Sound Pressure Level of the Steyr AUG Rifle

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April 2011
Abstract

The sound pressure level of the NZ Army's Steyr AUG rifle was measured at a number of angles and distances from the muzzle. Measurements were made on the rifle in its standard configuration without muzzle attachments and then again with a muzzle brake fitted. A muzzle brake improves accuracy by reducing recoil and barrel lift but increases muzzle blast noise. The increase in noise level with a muzzle brake was about 5–10 dB, depending on the measurement angle and range. The noise level estimated at the shooter's ear location when using the muzzle brake was 143 dB(C) which exceeds the recommended limit of 140 dB. However, the blast noise was below the more rigorous limit of 116 dB(A) SEL recommended by the NATO RSG-029 panel on impulse noise hazard.
Executive Summary

Background

The New Zealand Army is evaluating the potential of muzzle brakes to improve the accuracy of the Steyr AUG A3 rifle. A muzzle brake is a barrel attachment that diverts propellant gases to the side and rear to reduce the effects of recoil.

A side effect of propellant gas redirection is an increase in muzzle blast noise to the sides and rear of the weapon. This increase can be significant and there was concern regarding the adequacy of current hearing protection protocols.

Noise from firearms and explosive charges is known as impulse noise because of its high level and brief duration. Specialized equipment and techniques are required for measurement of impulse noise.

To measure muzzle blast noise DTA has been developing an impulse noise measurement system since February 2010. The system consists of: a miniature high pressure microphone; (optionally) a hydrophone; data acquisition hardware and custom designed processing software.

This system was tested for the first time in a trial at Waiouru military camp in which the sound pressure level of a Steyr AUG A3 rifle was measured, both with and without a muzzle brake.

Sponsor

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Results

The peak Sound Pressure Level (SPL) estimated at the shooter's ear location is 162 dB(C) for the unbraked Steyr and 168 dB(C) when the rifle is fitted with a muzzle brake. The effect of hearing protection is to reduce the estimated levels at the ear to 138 and 143 dB(C), respectively.

The estimated level at the ear exceeds the recommended limit of 140 dB when a muzzle brake is fitted.

A review of impulsive noise dose and related hearing loss was released by NATO Research Group RSG-029 in 2003 [17]. The objective of RSG-029 was to assess the risk of hearing loss from exposure to impulse noise, by identifying occurrences which are hazardous, and to develop measures which would protect hearing. RSG-029 suggested that the A-weighted SEL be used as an impulse hazard metric, and that for rifle shots the SEL should not exceed 116 dB(A).

For the Steyr rifle the SEL was below the recommended limit of 116 dB(A) in all configurations tested. The RSG-029 impulse noise criteria suggests that the Steyr rifle does not present an
auditory hazard when fitted with a muzzle brake, as long as the highest level of earmuff protection is used.

We recommend that the RSG-029 impulse noise hazard criteria be adopted by the NZDF for small arms fire instead of the present 140 dB limit on the peak SPL.
Contents

1 Background .................................................................................................................. 5
2 Materials and methods ............................................................................................... 6
3 Gunshot noise measurement ...................................................................................... 8
3.1 Pressure and free-field microphones ........................................................................ 9
4 Waveform analysis .................................................................................................... 9
4.1 Shot extraction ......................................................................................................... 10
4.2 Bullet shockwave and muzzle blast ......................................................................... 11
4.3 Ground reflections ................................................................................................... 13
4.4 Precursor waveforms ............................................................................................ 17
4.5 Muzzle blast waveforms ....................................................................................... 20
4.6 Muzzle blast spectra ............................................................................................. 22
5 Impulsive noise and hearing loss ............................................................................. 31
5.1 The NATO RSG-029 impulse noise review ............................................................. 31
5.2 The Auditory Hazard Assessment Algorithm for the Human (AHAAH) ................. 32
5.3 Occupational noise control standards ...................................................................... 34
5.3.1 Europe ................................................................................................................ 34
5.3.2 United States ..................................................................................................... 34
5.3.3 New Zealand ...................................................................................................... 34
5.4 Summary of noise control standards ......................................................................... 34
6 Performance of hearing protectors in impulse noise ............................................. 35
7 Results ...................................................................................................................... 35
7.1 Peak sound pressure levels .................................................................................... 36
7.2 Estimated levels at shooter's ear ............................................................................ 37
7.3 The RSG-029 noise metric applied to the Steyr rifle data ......................................... 38
8 Conclusions ............................................................................................................. 38

Appendix A Sound level metrics .............................................................................. 40
Appendix B The equal energy hypothesis .................................................................. 41
References .................................................................................................................. 42
1 Background

The Steyr AUG is a 5.56mm assault rifle and is the primary small arms weapon used by the New Zealand Defence Force (NZDF). It is of Austrian design and made in Australia under license. It has been in service with the NZDF since 1988.

Muzzle brakes are devices that are fitted to the muzzle of a firearm to redirect propellant gases away from the forward direction. They are intended to reduce recoil and counter the tendency of the barrel to rise\(^1\). A disadvantage of muzzle brakes is the increase in muzzle blast pressure behind the weapon. This exposes the firer and others nearby to higher sound pressure levels.

The NZ Army is currently evaluating the performance of a number of muzzle brakes for use with the Steyr AUG. As part of this program an auditory hazard assessment for the braked weapon is needed to satisfy Army health and safety requirements. The assessment requires measurements of sound pressure levels at different angles and ranges from a muzzle brake fitted rifle. These levels should be compared with unbraked noise emissions to see if any modification to current hearing protection and practices are needed.

Figure 1. Top: a Steyr rifle with a suppressor fitted. Bottom: a Steyr with the muzzle brake that was used in this trial.

To gain familiarity with the problem, and to experiment with pressure sensors and measurement methodology, a preliminary trial was held on 11 March 2010 at the NZ Army's Waiouru military camp.

The muzzle blast of a Steyr A3 rifle, fitted with and without a muzzle brake, was measured at four angles and four ranges. Acoustic pressure was recorded using both a hydrophone and a ¼

\[^1\] Sometimes referred to as "muzzle rise" or "barrel lift".
inch microphone. The sound pressure levels of the shots were extracted from the raw acoustic recordings and converted to the Decibel scale using C-type frequency weighting.

2 Materials and methods

A number of acoustic measurements of sound pressure levels from a Steyr A3 rifle, both with and without a symmetric muzzle brake, were made at the Old Class rifle range at Waiouru military camp on Thursday 11 March 2010. Measurements were attempted at distances of 0.5, 1, 2 and 5 metres range and at angles of 45, 90, 135 and 180 degrees from the barrel.

The acoustic sensors were mounted on a tripod that was kept at a fixed location and the position of the firer was adjusted to the desired angle and range. Both ranges and angles were measured using a tape measure.

This situation was not ideal as the angle of the barrel was not strictly controlled. The firer was instructed to aim the weapon downrange, and the experimenters checked to make sure this was approximately correct as the trial progressed. However, given the coarse angular resolution in this experiment small aiming errors are not significant.

Sound pressure levels were measured with a Quest 4110 ¼ inch microphone\(^3\) (sensitivity \(\sim 4.37 \text{ mV/Pa}\)) and a Brüel & Kjær 8105 hydrophone (sensitivity \(0.373 \text{ pC/Pa}\)). The microphone was connected to a Brüel & Kjær 2250 sound level meter using a ¼ to ½ inch preamplifier adaptor. The 2250 meter has an analog output socket which was configured to use Z-weighting and a gain of -20 dB (attenuation was needed to ensure that the input to the data acquisition card was not overloaded). Condenser type microphones, such as the Quest 4110, require a polarization voltage (typically 200V) which is provided by the preamplifier on the 2250 meter.

