Factors affecting sound exposure from firing an SA80 high-velocity rifle

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Abstract

The effect of distance on the peak sound pressure level and sound exposure level from an SA80 rifle has been investigated. Sound pressure waveforms were measured in two directions from the gun: downrange, from 50 m to 300 m, and to the left-hand side, from 0.3 m to 32 m. Some additional measurements were made to the right of the gun. Measurements made downrange showed three distinct features of the waveform; the shock wave from the supersonic bullet, the reflection from the ground, and the muzzle blast. The time elapsed between the shock wave and the muzzle blast increased with increasing distance: 94 ms for a distance of 50 m, and 507 ms for a distance of 300 m. The highest peak sound level downrange from a single round was between 151 dB(C) and 148 dB(C) at distances from 50 m to 300 m, and varied little if at all with distance. To the left of the gun, the peak sound pressure level of 161 dB(C) at 0.3 m reduced to 128 dB(C) at 32 m. The peak sound pressure level was estimated to be 137 dB(C) at a distance of approximately 20 m to the left-hand side. Hearing protection must therefore be worn by anyone closer than 20 m to a person firing. The peak sound pressure level was estimated to be 135 dB(C) at a distance of approximately 25 m and therefore hearing protection is recommended at distances of up to 25 m. The sound exposure level of 98 dB(A) at 20 m indicated that an observer at this distance could hear about 1440 rounds without hearing protection before the noise exposure reached the upper exposure action value specified in the Control of Noise at Work Regulations 2005. Peak sound pressure levels were on average 2.4 dB higher at the left ear compared with the right ear.

Keywords:
Noise; Rifle; Shock wave; Muzzle blast; Hearing protection; Localization

1. Introduction

The noise produced by high-velocity rifle fire has two main components. These are often referred to as the ‘crack and thump’ or ‘crack and boom’. The ‘crack’ is from the supersonic shock wave which travels with the bullet and the ‘thump’ is from the muzzle blast radiating from the open end of the rifle barrel. The generation of these sounds is discussed by Markula [1] and by Mäkinen and Pertilä [2] among others.

For the person firing, and for those nearby in the firing line, only the thump of the muzzle blast is apparent and the noise presents a hazard to unprotected hearing. For persons being fired at, for those in the line of fire, the ‘crack’ always occurs before the ‘thump’. A perceptible time delay between the two sounds can give an experienced listener a rough indication of the distance of the firer, while the thump may give an indication of the direction. The ‘crack’ can be localised separately, but does not indicate the direction of the firer [3].

Research is currently underway to develop functional hearing tests for military personnel [4, 5], and one aspect of this is the ability to localise small arms fire. As part of that research, binaural recordings were made at various distances from a rifle in the line of fire on an outdoor military firing range. An opportunity therefore arose to make conventional sound pressure level measurements at various distances downrange of the rifle, and also at various distances to the side of the person firing, at positions which could be occupied by other firers training on the range. This paper describes the conventional sound level measurements only.

2. Measurements made and methods used

2.1. Noise source, location, and environment

All noise measurements were made on a Ministry of Defence outdoor firing range at Warminster. The range, shown in Fig. 1, is generally flat with short grass. The rifle used in these tests was an SA80 (L85A2) 5.56 mm calibre “Individual Weapon” [6] as used by the British Armed Forces with standard NATO ammunition (5.56 mm × 45 mm). The rifle was fitted with a front grip incorporating a retractable bipod support. It was fired from a prone position on a slightly raised platform, and aimed using an optical sight which was “zeroed” before each set of tests for maximum accuracy.

Fig. 1. The firing range from the viewing platform.

Sound levels were measured downrange from the rifle and to the side of the firer's head. Fig. 2 shows a plan of the measurement positions, which are described in detail below.

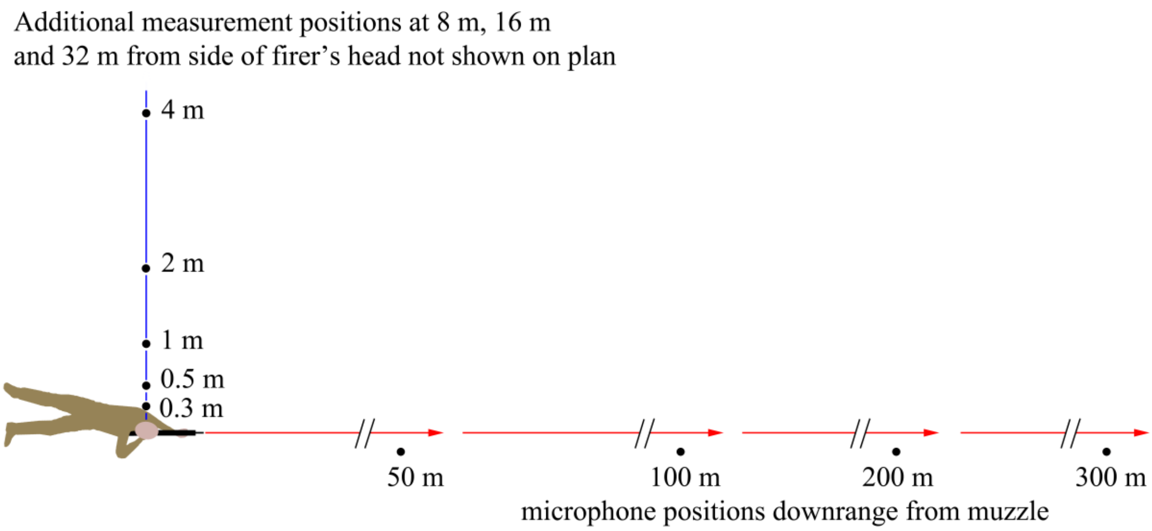

Fig. 2. Plan showing the sound measurement positions

2.2. Measurements downrange

Sound level measurements were made at 50 m, 100 m, 200 m and 300 m downrange from the rifle using a Brüel & Kjær (B&K) 4938 "quarter-inch" pressure microphone. The microphone was mounted on a weighted tripod and connected to a B&K 2250 sound level meter via a microphone extension lead. The microphone was 75 cm to the right of a 'Kemar' manikin (as viewed from the firing position) and level with the manikin's ear, approximately

