multiple impulse sources present.
- The Auditory Hazard Assessment Algorithm for Humans (AHAAH) has been reviewed regarding suitability for impulse noise risk assessment. While promising, a number of concerns with the model have been raised by an independent review panel. AHAAH should not be proposed for use in New Zealand until those issues have been addressed.
- The impulse noise exposure limits recommended by the NATO RSG-029 panel should replace Regulation 11 of the Health and Safety at Work Act for the NZDF. The current limits are excessively restrictive for low frequency impulse noise exposure, and too permissive for high frequency impulse noise.

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DOCUMENT CONTROL SHEET

1. ORIGINATING ACTIVITY Defence Technology Agency, Auckland, New Zealand	2. RELEASE AUTHORISED BY
3. REPORT NUMBER 425	4. CONTROL NUMBER NR 1715
5. DATE Sep 2017	6. NUMBER OF COPIES 7
7. SECURITY CLASSIFICATION UNCLASSIFIED	8. RELEASE LIMITATIONS
9. TITLE Impulse Noise Measurement and Assessment in the New Zealand Army: A Scoping Study	
10. AUTHOR(S) Nathaniel de Lautour	11. AUTOMATIC DOWNGRADING

12. KEYWORDS

EJC THESAURUS TERMS	NON-THESAURUS TERMS
Impulse noise, hearing protection, gunshot noise, blast noise	

13. ABSTRACT

The New Zealand Army Landworthiness Authority has recently considered the risk of hearing damage in the NZDF due to impulse noise exposure. The need for a consistent noise database of all in-service weapons was identified, with a view to informing a hearing protection program. This report considers the problem of impulse noise measurement and assessment of noise exposure, with the aim of meeting the requirements of the Health and Safety at Work Act. Existing standards and guidelines relating to impulse noise are reviewed, and a measurement system capable of capturing the necessary acoustic data is proposed. Finally, areas where scientific uncertainties remain are identified and mitigation approaches suggested.

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