The hydrophone was positioned vertically inside a length of PVC tube with a vertical slit cut into it to accommodate the cable. The hydrophone was fixed in place in the tube by surrounding it with vibration insulation foam. The ¼ inch microphone was attached directly to the 2250 meter using the Brüel & Kjær UA0035 preamplifier adaptor, and protected with a windshield. However, the windshield was designed for a ½ inch microphone and did not fit adequately to the adaptor. The setup is shown in Figure 2.

Calibration of the microphone signal processing chain was carried out using a B&K 4231 calibrator with a ¼ inch adaptor. The calibrator produces a 1 kHz sine wave at 94 dB (1 Pascal rms pressure). No hydrophone calibrator could be sourced in time for the trial and so the

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\(^2\) The angle of the barrel relative to the sensors was changed in 45 degree increments, these are easy to setup using distances on a tape measure. For smaller angular increments a surveying instrument will be necessary.

\(^3\) Loaned by the Acoustic Testing Service (ATS) of Auckland University. The author is grateful to Gian Schmidt of ATS for his assistance.
hydrophone channel was not calibrated. For the work presented here the sensitivity values quoted in the original calibration chart have been used.

The hydrophone was amplified by a Brue & Kjaer 2260 precision conditioning amplifier (used in charge mode) configured to provide an output of 0.1 V/kPa. The lower frequency limit knob on the 2260 was set to 3 Hz (charge mode) and the upper frequency limit knob was set to Lin. (200 kHz).  

![Image](image.png)

Figure 2. The tripod with 2250 sound level meter (acting as an amplifier for the ¼ inch high SPL microphone) and the 8105 hydrophone. The Quest ¼ inch microphone is covered by a windshield. The hydrophone was mounted vertically inside a section of PVC tubing using vibration insulation foam (the yellow material at the top of the gray tube in the picture).

Charge mode amplifiers are preferable for piezoelectric transducers with weak signal levels. However, impulsive signals from explosive sources at close range are loud and a cheaper voltage amplifier would probably suffice. These are also less susceptible to noise, particularly from unintended cable movement. At the time of the trial the Bruel & Kjaer 2260 was the only amplifier available, and it was decided to follow the manufacturer's recommendation and use it in charge mode. In future work other amplification options will be considered. Some data acquisition cards have variable gain analog input amplifiers and this may be viable in the present application.

When running on internal batteries the 2250 sound level meter will go into standby mode after a certain time by default. This feature should be disabled in the power management options screen before recordings are made, if the meter is powered by the internal battery. The meter's rechargeable battery should last for several hours in pass-through recording mode. However, in this trial an external AC supply was used to power the meter.

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4 For example the National Instruments PCI 4462.
The amplified sensor outputs were digitized by a National Instruments PCI-4472 data acquisition card at 102400 samples/sec with 24 bit resolution. The digitized signal was recorded to a PC hard drive in two-channel WAV format, with 32 bit sample size. The bits of data are shifted right by 8 bits so that they occupy the most significant three bytes of the 32 bit word. The pressure \( P \) is recovered from a digitized sample value using the formula

\[
\text{Pressure (Pascals)} = \frac{1}{SGa} \left( \frac{V_{\text{max}}}{R_{\text{max}} G} \right) \times \text{(Sample Value)}
\]  

(2.1)

where \( S \) is the transducer pressure sensitivity in Volt/Pa, \( G_a \) is the transducer amplifier gain, \( V_{\text{max}} \) is the maximum DAQ card input voltage (10V for the PCI-4472), \( G \) is the input voltage gain on the card (unity for the 4472), and

\[
M = (2^{22} - 1) \times 2^8 = 1073741568
\]  

(2.2)

is the maximum digitized sample value for the PCI-4472 (although it is advertised as having a 24 bit capability only 23 bits are useable, the final bit is at the noise floor and is not stored).

3 Gunshot noise measurement

Before making acoustic measurements it is necessary to estimate the maximum acoustic pressure the sensors may be exposed to. This determines the level of gain or attenuation required to ensure the sensor outputs are within the dynamic range of the signal conditioners and analog-to-digital converters. The analog inputs on the PCI-4472 data acquisition card are limited to between ±10V. The input channels should use as much of this range as possible while being careful not to exceed the limit.

It was not known exactly how loud the muzzle blast would be since previous measurements of the Steyr rifle were not available. However, publicly available data on the M4 rifle suggested the peak level would be in the range 160-170 dB @ 1 m (although the M4 has a shorter barrel than the standard Steyr rifle and so will have a louder muzzle blast when firing the same type of ammunition.)

According to online documentation the dynamic range of the Quest 4110 ¼ inch microphone is 65 – 167 dB [2]. The sensitivity of the microphone was determined to be 4.37 mV/Pa using the calibrator and 2250 sound level meter. A gain of -20 dB was applied to the output socket of the 2250. The maximum output voltage is 4.46 V which corresponds to an input pressure of about 10 kPa or 174 dB, after taking the 20 dB attenuation into account. Acoustic pressures recorded in the trial were always < 170 dB and so the 2250 output socket was not overloaded at any time.

It is not possible to physically damage the hydrophone through accidental over-exposure, but it can electrically overload amplifiers and recording equipment if the acoustic pressure is high.
enough. The sensitivity of the 8105 hydrophone is given as 51.3 μV/Pa on the calibration chart [5]. At 10 kPa the output voltage is about 0.5V, which is well inside the 10V limit allowed on the 2650 amplifier inputs.

The amplifier was adjusted to yield an output sensitivity of 0.1 V/kPa. For an input pressure of 10 kPa the output voltage is equal to 1V, well within the 10V peak output voltage permitted on the 2650. Given that the peak acoustic pressure never exceeded 170 dB we conclude that the hydrophone channel was not overloaded.

3.1 Pressure and free-field microphones

The presence of a microphone distorts the sound field it is intended to measure. The total pressure around the microphone diaphragm is the sum of the incident sound field and the field scattered by the microphone itself. When the wavelength is much larger than the microphone the scattered field is small. However, when the wavelength approaches the size of the microphone the scattering becomes more significant.

Free-field microphones are designed to compensate for the effect of high frequency distortions of the incident field when sound arrives at the microphone at zero degrees incidence. Pressure microphones are designed to respond to the actual pressure field on the microphone diaphragm and do not attempt to compensate for distortions introduced by scattering from the microphone [3].

In free-field conditions (where the sound is predominantly incident from a single direction) a pressure microphone should be oriented at 90 degrees to the incident direction. Many ¼ inch high SPL microphones, including the BK4941⁵ for example, have been designed as pressure microphones.

Ideally, the microphone used in this trial would have been oriented at 90 degrees to the muzzle blast. Because of problems with the screw attachment of the sound level meter to the tripod it was not possible to achieve this. Throughout most of the trial the microphone was oriented at approximately 60-90 degrees to the sound field. However there was very little energy in frequencies above 1 kHz and so the effect of microphone orientation is not likely to be significant.

4 Waveform analysis

A sample gunshot waveform is shown in Figure 4. This illustrates the main features that may be recorded on pressure sensors placed near explosively launched projectiles. Those features are (in order of arrival at the sensor)

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⁵ It is a piezoelectric transducer and is insensitive compared to a condenser microphone.

⁶ DTA now uses the BK4941 for impulse noise measurements.
1. the bullet shockwave (the sonic boom accompanying a supersonic projectile),
2. the direct path muzzle blast,
3. the ground reflection of the muzzle blast.