1.6 m above ground level. Fig. 3 shows the manikin and microphone as seen from the firing position.

Fig. 3. Firer's view of the Kemar manikin with the quarter-inch microphone to the right.
(The more distant microphone was not in use.)

The manikin was used for a separate study, but its presence dictated the location of our measurement microphone. The firer aimed approximately 30 cm above the head of the manikin, and fired one round at a time, not bursts. The axis of the quarter-inch microphone was vertical, i.e. the diaphragm was at grazing incidence to the sound from the muzzle, but slightly off grazing incidence, by about 30°, for the bullet shock wave. The microphone was fitted with a foam windscreen.

The sound level meter was programmed to record the microphone signal as a 'wav' audio file with 24 bit resolution and 48 kHz sampling rate. The meter, being downrange and close to the line of fire, was left to record unattended. Therefore it was not possible to measure levels of individual shots on site, only the single peak level of the complete recording period at each distance; levels of individual shots were obtained from the recordings later. Forty-eight single rounds were recorded and measured at 50 m and 100 m, while twenty-six rounds were recorded at 200 m and 300 m. The recordings at 50 m were made on 13 January 2014, and the remaining recordings were made on 12 March 2014. Temperatures were between 9 °C and 14 °C during the tests. Wind speeds were very low, between 0.5 m/s and 2.0 m/s on both days.

The microphone calibration was checked before and after each day's tests using a B&K 4231 sound level calibrator. The calibration was stable, and the tones were also recorded as 'wav' files at the same settings as the gunshot recordings.

2.3. Analysis of recordings made downrange

The recordings were downloaded to a personal computer. Fig. 4 shows an example waveform of a single rifle shot recorded at 50 m. The initial shock wave from the bullet was followed after approximately 7 ms by a reflection from the ground, and after 94 ms by the muzzle blast.   The same features were visible in all the waveforms at each distance.

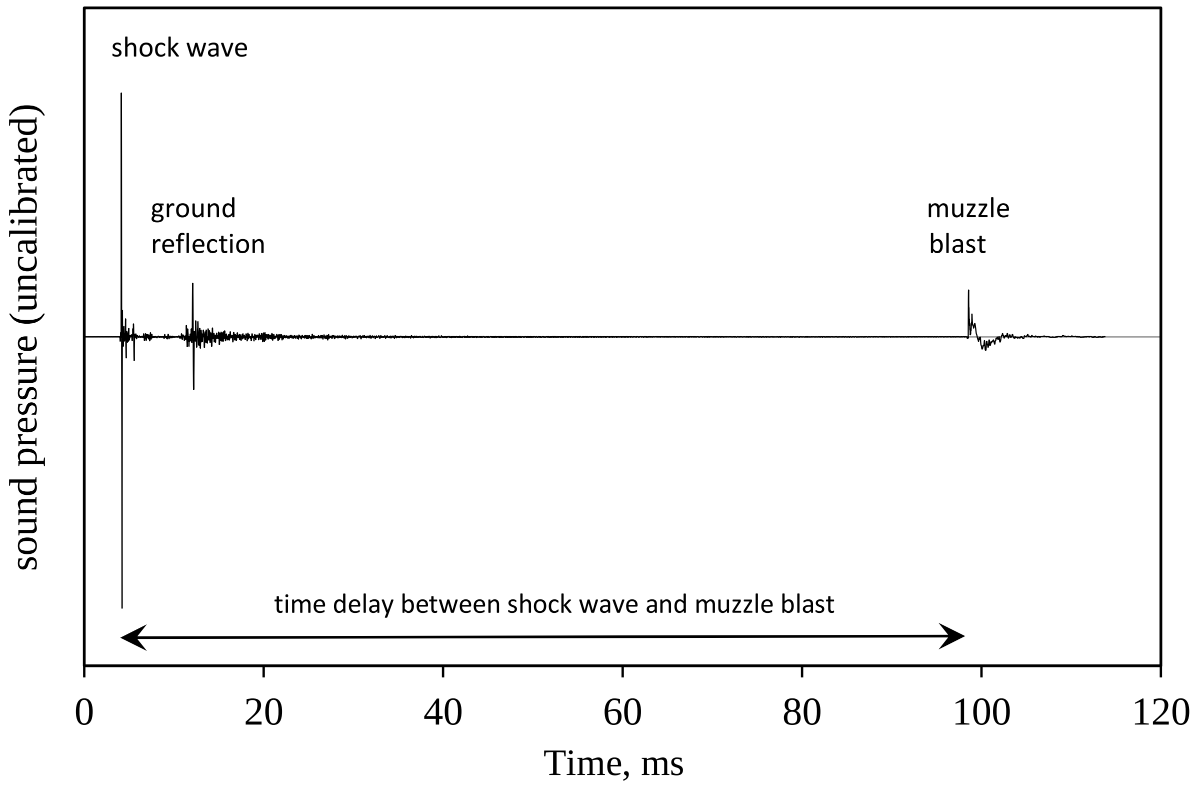

Fig. 4. A typical waveform of a single rifle shot recorded 50 m downrange.

The recordings of individual shots were analysed by replaying them through a Digital Audio Labs CardDeluxe high fidelity sound card into the line input of the B&K 2250 sound level meter to measure the levels. Adobe Audition software was used to replay the selected recordings. The recorded calibration tones provided a reference sound level for the gunshot analyses.

The C-weighted peak sound levels (L_{Cpeak}) and the A-weighted sound exposure levels (L_{AE}) were measured for each individual recorded gunshot, including the bullet shockwave and the muzzle blast. Other parameters including one-third octave band spectra were also recorded. Recordings of the muzzle blast of the individual shots were then selected and the analysis repeated to obtain the peak levels and sound exposure levels of the muzzle blast only, without the shockwave. In addition to the sound levels, the elapsed time between the initial shockwave of the bullet and the sound of the muzzle blast was determined for each shot at each distance to the nearest millisecond.

2.4. Measurements to the side of the person firing and analysis of recordings

Recordings were made to the side of the person firing using G.R.A.S. type 40BH quarter-inch pressure microphones with G.R.A.S. type 26AC microphone preamplifiers, a B&K Nexus 2690 four-channel conditioning amplifier, a Prosig P8004 four-channel data acquisition system and a Dell laptop computer running Prosig DATS software. The microphones were orientated at grazing incidence to the muzzle and fitted with foam windshields. Recordings were made with 24 bit resolution and 100 kHz sampling rate. Microphone positions were at 0.3 m, 0.5 m, 1 m, 2 m, 4 m, 8 m, and 16 m to the left of the firer and level with his ear. The calibration of the recording system was checked before and after sound recordings using a G.R.A.S. type 42AB sound calibrator. The calibration was stable. The recorded data were analysed using the HVLab (v3.81) software package.

An additional measurement position was added at 32 m using a B&K 2250 sound level meter. The recordings were analysed as described in Section 2.3 above.

On a separate occasion at the same location (but with a different firer), noise measurements were made at the shoulders (left and right) of the firer to determine the effect of the measurement position. As these measurements provide additional information they are discussed in Section 3.5 below.

3. Results and discussion

3.1. Sound levels measured at positions downrange

Table 1 shows the C-weighted peak sound levels (L_{Cpeak}) and the sound exposure levels (L_{AE}) measured downrange from the rifle at the various distances. The sound levels are shown separately for (i) the complete sound event which includes the bullet shockwave, its reflection from the ground, and the muzzle blast and (ii) the muzzle blast only.

Table 1. Sound levels measured downrange of the rifle.

Sound selected for analysis	Distance metres	Number of rounds measured	Peak sound level, L_{Cpeak}, dB(C) re 20 µPa				Sound exposure level, L_{AE}, dB(A) re 400 × 10-12 Pa2s			
			Max	Min	Mean	Std. devn.	Max	Min	Mean	Std. devn.
Complete sound	50	48	150.1	148.6	149.4	0.4	110.5	109.5	110.0	0.3
	100	48	150.9	149.5	150.2	0.4	111.0	109.7	110.2	0.3
	200	26	147.5	146.1	146.7	0.4	108.0	106.9	107.4	0.3
	300	26	148.4	145.5	146.9	0.7	108.8	106.7	107.6	0.5
Muzzle blast only	50	48	135.5	126.5	129.9	1.7	96.4	91.0	93.5	1.2
	100	48	123.0	116.0	118.8	1.9	86.1	80.4	82.8	1.6
	200	26	113.1	103.8	107.9	2.3	76.6	67.0	71.0	2.3
	300	26	102.8	97.9	100.4	1.3	64.4	59.8	62.3	1.1

The sound levels are shown to the nearest tenth of a decibel as measured, to allow comparisons to be made without rounding errors, but the instrumentation and calibration will introduce an uncertainty of between ±0.5 dB and ±1.0 dB. The sound level meter used for measurements conforms to IEC 61672 [7], which quotes a maximum-permitted uncertainty of 0.35 dB for C-weighted peak sound level measurements. This uncertainty is much smaller than the spread of the measured results.

Fig. 5 is a scatter plot and shows the peak levels, L_{Cpeak}, of individual rounds for the complete gunshot (denoted as +) and for the muzzle blast only (denoted as ×). The peak level of the whole gunshot sound was dominated by the bullet shockwave which hardly varied with distance, and remained above 140 dB(C) at each distance. The peak levels of the muzzle blast, however, decreased from 50 m to 300 m and the best fit line shown on Fig. 5 has an attenuation rate of approximately 11.3 dB per doubling of distance (R^2 = 0.973) or 37.6 dB per decade of distance. The attenuation with distance of the muzzle blast will, however, vary according to the ground surface and meteorological conditions.