While item (2) is always present the bullet shockwave does not occur if the projectile travels at subsonic speed. At ranges of a few metres from the weapon the muzzle blast is significantly louder than the bullet shockwave. The bullet shock only intersects points forward of the muzzle, and so is not present in recordings where the microphone was positioned behind the weapon.

For the pressure histories shown in Figure 4 the sensors were placed forward of the muzzle and so the bullet shockwave wave is present. Note that the time origin of the clips was shifted so that the peak pressure in the muzzle blast direct arrivals at microphone and hydrophone locations are coincident. In the experiment there was a separation of 15-20 cm between the microphone and the hydrophone (see Figure 2). Hence the waveforms recorded by each sensor are time shifted by an amount dependent on the angle of the muzzle relative to the microphone-hydrophone axis. It was not possible to orientate the sound level meter in the vertical direction as desired because of problems with the screw-type attachment to the camera tripod. Future experiments will use a microphone extension cable and an acoustic isolated microphone holder (these accessories were not available for this trial).

The time origin of the clips in Figure 4 has been shifted so that the peak pressure in the muzzle blast direct arrivals at microphone and hydrophone locations are aligned. The three components of the waveform can be identified by geometric considerations, given the known speed of sound and the speed of the bullet.

The peak pressure in the bullet shockwave was measured at 100 Pa on the microphone, whereas the muzzle blast peak was 450 Pa. The muzzle blast was always much louder than the bullet shockwave in this experiment (when the latter was present).

These features are well known acoustic characteristics of small arms fire [4]. They were identified in the acoustic data using an assumed speed of sound of 340 m/s, a nominal muzzle velocity of the SS109 bullet of 940 m/s, and the estimated positions of the sensors and the rifle muzzle. Understanding the various features of the recorded waveforms is necessary to correctly interpret the measurements.

4.1 Shot extraction

Most impulse recordings contained five shots, fired at different intervals. Occasionally there were long gaps between successive shots due to the need to reload. Each file was reviewed in an audio file editor (Goldwave 4.24) to remove large gaps between impulses in order to speed up the extraction process which was performed in MATLAB.
Shot extraction was carried out by first locating the global peak pressure sample in each recording. A threshold level was set at \(2/3\) of that value. Then all samples exceeding this threshold which were separated by at least 60 milliseconds from each other were located. Then around each peak a block of 60 milliseconds duration, starting 200 samples before the sample containing the peak, was extracted. Each extracted shot was plotted to verify that the algorithm had correctly identified the individual impulse events. The extracted clips were saved in a file for subsequent processing.

### 4.2 Bullet shockwave and muzzle blast

By compressing air ahead of itself a projectile continuously generates outgoing pressure waves. When it travels at supersonic speeds the waves overlap to form a cone-shaped shock wave. The cone angle is given by

\[
c \sin \alpha = \frac{c}{v}\tag{4.1}
\]

where \(c\) is the speed of sound and \(v\) is the speed of the projectile.

The muzzle blast is a spherically expanding shockwave centred just forward of the muzzle [5]. It is created by the rapid escape of propellant gases under high pressure when the bullet exits the muzzle, like the pop when uncorking a champagne bottle. These gases are initially traveling with supersonic speed and compress the surrounding air forming a shockwave. The muzzle blast pressure at a fixed point in space as a function of time is approximated by the Friedlander waveform [6]

\[
P - P_\infty = \begin{cases} 0, & t < 0 \\ P_\infty [1 - (t - t_\text{a})/\tau] e^{-(t - t_\text{a})/\tau}, & t \geq t_\text{a} \end{cases}\tag{4.2}
\]

for the total pressure \(P\), where \(P_\infty\) is the ambient atmospheric pressure, \(P_\text{p}\) is the peak blast pressure, \(t_\text{a}\) is the time of arrival of the blast pressure peak, and \(\tau\) is the duration of the positive part of the waveform (known as the A-duration).

The arrival times of the bullet shockwave and the muzzle blast can be predicted from basic geometry, as depicted in Figure 3. In this diagram, the bullet exits the muzzle at point A at \(t = 0\), and has traveled to point C by time \(t\). It trails a cone shaped shockwave behind it, indicated in the diagram by the dotted lines leaving the bullet at angle \(\alpha\) to its trajectory. Near the muzzle (before the bullet has slowed appreciably) the shockwave cone satisfies the equation

\[
(z - H)^2 + y^2 = (vt - x)^2 \tan^2 \alpha\tag{4.3}
\]

assuming the bullet travels along a line parallel to the \(x\)-axis a height \(H\) above ground. The bullet shockwave is formed by overlapping spherical shockwaves that are continuously emitted along the bullet trajectory, and travel away from the emission point at the speed of sound. At time \(t\)
the shockwave arrives at the sensor at point D; the part of the shockwave incident at D was emitted earlier at point B.

The time of arrival of the muzzle blast, assuming the shockwave speed rapidly slows to the ambient sound speed, is

\[ t_{MB} = \frac{R}{c}, \]  

(4.4)

where \( c \) is the speed of sound and \( R \) is the distance from A to D. The time of arrival of the bullet shockwave at the sensor location \((R \cos \theta, R \sin \theta, H)\) is

\[ t_{SW} = \frac{R \cos \theta + L \cos \alpha}{v} = \frac{R}{c} \sin(\theta + \alpha) \]  

(4.5)

where \( v \) is the speed of the bullet, \( \alpha \) is the angle of the bullet shockwave cone, \( \theta \) is the angle of the sensor to the boreline, and \( L \) is the distance from point D to C in the diagram. Eliminating \( L \) we have

\[ t_{MB} - t_{SW} = \frac{R}{c} [1 - \sin(\theta + \alpha)] \geq 0. \]  

(4.6)

Since the sine of any angle never exceeds 1, the muzzle blast never precedes the arrival of the bullet shockwave (that is, \( t_{MB} \geq t_{SW} \)).

Figure 3. The geometry of the bullet shockwave and the muzzle blast. Point A is the muzzle of the rifle, C is the bullet at time \( t \), D is the microphone, and finally B is the point at which the bullet emits a spherical shockwave which arrives at the microphone at time \( t \).
Figure 4. Sample waveform gunshot impulse waveforms recorded at a range of 5 m and at an angle of 45° from the rifle barrel.

The muzzle blast and the bullet shockwave arrive at the same time when \( \theta + \alpha = 90^\circ \) since the term in brackets in (4.6) is then zero. We then have

\[
\theta = 90^\circ - \sin^{-1}\left(\frac{c}{v}\right) = 68.8^\circ
\]

(4.7)

assuming \( c = 340 \) and \( v = 940 \). Measurements were not made around this angle and so there was no overlap between bullet shockwave and muzzle blast in the trial.

Assuming that the muzzle velocity of a Steyr rifle firing an SS109 cartridge is approximately 940 m/s [7], the time difference of arrival given by (4.6) for \( R = 5 \) and \( \theta = 45^\circ \) is 1.25 ms, which is similar to the measurements shown in the top plot of Figure 4 (approximately 1.1 ms for the hydrophone and 1.4 ms for the microphone). These sensors were displaced by about 15 cm and hence the TDOA recorded by each will be different (the exact sensor displacement was not measured in the experiment).