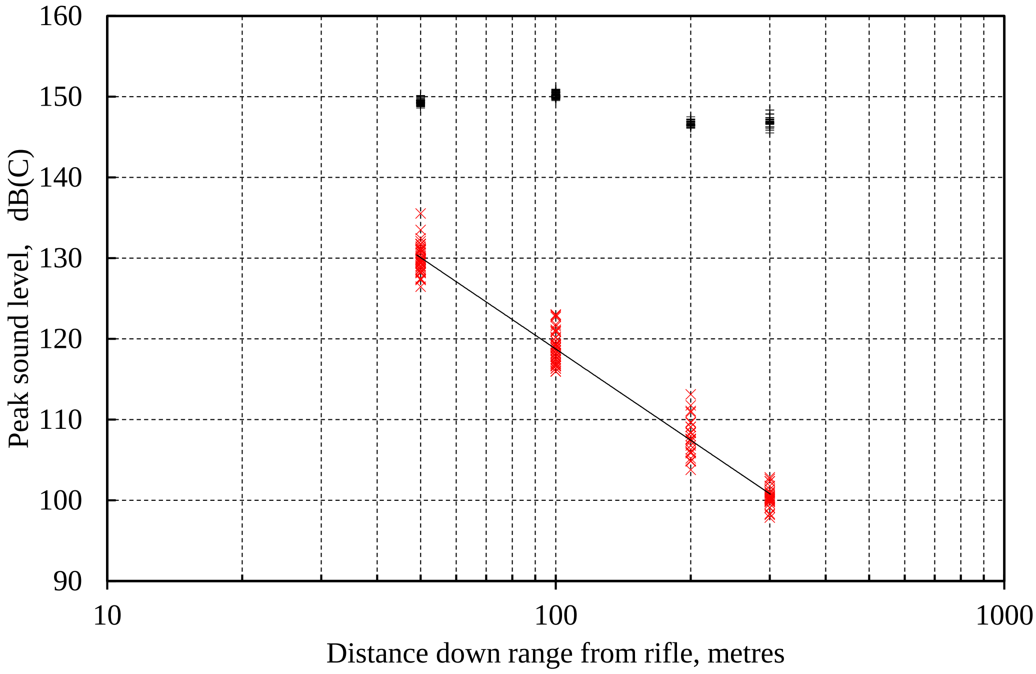

Fig. 5. Peak sound levels of the shockwave and muzzle blast (top group +) and of the muzzle blast only (bottom group ×). Data points are plotted for individual rounds.

A peak sound level, L_{Cpeak}, of 140 dB(C) is the peak 'exposure limit value' specified in the *Control of Noise at Work Regulations 2005* [8], the *Control of Noise at Work Regulations (Northern Ireland) 2006* [9] and in the European Union's *Physical Agents (Noise) Directive* [10]. The policy of the UK Ministry of Defence is to comply with the regulations except in certain specific circumstances where this is not practical, and for which exemptions have been obtained [11]. As the peak exposure limit was exceeded at distances of 300 m and beyond downrange, strictly speaking, hearing protection needs to be worn to protect against noise from incoming fire, even if not returning fire. Earmuff and earplug based hearing protectors or headsets with talk-through systems are available and effective as a practical option.

Fig. 6 is similar to Fig. 5 but shows the sound exposure levels, L_{AE}, for the complete gunshot waveform (denoted as +) and for the muzzle blast only (denoted as ×). The sound exposure level of the whole gunshot sound is dominated by the bullet shockwave which hardly varies with distance. The sound exposure level from the muzzle blast decreased from 50 m to 300 m with an attenuation rate of approximately 11.8 dB per doubling of distance (R^2 = 0.978).

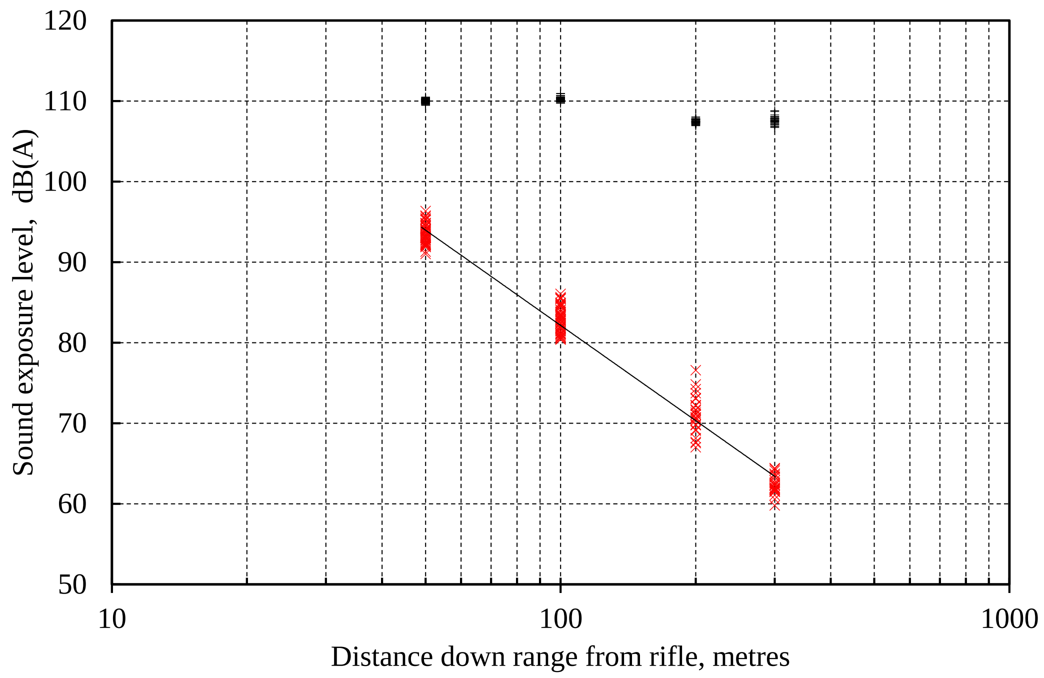

Figure 6. Sound exposure levels of the shockwave and muzzle blast (top group +) and of the muzzle blast only (bottom group ×). Data points are plotted for individual rounds.