### 4.3 Ground reflections

In this experiment the sensors and muzzle were at approximately the same height (about 1.6 m). Denote this height by \( H \), and the muzzle-sensor direct path distance by \( R \). Then by straightforward geometry the time difference of arrival (TDOA) between arrival times of the direct wave \( (t_{MB}) \) and ground reflected wave \( (t_{GR}) \) is

\[
t_{MB} - t_{GR} = \frac{R}{c} \left( \sqrt{1 + \frac{4H^2}{R^2}} - 1 \right)
\]

(4.8)
where \( c \) is the speed of sound. As the distance from the muzzle to the sensors increases the TDOA reduces, and ultimately these waveforms overlap. The ranges in this experiment were too short for this to occur.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>( t_{MB} - t_{GR} ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.0</td>
</tr>
<tr>
<td>2</td>
<td>5.2</td>
</tr>
<tr>
<td>5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 1. The time difference of arrival between direct and ground reflected paths of the muzzle blast shockwave, assuming a speed of sound of 340 m/s.

The acoustic pressure waveforms displayed in Figure 4 were recorded at a distance of approximately 5 m from the rifle muzzle. From Table 1 the interval between the muzzle blast and the ground reflection should be about 3 ms. From Figure 4 the measured interval is about 3 ms for the microphone and 3.2 ms for the hydrophone, these results are reasonably consistent with the theoretical values given the uncertainties in the experimental geometry.

In Figure 5 three acoustic pressure histories are plotted for an unbraked rifle fired at ranges of 0.5, 2 and 5 metres from the sensor, respectively. The microphone was located 90° from the boreline. The arrows in the plots indicate the time a ground reflected muzzle blast wave would be expected to arrive, based on (4.8) and assuming \( H = 1.6 \text{m} \). There is reasonable agreement between the predicted arrival time and the location of a secondary peak in the waveforms.

We conclude that this peak is the ground reflection of the muzzle blast. It does not overlap the direct path muzzle blast at any of the sensor-muzzle ranges used in this experiment. Note also the slight change in waveform shape with distance in Figure 5. This indicates that there are non-linear processes involved in the propagation of the shockwave over this distance. Non-linear effects are discussed in Ref. [10].

It is also possible that a bullet shockwave might reflect from the ground and other objects into the sensors. Figure 6 shows the acoustic pressure recorded on the microphone placed at 45 degrees to the bullet path at a range of 5 metres. A total of 5 shots were fired and all are displayed in the plot. The time origins of the waveforms have been shifted so that the muzzle blast peak in each is coincident (it occurs at about \( t = 2 \text{ms} \) in the plot).

Each bullet shockwave is followed about 1 ms later by a smaller pressure waveform of the same duration. The regularity of the spacing and the similarity of the waveforms suggests the subsidiary peaks may be reflections of the direct path shockwave arrival.
First we look at the possibility this is a ground reflection of the bullet shockwave. The primary shockwave forms a cone described by Eq. (4.3). The ground reflection of this shockwave cone satisfies

\[(z + H)^2 + y^2 = (vt - x)^2 \tan^2 \alpha\]

which is the locus of spherical shockwaves emitted by an image bullet traveling on a line parallel to the x-axis a height \(H\) below the ground. From (4.3) and (4.9) the time difference of arrival \(\Delta t\) between the direct and ground reflected bullet shockwave paths is

\[\Delta t = \frac{R}{c} \cos \alpha \left( \sqrt{\sin^2 \theta + 4H^2/R} - \sin \theta \right).\]  

(4.10)

For the present geometry (assuming that \(H \approx 1.6\) m) this relation yields \(\Delta t = 3.4\) ms for the interval between these two signals. However, inspection of Figure 6 shows the interval between the direct path shockwave and the suspected reflection is only about 1 ms (which corresponds to an acoustic path difference of 0.3 m).
Figure 6. The acoustic pressure recorded on the microphone at 45 degrees to the bullet trajectory at a range of 5 metres (pressure histories from five shots are shown).

Figure 7 shows an image of the firer (with a suppressor fitted to the rifle) standing alongside the sensor tripod. The case containing signal conditioning equipment and power supply is visible behind the tripod. It is possible that the unknown waveform in Figure 6 is a reflection from some part of the tripod, but without additional measurements it is not possible to be certain.

Figure 7. A picture of the firer showing the sensor tripod and the case containing the power supply signal conditioning equipment.

Future experimentation should give greater attention to the presence of acoustic contaminants near the sensors. Possible sources of multipath interference should be measured and their position relative to the sensors recorded if it is not possible to remove them. Application of sound absorbing foam to potential sources of acoustic reflection should be considered, in particular the mountings of the sensors to the tripod.
4.4 Precursor waveforms

The acoustic pressures recorded directly behind the rifle (180 degrees from the line of fire) show an impulse before the muzzle blast arrival (the muzzle blast signal has been identified in section 11 on the basis of its expected shape and the expected transit time of the shockwave from the muzzle to the sensors). Waveforms are displayed in Figure 10 (the time origin has been chosen so that the muzzle blast appears at $t = 2$ ms).

The heights of these precursor impulses are approximately the same for both braked and unbraked weapons, even though the main muzzle blast is far greater at this angle for the braked weapon. This indicates that the precursor waveform is not a reflection of the muzzle blast wave. There is a slight difference in precursor waveform shape between the braked and unbraked weapons, but the main difference is in the time delay with the muzzle blast: the precursor arrives about 0.75 ms ahead of the muzzle blast for the unbraked weapon and about 0.5 ms ahead for the braked weapon (see Figure 10). The slight change in waveform shape when the brake is present shows that the precursor waveform is emitted from the rifle after the propellant gases have interacted with the muzzle in some way.

The precursor arrival time is dependent on the measurement angle. Figure 8 shows waveforms recorded on the hydrophone for measurement angles of 180 degrees (directly behind the rifle) and 135 degrees at a range of five metres. At 180 degrees the TDOA between the muzzle blast and the precursor impulse is about 0.8 ms, while at 135 degrees this has reduced to 0.4 ms.

![Figure 8. Pressure waveforms at a range of 5 metres at angles of 180 and 135 degrees from the barrel of the unbraked weapon. The main muzzle blast wave occurs at $t = 2$ milliseconds. Point A marks the arrival of the precursor in the waveform recorded at 180 degrees at about 1.25 milliseconds, B the precursor arrival recorded at 135 degrees at about 1.55 milliseconds.](image-url)
One possibility is that the precursor waveform is a typical muzzle blast precursor, that is, an impulse produced by compression of the air ahead of the bullet and released from the muzzle shortly ahead of the muzzle blast [8]. However, if this was the case one would expect the TDOA to be independent of the measurement angle. The dependence on measurement angle indicates the precursor originates at a point distant from the muzzle, and we suggest the ejection port as a possible source.

To investigate this possibility consider the geometry in Figure 9. In the diagram point A is the source of the muzzle blast, point B is the source of the unknown precursor (which we assume lies on the barrel a distance $L$ back from the muzzle), the microphone indicates the measurement position at a range $R$ from the muzzle and grazing angle $\gamma$ from the barrel.

Define $\Delta_{\gamma}$ by

$$\Delta_{\gamma} = t_A - t_B$$

where $t_{A(B)}$ is the arrival time at the measurement point of the impulse from point A(B).

Suppose that the impulse at B is emitted an unknown time $\tau$ after the impulse at A, and that both impulses propagate at speed $c$ to the measurement position (it can be shown that the value of $L$ is depends only on the average speed of propagation from points A and B to the microphone, as long as the speed profile depends only on distance from the source point and not on angle).

When $\gamma = 0$ the time difference of arrival defined in (4.11) is

$$\Delta_0 = -\tau + \frac{L}{c},$$

while at non-zero angles from the barrel

$$\Delta_{\gamma} = \frac{R}{c} - \tau - \frac{1}{c} \sqrt{R^2 + L^2 - 2RL \cos \gamma},$$

where $c$ is the speed of sound (this assumes that the muzzle blast shockwave speed decays rapidly to the ambient speed of sound). Solving these equations for $\tau$ and $L$ yields

$$L = \frac{c^2 (\Delta_{\gamma} - \Delta_0)(2R/c - \Delta_{\gamma} + \Delta_0)}{D},$$

$$\tau = \frac{\Delta_0 (2R \cos \gamma - c\Delta_0) + \Delta_{\gamma} (c\Delta_{\gamma} - 2R)}{D},$$

where
Figure 9. The geometry for testing whether the ejection port could be the source of a signal prior to the muzzle blast. Point A is the muzzle, point B is the hypothetical location of a second acoustic source a distance $L$ down the barrel.

This approach was applied to waveforms recorded at 5 m range at angles of 180 and 135 degrees from the barrel (see Figure 8). Time differences between components of the waveforms were measured from the zero crossings of the waveform features, to avoid ambiguity in the cases where the waveform peak was ill-defined (e.g. the first impulse in the 135 degree waveform in Figure 8).

In the present case, the lag between the precursor wave and the muzzle blast in the 135 degree waveform was estimated to be 0.4 ms, while the lag in the 180 degree waveform was about 0.8 ms. Application of Eqs. (4.14) – (4.16) gives $L = 43$ cm and $\tau = 0.5$ ms. The same analysis performed on the waveforms recorded at 2 m range yielded $L = 35$ cm and $\tau = 0.2$ ms.

Neither of these estimated emission points matches the midpoint of the ejection port, which is located about 0.6 m behind the muzzle. The same analysis applied to the waveforms obtained from the braked weapon yields $L = 58$ cm, which is much closer to the ejection port.

Angles from the barrel and distances from the muzzle were not at all well controlled in this experiment. This may introduce an unknown level of error into the analysis. It is also possible that an angular dependence of the speed of the muzzle blast shockwave could influence the result (it has already been noted that a shockwave speed dependent only on the distance from the muzzle and not the direction does not change expression (4.14) for $L$).

A improved measurement methodology might involve placing two microphones at precisely known locations and making simultaneous measurements. These microphones could also be situated near the muzzle to measure directional dependence on propagation speed, which can influence the result. However, this aspect of the measurements is not of major concern and there are no plans to conduct further experimentation.
4.5 Muzzle blast waveforms

Acoustic pressure measurements of the Steyr rifle muzzle blast were attempted at angles of 45, 90, 135 and 180 degrees from the barrel and ranges of 0.5, 1, 2 and 5 m. The geometry of the trial is indicated in Figure 3, where $\theta$ is the angle of the sensor from the barrel.

It was not possible to make measurements at all these angles and ranges. At the outset of the trial it had been intended to only measure pressures at ranges of 0.5, 2 and 5 m from the muzzle. However, the trial proceeded faster than expected and additional measurements were made at 1 m range on the braked weapon.

A considerable amount of combustion byproduct was ejected to broadside of the muzzle at close ranges. It was possible for this discharge to damage the microphone and so that sensor was not used at 0.5 m range, except at an angle of 180 degrees (microphone directly behind the firer). At ranges of 2 and 5 m the acoustic pressure recorded by the microphone and the hydrophone were reasonably consistent (general characteristics of gunshot waveforms were already discussed in sections 4.2 and 4.3). However, the measurement at 0.5 m range and 180$^\circ$ angle shows significant disagreement between the two sensors. This was the only measurement in the trial that was performed using both sensors at 0.5 m range. The peak overpressure recorded on the microphone was actually negative (below ambient) in that case, which is incorrect since the
muzzle blast peak overpressure is always positive. The fact that this anomalous measurement occurred at close range suggests the microphone was overloaded.

The lowest peak pressure level at which complete distortion was noticeable in the microphone signal was about 1.5 kPa (by comparison with hydrophone measurements). This corresponds to a sound pressure level of about 158 dB re 20 μPa, with an unweighted spectrum. The highest peak pressure for which no distortion is evident was about 1.4 kPa (~156 dB). We conclude that the microphone signal is significantly distorted at about 157 dB. It is likely that non-linearity in its response has set in before this.

Since the pressure signals that are of interest in this trial are generally over 160 dB it was decided to ignore the recordings made using the microphone and present an analysis based on hydrophone measurements only. The hydrophone is not an ideal sensor in air since its response begins to roll off at about 2.5 kHz. It is down by 2.5 dB at 5 kHz and about 5 dB at 10 kHz (Fig. 10, Ref. [9]).

From (non-saturated) measurements recorded on the microphone, about 85% of the energy in a shot lies below 2.5 kHz, and 95% is below 5 kHz. Numerical experiments applying the hydrophone roll off characteristic to microphone data indicate that 6-7% of the total energy in these signals are lost to hydrophone roll off. This was not significant in the context of the current experiment.

![Figure 11](image.png)

Figure 11. A comparison of the energy spectral densities measured by the microphone and the hydrophone at 90 degrees from the bullet path at a range of two metres.

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7 The manufacturer claims 167 dB(A) maximum pressure for the QE4110.
Pressure waveforms for the braked and unbraked Steyr rifle are shown in Figure 12 – Figure 15. Only pressure waveforms recorded on the hydrophone are shown. The pressure axis is scaled in units of kilopascals (kPa), the time axis in units of milliseconds (ms). The pressure history for the first shot (out of the five shots fired in each configuration) is shown in each case.

The acoustic pressure histories of each shot were found to be quite consistent. For the purpose of extracting peak SPL, it is sufficient to consider data from any one shot in each series, given the sensor error and the imprecision in the geometry.

The signals all have the characteristics expected from a muzzle blast, namely, a fast rise to peak positive overpressure followed by exponential decay to a partial vacuum, and finally recovery to ambient pressure [6,10,11].

4.6 Muzzle blast spectra

Energy spectral densities for the unbraked and braked pressure signals were calculated for a single shot. The spectra are shown in Figure 16 – Figure 19.

All energy spectra show a gradual loss of high frequency content in the blast wave with distance traveled. The spectra were generally fairly consistent from shot to shot, with the exception of recordings taken at 90 degrees at 0.5 and 1 m range where there was greater variability in the 0-500 Hz band (not shown). The greater inter-shot variability at short ranges is expected since small and unavoidable movements in the rifle's position are a greater proportion of the muzzle-sensor distance. In these measurements most of the energy in a shot lies below 5 kHz, although the hydrophone is likely to begin attenuating the signal at around that frequency.
Figure 12. The acoustic pressure recorded by the hydrophone 180 degrees from the line of fire (i.e. directly behind the weapon) for the braked and unbraked weapons.
Figure 13. The acoustic pressure recorded by the hydrophone 135 degrees from the line of fire.
Figure 14. The acoustic pressure recorded by the hydrophone 90 degrees from the line of fire.
Figure 15. The acoustic pressure recorded by the hydrophone 45 degrees from the line of fire.
Figure 16. The energy spectral density of shots at 180 degrees angle from the line of fire.
Figure 17. The energy spectral density of shots at 135 degrees angle from the line of fire.
Figure 18. The energy spectral density of shots at 90 degrees angle from the line of fire.
Figure 19. The energy spectral density of shots at 45 degrees angle from the line of fire.
5 Impulsive noise and hearing loss

Noise Induced Hearing Loss (NIHL) is a permanent loss of hearing sensitivity caused by exposure to high sound levels. Any type of sound can lead to NIHL, provided sufficient intensity and exposure time. NIHL initially manifests as a Temporary Threshold Shift (TTS), also known as auditory fatigue.