The spectrum of the 'crack and thump' measured at 50 m downrange shows two broad and distinct local maxima (see Fig. 7). One is centred on the 250 Hz and 315 Hz bands, and the other is centred on the 6.3 kHz band. The spectrum of the 'thump' alone also shows the maximum centred on 250 Hz, but not the major component around 6.3 kHz. Hence we can deduce that the thump of the muzzle blast is centred on the 250 Hz and 315 Hz bands and the 'crack' of the bullet shockwave is centred on the 6.3 kHz band. This deduction is supported by the spectra of the crack and thump and the spectra of the thump alone at the greater distances. While the crack centred on 6.3 kHz is fairly constant over distances from 50 m to 300 m, the thump centred on 250 Hz or 315 Hz reduces consistently as the distance increases. There is also a tendency with the thump sound for the band with the maximum level to fall from 315 Hz at 50 m to 200 Hz at 300 m, as the lower frequencies are less attenuated than higher frequencies with distance.

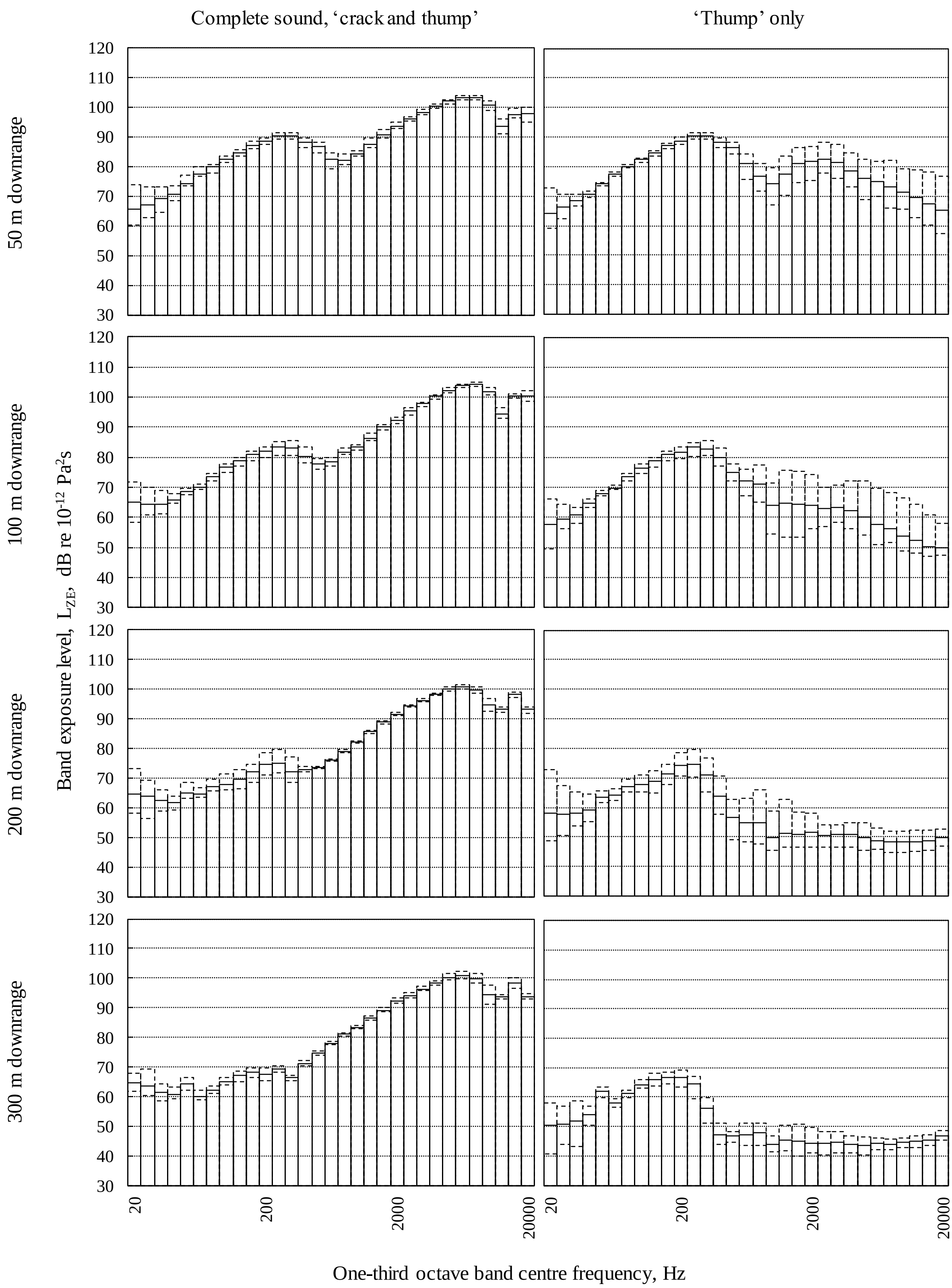

Figure 7. One third-octave band sound exposure levels (mean and range) for the 'crack and thump' and the 'thump' alone of single rounds at distances of 50 m, 100 m, 200 m and 300 m downrange.

Coles and Rice [12] and Powell and Forrest [13] both show peak sound pressure level contours around a rifle. Neither of these contour plots give any indication of the bullet shockwave, but both plots are limited to a radius of 4 m or 5 m around the muzzle. Powell and Forrest show the peak level decaying at roughly 9 dB per doubling of distance downrange from the muzzle with a peak level of 160 dB at 3.5 m. It is therefore likely that the muzzle blast causes a far higher peak level than the shock wave at these close distances, so the shock wave will not be apparent.

It was not possible to measure levels from individual gunshots live on site, but it was possible to obtain the peak level for the complete series of measurements at each distance downrange. The peak level measured live at each distance on site can be compared with the peak level of the individual shot with the highest peak level as obtained from replaying the recording at the same distance. Table 2 shows that there was good agreement, better than ±0.4 dB, between the peaks obtained from playing back the recordings and those obtained live on site. Therefore, this shows the high degree of confidence in the measured data.

Table 2. Comparison of peak sound levels measured (i) live on site and (ii) from the recordings.

Distance downrange metres	L_{Cpeak} measured live on site over a period including N rounds dB(C)	Number of rounds, N	Highest value of L_{Cpeak} for any individual round, measured from the recording dB(C)	Difference (live minus recorded) dB
50	150.1	48	150.1	−0.1
100	151.3	48	150.9	+0.4
200	147.2	26	147.5	−0.3
300	148.4	26	148.4	0.0

3.2. Time delay between shockwave and muzzle blast measured downrange

Table 3 shows the elapsed time between the bullet shockwave and the muzzle blast sounds for individual rounds at the four distances downrange. The elapsed time increases with distance from 94 ms at 50 m range to around 507 ms at 300 m range.

Table 3. Time elapsed from the start of the shock wave to the start of the muzzle blast.

Distance downrange metres	Number of rounds	Time elapsed from shock wave to muzzle blast ms		Time taken for bullet to travel the distance ms	Average speed of bullet over the distance m/s
		Mean	Std. devn.		
50	48	94.1	0.3	53.7	930
100	48	184.5	0.9	111.2	899
200	26	350.1	2.0	241.3	829
300	26	507.1	3.5	379.9	790

It is possible to estimate the speed of the bullet from the elapsed times, and the speeds are also shown in Table 3. The time taken (T_{mb}) for the muzzle blast sound to reach each microphone position was estimated assuming the speed of sound to be 338 m/s at an average temperature of 12 °C. The time taken for the bullet to travel the same distance was then estimated by subtracting the elapsed time from T_{mb}, and the speed of the bullet then calculated by dividing the measurement distance by the time taken for the bullet to reach that point.

This technique gives an estimated average bullet speed of 930 m/s over the first 50 m, but only 790 m/s over the first 300 m as the bullet slows down as it travels. The average time for a bullet to travel the 100 m distance from the 200 m to the 300 m measuring positions was 139 ms giving a mean speed of 720 m/s over this distance. This speed, 720 m/s, is still more than twice the speed of sound. The time taken for the bullet to travel a given distance can be approximated by the equation $t = 0.0007d^2 + 1.054d$ (R^2=0.9999) where t is the time in milliseconds to travel distance d in metres. This equation predicts a muzzle velocity of 948 m/s at zero distance reducing to 678 m/s at 300 m. The estimated muzzle velocity is in good agreement with the declared muzzle velocity of 940 m/s [6].

3.3. Sound levels to the side of the person firing

Table 4 shows the sound levels measured at specified distances to the side of the person firing.

Table 4. Sound levels measured to the side of the rifle.

Distance to side metres	Number of rounds measured	Peak sound level, L_{Cpeak}, dB(C) re 20 µPa				Sound exposure level, L_{AE}, dB(A) re 400 × 10^{-12} Pa^2s			
		Max	Min	Mean	Std. devn.	Max	Min	Mean	Std. devn.
0.3	10	161.6	160.5	161.2	0.3	125.3	124.3	124.7	0.3
0.5	77	160.0	159.0	159.5	0.2	124.5	123.4	123.9	0.3
1	77	158.7	157.6	158.2	0.3	123.7	121.6	122.6	0.4
2	77	156.0	155.0	155.5	0.2	119.8	118.9	119.3	0.2
4	46	153.6	152.3	152.9	0.3	115.3	114.3	114.8	0.2
8	46	144.8	143.1	143.9	0.4	106.3	105.2	105.7	0.2
16	51	137.8	133.9	136.0	1.1	100.5	98.6	99.4	0.5
32	34	131.0	125.4	128.1	1.7	92.4	89.4	90.9	0.8

The peak sound levels, L_{Cpeak}, are plotted in Fig. 8, which also shows three horizontal lines at 140 dB(C), 137 dB(C) and 135 dB(C). These lines show the 'exposure limit value', 'upper exposure action value' and 'lower exposure action value', respectively for peak sound levels as specified in the *Control of Noise at Work Regulations* and the *Physical Agents (Noise) Directive*.