TTS is a temporary hearing loss that recovers almost completely once the noise stimulus is removed. The amount of time necessary for recovery from TTS varies according to the type of noise, its level and the individual affected [12]. Some indicative curves relating the level of TTS and time following the causative noise exposure are given by Gelfand (Fig. 17.5, Ref. [12]). For TTS of 20 dB or less complete recovery generally takes place within 16 hours. However, once TTS reaches 30 dB a full 48 hours are typically needed for recovery.

For TTS of around 40 dB or greater full recovery does not occur resulting in a permanent hearing loss called Permanent Threshold Shift (PTS). Early hearing damage is greatest between 3000 and 6000 Hz, with a pronounced notch often occurring at 4000 Hz. The 4000 Hz dip in an audiogram is believed to be an early sign of occupational hearing loss and loss from gunfire [13,14].

Noise can damage most types of cell in the cochlea of the ear, but the outer hair cells are the most susceptible. Higher levels of noise exposure lead progressively to loss of inner hair cells, loss of auditory nerve fibres and shrinkage of the stria vascularis. Some damage, particularly for lower levels of continuous noise, may be due to metabolic exhaustion. In this damage mechanism the hair cells run out of energy to transduct noise into nerve impulses. They subsequently generate excessive quantities of toxic reactive oxygen species causing cell damage and ultimately death [15]. Impulse noise, if loud enough, can cause damage to the tympanic membrane and tissue in the middle ear and the cochlea [16].

5.1 The NATO RSG-029 impulse noise review

A review of impulsive noise dose and related hearing loss was released by NATO Research Group RSG-029 in 2003 [17]. According to this report the relationship between noise dose and hearing damage for impulsive sound is still not completely understood. Assessment of appropriate metrics continues to be an active area of research. After a survey of the most relevant experimental results, the RSG-029 report suggested the following noise exposure rules for rifle shots (defined as an impulse with an A-duration of 0.2 - 0.3 ms, §1.7.4, [17]):

1. The SEL for a single shot should not exceed 116 dB(A) when measured in free field at the ear at normal incidence;

2. For multiple shots the $L_{\text{Aeq,8hr}} = L_{\text{IP,d}}$ should not exceed 80 dB(A).
Item 2 is known as the Equal Energy Hypothesis (EEH, see Appendix B). However, experimental results show there can be a significant non-linearity in the energy dose-TTS relation (i.e. the EEH does not apply). For $< 50$ impulses the evidence suggests that the $25 \text{ dB}$ TTS criterion does not depend on the number of rifle shots, only the SEL of a single shot. Above this number the total energy of the shots starts to become important in determination of TTS. Hence, for shot numbers in the range $5-100$ (where the EEH does not apply) the suggested limits given above are actually overprotective, as RSG-029 themselves have noted. The maximum overprotection is $9 \text{ dB}$ at $50$ impulses ([17], p1-17).

Although the EEH is not correct in all noise dose regimes it is still an important metric: it has a physically plausible basis; for large numbers of shots it usefully approximates available experimental results; it is easy to measure.

5.2 The Auditory Hazard Assessment Algorithm for the Human (AHAAH)

In 1991, Price and Kalb (of the US Army Research Laboratory) proposed a temporal model which assesses the damage of a pressure waveform based on an electro-acoustic model of the ear [18]. A year 2000 version of this model, the Auditory Hazard Assessment Algorithm for the Human (AHAAH), was reviewed in the RSG-029 report. The reviewers believed that AHAAH was an important contribution, but they raised two specific objections:

1. There is data showing that hearing damage may decrease as impulse duration increases ([17], §1.3), despite the increase in total energy, and AHAAH models this effect. However, based on a test using Friedlander waveforms the RSG-029 reviewers concluded that the AHAAH model over-estimated the magnitude of this effect.

2. The reviewers were more concerned regarding the model’s treatment of the tradeoff between the SEL of a single impulse and the number of impulses. In order to estimate this for AHAAH they noted that the model predicts equal hearing damage for (a) a single impulse with $20 \text{ kPa}$ peak (180 dB) and $1$ ms duration, and (b) $10.6$ impulses of $1 \text{ kPa}$ peak (154 dB) also of $1$ ms duration. This corresponds to a level/number tradeoff of $(154 - 180)/\log_{10}10.6 = -25 \text{ dB/decade}$. This is significantly greater than the value of $-7 \text{ dB}$ found from TTS measurements and $-10 \text{ dB}$ based on the equal energy principle ([17], p1-17)\(^8\). The report concluded that while the model was a promising advance, they were not entirely satisfied with its predictions and did not recommend its adoption by NATO.

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\(^8\) The experimental tradeoff data used for this comparison was in terms of the A-weighted SEL and not the peak SPL, as the reviewers assumed for the AHAAH prediction. Assuming a Friedlander waveform it can be shown that $\text{SEL}(A) = \text{SPL}_{\text{peak}} + 10\log_{10}(\tau) + K_A$, where $\tau$ is the A-duration (1 ms for both impulses), and the constant $K_A$ has been introduced to account for the effects of A-weight filtering. Since both waveforms differ only by scale this constant is the same for both impulses and does not affect the calculation. The SEL vs. number tradeoff is then $(124 - 150)/\log_{10}10.6 = -25 \text{ dB/decade}$, which confirms the value given in the NATO report.
More recently, one of the model developers (Price) has published the results of a validation of AHAAH using exposures for which measurements of both impulse waveform and TTS were available [19]. They were able to source about 70 waveforms that met their requirements. The bulk of the data came from the U.S. Army Blast Overpressure (BOP) study of TTS in human volunteers exposed to impulse noise [20]. On this data set Price claims that AHAAH correctly classified 95% of the exposures as either hazardous or non-hazardous, while the MIL. STD 1474D had only a 42% success rate (this interpretation is disputed by Murphy et al. [21]).

The U.S. Army Research Laboratory website reports that in 2001 the American Institute of Biological Sciences (AIBS) reviewed the AHAAH model as a potential replacement for the MIL. STD 1474D, and concluded that AHAAH was superior. It is not known if there were any differences between the versions reviewed by AIBS and the RSG-029 panel. The AIBS reviewers noted that the model needs to be better documented so that other researchers can generate their own implementations. However, as of the writing of this report this has not occurred.

The AHAAH model is available as a windows executable that can be downloaded from the ARL website. Input waveforms must be in WAV format. Two examples are provided: Howitzer.wav and M16Rifle.wav. The Howitzer.wav file must be erroneous, however, as it contains a pure tone rather than an impulsive waveform. The M16Rifle.wav sample is more plausible, although it does not have a classic Friedlander shape. The program can then calculate waveform hazard for protected and unprotected ears, and for warned and unwarned conditions, at the option of the user. The program does not have a batch mode, making it inefficient for use with large data sets.

In 2009 Murphy et al. published a study comparing AHAAH, the MIL-STD-1474D and $L_{eq,8hr}$ in assessing the auditory damage potential from impulse noise [21] using the U.S. Army BOP data [20]. The study concluded that $L_{eq,8hr}$ was a better predictor of audiometric failure (defined as a TTS of 25 dB or greater at any audiometric frequency) than AHAAH or MIL-STD-1474D.

In turn, Price has disputed certain aspects of the 2009 Murphy et al. study and pointed out that there are differences between the blast waveforms in the U.S. Army BOP study and that from small arms fire [22]. Price also criticizes Murphy et al. for what he sees as misuse of the AHAAH model in their comparison with other metrics.

In the assessment of the first author the AHAAH model is not yet widely enough accepted to justify use by the NZDF at this time. This situation may change if AHAAH is incorporated into an updated MIL. STD 1474, particularly if better documentation and model implementation become available.
5.3 Occupational noise control standards

5.3.1 Europe
Current workplace noise limits in the European Union (EU) are defined in EU directive 2003/10/EC [23]. The directive prescribes an "upper action value" of 137 dB(C) on the peak SPL, and 85 dB(A) on the $L_{EP,d}$. When noise matches or exceeds the upper action values hearing protection must be used. The directive stipulates a noise limit of 140 dB(C) on the peak SPL, and a limit 87 dB(A) on the $L_{EP,d}$. Noise levels must not exceed these limits, after taking into account the effect of hearing protection. The action values and limits in the EU directive have been incorporated by the United Kingdom (UK) into its 2005 noise control legislation, and are also used by the UK Ministry of Defence [24,25].

5.3.2 United States
In the U.S. military, on the other hand, impulse exposure is still governed by MIL STD-1474D (1997) [26]. This standard limits the number of impulses to which a person may be exposed based on the peak level of the impulse and its B-duration$^9$, after taking into account the effect of hearing protection. The standard suffers from the problem that its chosen sound level metric is not measured by commercially available sound level meters. The definition of the B-duration is unambiguous (the MIL STD-1474 provides a detailed algorithm) but is complicated. In the view of the NATO reviewers the MIL STD-1474D is somewhat arbitrary and not supported by known dose-effect relationships [17].

5.3.3 New Zealand
In New Zealand, the exposure limits for noise are stated in Regulation 11 of the Health and Safety in Employment Regulations, 1995 (stated in §A.2.2 in [27]). Regulation 11 requires employers to take all practicable steps to ensure that no employee is exposed to noise above the following levels

1. An eight hour equivalent continuous A-weighted sound pressure level of 85 dB(A);
2. A peak sound pressure level of 140 dB (unweighted).

The wearing of hearing protectors as a long-term solution is allowed provided the employer has taken all practicable steps to reduce noise to below the exposure limits. This is clearly the case for the NZDF where impulse noise is an unavoidable hazard for uniformed personnel.

5.4 Summary of noise control standards
The 2003 NATO impulse noise review and the 2009 Murphy study both suggest that $L_{Aeq,8hr}$ is the most well accepted metric presently available for assessing impulse noise hazard. In

$^9$ The length of time for which the pressure envelope exceeds a level 20 dB below the impulse peak.
particular, we advise that the RSG-029 hazard criteria be adopted by the NZDF for small arms fire.

6 Performance of hearing protectors in impulse noise

The attenuation of hearing protection devices is usually assessed with sound pressure levels that are far lower than impulsive sources such as rifles and explosive charges. At very high sound pressure levels the performance of the device may differ significantly from the values assessed at lower levels.

Measurement of attenuation by earmuffs of impulsive noise was conducted in the U.S. Army BOP study [20]. In these experiments the BOP study used a standard (at the time) U.S. Army RACAL earmuff [17]. The study found some reduction in hearing protection performance above 500 Hz at the highest level of explosive charge used (level 6) in the standard earmuff. The blast wave in these experiments was always normally incident on the ear.

The results of these experiments are reproduced in RSG-029 report [17]. To model the effect of an earmuff on impulsive noise, we use the following piecewise linear approximation to the attenuation curve for the level 6 (strongest) charge given in Fig. 23 of [17]:

$$AT = \begin{cases} 5, & 0 \leq f < 50, \\ 5 + \frac{25}{950} (f - 50), & 50 \leq f < 1000, \\ 30, & f \geq 1000, \end{cases} \quad (6.1)$$

where $AT$ is the attenuation in dB at frequency $f$ in Hz.

7 Results

Measurements of the acoustic pressure around a Steyr A3 rifle with a standard length barrel were made at a number of different ranges and angles from the line of fire. At each range/angle combination five rounds were fired and signals from the microphone and hydrophone recorded. The sensor voltages were digitized by the PCI-4472 data acquisition card and saved in a two-channel audio file in WAV format. Conversion of voltage to pressure based on calibration data was carried out in subsequent processing.

The measurement ranges were approximately 0.5, 1, 2 and 5 metres from the muzzle and the measurement angles were approximately 45, 90, 135 and 180 degrees from the rifle barrel. The trial was not expected to yield definitive measurements, but rather to test sensors, recording equipment and methodology in a realistic situation.

10 A second set of measurements were conducted with the same earmuff type modified by inserting plastic tubes to simulate a poor fit. This was called the "modified muff" in the study report.
Acoustic measurements were made at the above ranges and angles for both rifle configurations (braked and unbraked) for a firer in the standing position. The height of the muzzle was approximately 1.6 m (about the same height as the hydrophone). Although some care was taken to keep the position of the muzzle as close to the reference location it was not possible to do this with precision.

7.1 Peak sound pressure levels

The peak sound levels around the Steyr rifle both in its standard configuration (20 inch barrel, unbraked), and with a muzzle brake fitted, are given in Table 2. The effect of earmuffs against impulse noise has been estimated using the attenuation levels given in (6.1). The results are given in Table 3. For comparison, the peak SPL using A-weighting is given in Table 4.

The sound levels around the unbraked rifle show the expected directional dependence of the blast wave strength [4]. The levels are highest forward of the muzzle and decrease with increasing angle to the line of fire.

Comparing the levels of the braked and the unbraked weapons: at 45 degrees the braked level is slightly down on the unbraked level (-4 dB at 0.5 metres, -2 dB at 2 metres, and -1 dB at 5 metres), whereas levels at 180 degrees are up by +6 dB at 0.5 metres, +12 dB at 2 metres and +11 dB at 5 metres.

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Table 2. The Sound Pressure Level (SPL) in dB(C) near the Steyr A3 in standard configuration (20 inch barrel, unbraked) and with a muzzle brake fitted. Ranges given are the approximate distance from the muzzle to the sensor location. Angles are measured from the line of fire to the line connecting the muzzle and the sensor. A dash (-) indicates that no measurement was taken.
7.2 Estimated levels at shooter's ear

The measurement location which approximates the shooter's ear is that at 180 degrees 0.7 metres behind the muzzle. To estimate the sound levels at this position we take the measured level at 0.5 metres and reduce it by 3 dB to account for the spreading in the blast wave.

Using this procedure the estimated level at the shooter's ear with the muzzle brake is 168 dB(C) without protection and 143 dB(C) with hearing protection. The latter exceeds the European regulatory limit by 3 dB. The level with the unbraked weapon, by contrast, is 138 dB(C) with earmuffs which is within the permitted level.

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Table 3. As per Table 2 but with estimated hearing protection attenuation given in (6.1).

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Table 4. Sound pressure levels in dB(A) near the Steyr A3 in standard configuration (20 inch barrel, unbraked) and with a muzzle brake fitted. Hearing protection attenuation given by (6.1) is assumed.
7.3 The RSG-029 noise metric applied to the Steyr rifle data

The NATO RSG-029 panel recommended the use of the A-weighted Sound Exposure Level (SEL) to assess impulse noise risk, based on empirical data (see (A.2)). The upper limit on the SEL suggested by RSG-029 for rifle shots is 116 dB(A).

The SEL for the Steyr rifle data is given in Table 5 (assuming hearing protection). The levels for the braked Steyr are lower than the recommended limit at all measurement locations. In particular, the SEL estimated at the shooter's ear is 107 dB(A).