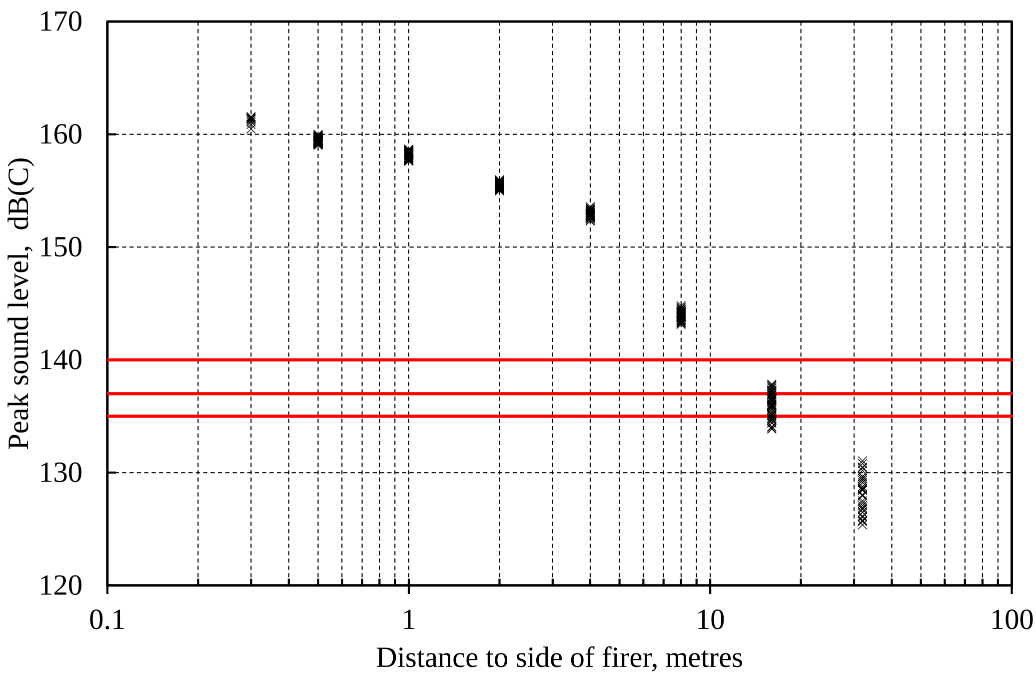

Fig. 8. Peak sound levels to the side of the person firing.

Suitable hearing protection should be provided if peak levels reach 135 dB(C) and suitable hearing protection is mandatory at and above 137 dB(C). Peak levels will exceed 135 dB(C) if the distance to the side of the firer is less than 25 m in round numbers (23 m unrounded by interpolation), and peak levels will exceed 137 dB(C) for distances of less than 20 m in round numbers (18 m unrounded). Hearing protection is routinely used by persons firing or supervising firearms training on the range. But these tests show that hearing protection must also be worn by any observer within 20 m to the side of the nearest weapon firing, and probably within the semicircle of radius 20 m behind and to each side of the nearest rifle. Hearing protection is recommended and should be made available for any observer within 25 m of the nearest rifle.

Fig. 9 shows the sound exposure levels, L_{AE}, to the left of the person firing.

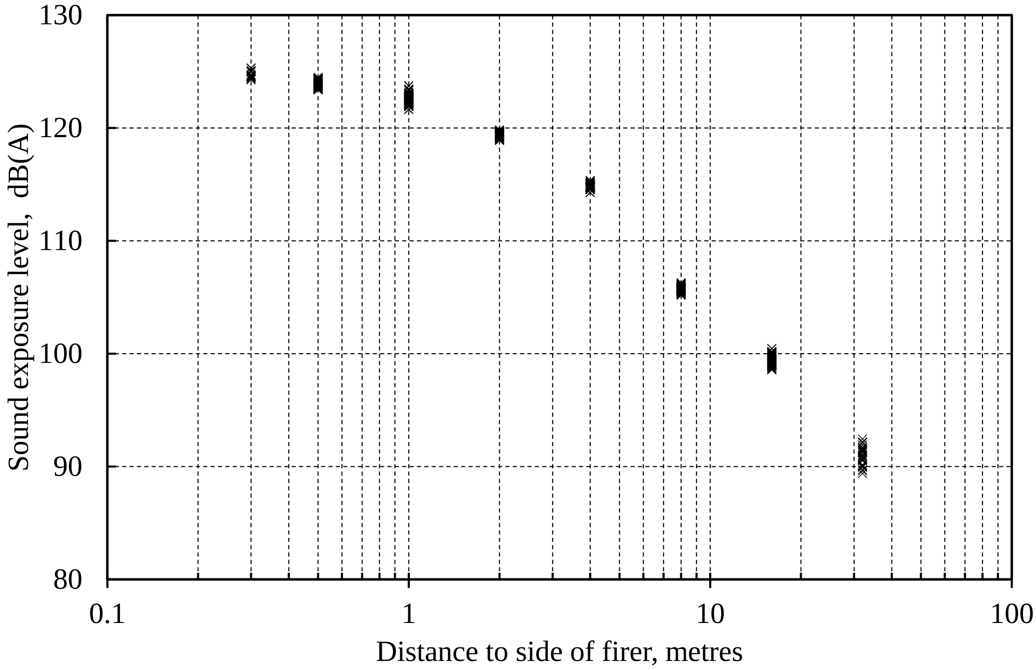

Fig. 9. Sound exposure levels to the side of the person firing.

The *Control of Noise at Work Regulations* and the European *Physical Agents (Noise) Directive* specify action values and limit values for daily personal noise exposures ($L_{EP,d}$ or $L_{EX,8h}$) in addition to those for peak sound levels. Suitable hearing protection should be provided if daily noise exposure is 80 dB(A) or higher. Suitable hearing protection is mandatory at and above noise exposures of 85 dB(A) unless the noise can be reduced at source or by means other than personal protection. A good sound suppressor or sound moderator fitted to the muzzle of a rifle can generally reduce the sound of the muzzle blast by between 18 dB and 28 dB [14–17] for the person firing and others to the side or behind. Noise exposure however is not the only consideration and the weight, handling, reliability, range, accuracy and cost of using a moderator must also be considered. Moderators are therefore not routinely used by the military. The sound levels downrange caused by the bullet shock wave will not be reduced by a moderator [14].