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Table 5. The Sound Exposure Level (SEL) in dB(A) with hearing protection attenuation given by (6.1). The levels are all below the RSG-029 recommended limit of 116 dB(A) for rifle shots.

8 Conclusions

The New Zealand Army is evaluating the potential of muzzle brakes to improve the accuracy of the Steyr AUG A3 rifle. A muzzle brake is a barrel attachment that diverts propellant gases to the side and rear to reduce the effects of recoil.

A side effect of muzzle brakes is an increase in blast noise level to the sides and rear of the weapon. This increase can be significant and there was concern regarding the adequacy of current hearing protection protocols.

To measure muzzle blast noise DTA has been developing an impulse noise measurement system since February 2010. This system was tested for the first time in a trial at Waiouru military base in which the sound pressure level of a Steyr A3 rifle was measured, both with and without a muzzle brake.
The peak SPL at the shooter's ear was estimated to be 162 dB(C) for the unbraked Steyr and 168 dB(C) when the rifle is fitted with a muzzle brake. The effect of hearing protection is to reduce these levels to 138 and 143 dB(C), respectively. The estimated level at the ear for the muzzle brake exceeds the regulated level of 140 dB.

A review of impulsive noise dose and related hearing loss was released by NATO Research Group RSG-029 in 2003 [17]. The objective of RSG-029 was to assess the risk of hearing loss from exposure to impulse noise, by identifying occurrences which are hazardous, and to develop measures which would protect hearing.

After consideration of available empirical data RSG-029 suggested that the A-weighted SEL be used as an impulse hazard metric, and that for rifle shots the SEL should not exceed 116 dB(A). The panel noted that this criterion exceeds the 140 dB(C) limit for impulse noise. Although the Steyr rifle exceeds the limit of 140 dB(C) when fitted with a muzzle brake the levels are always within the more rigorous RSG-029 limit.

Application of the RSG-029 impulse noise hazard metric suggests that the Steyr rifle does not present an auditory hazard when fitted with a muzzle brake, as long as the highest level of earmuff protection is used.

We recommend that the RSG-029 impulse noise hazard criteria be adopted by the NZDF for small arms fire instead of the present 140 dB limit on the peak SPL.
Appendix A  Sound level metrics

In quantifying the intensity of sound a number of different metrics are in common use. These include the peak sound level, measures of the average sound level, a number of different frequency weightings (most commonly A, B, C and Z weighting), and fast or slow time averaging. Some of the more commonly used metrics are described below.

A.1 Equivalent continuous sound level

The equivalent continuous sound level is the mean square acoustic pressure expressed in decibels. It is defined by

\[
L_{eq} = 10 \log_{10} \left( \frac{1}{T} \int_{T_0}^{T} \frac{p^2(t)}{p_0^2} \, dt \right),
\]

where \( T \) is the measurement duration, \( p(t) \) is the sound pressure, and \( p_0 \) is a reference pressure (20\( \mu \)Pa for aero-acoustics). The pressure is often A-weighted in which case the quantity is called \( L_{eq,A} \).

A.2 Sound exposure level

The Sound Exposure Level (denoted SEL or \( L_e \)) is the constant sound level that has the same amount of energy in one second as the original noise event. The SEL is a measure of the total energy in a sound. It is defined as

\[
SEL = 10 \log_{10} \left( \frac{1}{T_0} \int_{T_0}^{T} \frac{p^2(t)}{p_0^2} \, dt \right)
\]

where the reference time \( T_0 \) is usually 1 second. When an A-weighting is applied to the pressure the SEL is often denoted by the symbol \( L_{AE} \).

A.3 A-weighted 8-hour equivalent level

Internationally, it is common for health and safety legislation to prescribe limitations on the total sound energy received over a working day (which is assumed to be eight hours long). To this end, the A-weighted 8-hour equivalent level has been introduced. It is defined as

\[
L_{Aeq,8hr} = 10 \log_{10} \left( \frac{1}{T} \int_{T_0}^{T} \frac{p^2_A(t)}{p_0^2} \, dt \right) + 10 \log_{10} \left( \frac{T}{28800} \right)
\]

where the A denotes A-weighting of the pressure waveform.
Note: $L_{Aeq,8hr}$ is a measure of total energy whereas $L_{eq}$ is a measure of intensity. Despite the similarity in notation the meanings are quite different.

In the report by Murphy, Khan and Shaw the $L_{Aeq,8hr}$ statistic for $N$ impulses was defined as [21]

$$L_{Aeq,8hr} = 10 \log_{10} \left( \frac{1}{T} \int_0^T \frac{P^2(t)}{p_0^2} dt \right) + 10 \log_{10} \left( \frac{T}{28800} \right) + 10 \log_{10} N$$

(A.4)

where $T$ is the duration of a single impulse in seconds. This statistic (applied to free-field data and adjusted for hearing protection) was, in the authors opinion, the best predictor of TTS for the Albuquerque impulse noise data (but Price disputes this interpretation).

### A.4 Daily noise exposure level

The daily noise exposure level, denoted either $L_{EX,8h}$ or $L_{EP,d}$, is equal to the SEL in the special case where $T_o = 28800$ seconds (eight hours). It is the same as the 8-hour continuous level defined in the previous section. That is,

$$L_{EP,d} = L_{eq} + 10 \log_{10} \left( \frac{T}{28800} \right) = L_{eq,8hr}.$$  

(A.5)

where $T$ is the duration of the measurement in seconds.

### Appendix B  The equal energy hypothesis

The equal energy hypothesis (EEH) is based on the idea that it is the total amount of energy in a sound pressure waveform that correlates most strongly with hearing damage (measured by permanent threshold shift).

Consider $N$ identical impulsive pressure waveforms $p(t)$ with peak pressure $p_{max}$ and approximate duration $T$. The total energy contained in the $N$ impulses is

$$W = N \int_0^T \frac{P^2(t)}{p_0^2} dt \approx NT \frac{p_{max}^2}{p_0^2}$$

(B.1)

in arbitrary units. Using a logarithmic scale this relation becomes

$$10 \log_{10} W = 10 \log_{10} N + \text{SPL} + 10 \log_{10} T.$$  

(B.2)

When either the number of impulses or the duration of a single impulse increases by a factor of 10 (an increase of 10 dB) the peak SPL must decrease by 10 dB for the total energy to remain constant.
References

1 Precision Conditioning Amplifier Type 2650, Brüel & Kjær.

2 SoundPro DLX meter Preliminary Specifications document, Quest Technologies.


9 Product Data for Hydrophone Types 8103, 8104, 8105, and 8106. Brüel & Kjær.


25 The Control of Noise at Work Regulations, Statutory Instrument No. 1643, Office of Public Sector Information, United Kingdom, 2005.


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<td>14. ABSTRACT</td>
<td>The sound pressure level of the NZ Army's Steyr AUG rifle was measured at a number of angles and distances from the muzzle. Measurements were made on the rifle in its standard configuration without muzzle attachments and then again with a muzzle brake fitted. A muzzle brake improves accuracy by reducing recoil and barrel lift but increases muzzle blast noise. The increase in noise level with a muzzle brake was about 5–10 dB, depending on the measurement angle and range. The noise level estimated at the shooter's ear location when using the muzzle brake was 143 dB(C) which exceeds the recommended limit of 140 dB. However, the blast noise was below the more rigorous limit of 116 dB(A) SEL recommended by the NATO RSG-029 panel on impulse noise hazard.</td>
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