In these tests the average sound exposure level at 25 m to the side or behind the person firing was approximately 95 dB(A). An observer at 25 m could therefore hear up to 910 or 2880 rounds per day without hearing protection before their daily personal noise exposure could reach the lower or upper exposure action value, respectively.

At a distance of 20 m the average sound exposure level was approximately 98 dB(A). An observer at 20 m could hear up to 1440 rounds per day without hearing protection before their daily personal noise exposure reached the upper exposure action value. The lower exposure action value would, however, be exceeded, even if a single round were fired, because the peak sound level would reach 135 dB(C). The requirement for hearing protection is likely to be determined by the peak sound level of individual rounds rather than by the daily personal noise exposure or the number of rounds.

3.4. Variability in sound levels

It is seen that the variation, or the spread of the measured values, appears to be dependent on the measurement location. For example, the peak sound levels in Fig. 8 and the sound exposure levels in Fig. 9 show larger variation for greater distances from the weapon. However, the absolute value of the sound pressures would also need to be taken into account when determining the spread in the data: that is, a large visual variation for high sound values could show similar relative variation to low variation for low sound values. A quantitative measure of the variation, normalised variability Nv, in the measured sound pressure levels can be determined using Eq. (1) (Paddan and Griffin [18]).

$$Nv = 100 \times (\text{interquartile range} / \text{median})\ \% \qquad (1)$$

Table 5 shows the relative variation in the measured peak sound levels and the sound exposure levels. Higher variation (2.1%) occurred in the peak sound level at a distance of 32 m from the weapon compared with a distance of 0.3 m (0.2%). Apart from the 16-m and 32-m distances, both parameters, peak sound levels and the sound exposure levels, show similar variation for the different measurement distances.

Table 5. Variation in sound levels measured to the side of the rifle.

Distance metres	Peak sound level, L_{Cpeak}, dB(C) re 20 μPa				Sound exposure level, L_{AE}, dB(A) re 400 × 10^{-12} Pa^2s			
	25% quartile	75% quartile	Median	*Nv* (%).	25% quartile	75% quartile	Median	*Nv* (%).
0.3	161.1	161.4	161.4	0.2	124.5	124.9	124.6	0.3
0.5	159.3	159.6	159.4	0.2	123.8	124.0	123.9	0.2
1	157.9	158.4	158.2	0.3	122.3	122.8	122.5	0.4
2	155.3	155.6	155.5	0.2	119.2	119.4	119.3	0.2
4	152.6	153.0	152.8	0.2	114.7	115.0	114.8	0.2
8	143.7	144.2	143.9	0.3	105.6	105.8	105.7	0.2
16	135.0	136.7	136.0	1.2	99.1	99.7	99.3	0.6
32	126.7	129.5	128.2	2.1	90.2	91.5	90.9	1.4

3.5. Comparison of sound levels at the left and right ear

Fig. 10 shows peak sound pressure levels measured at the left and right shoulders of the firer (8 individual rounds); also shown are the median data corresponding to these two locations. The median peak sound pressure at the left ear of the firer was approximately 2.4 dB higher than that measured at the right ear. This difference in sound pressure levels is thought to be due to the 'head shadow effect' whereby the left ear is in direct line with the muzzle of the weapon and the right ear is shielded by the head. This finding is in agreement with other published research (Keim [19]; Moon et al. [20]; Razaee et al. [21]; Job et al. [22]). The peak sound pressure levels shown in Fig. 10 are lower than those presented in Fig. 8 since an attachment was fitted to the muzzle of the weapon to reduce the visibility of the flash during firing for the data presented in Fig. 10.

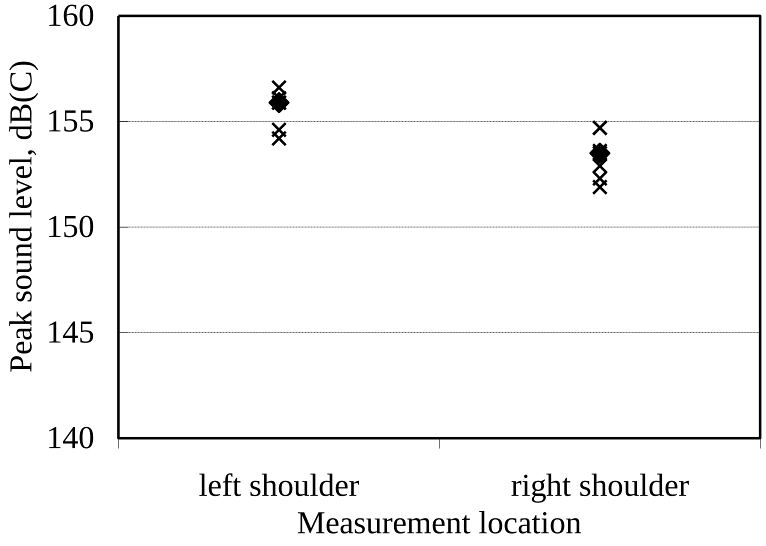

Fig. 10. Peak sound pressure levels at the left and right shoulder (♦ median).

4. Conclusions

Peak sound levels in excess of 145 dB(C) were measured downrange from an SA80 high-velocity rifle, even at 300 m which was the farthest distance in these tests. Such peak sound levels, caused by the shockwave from the bullet, exceed the limit value of 140 dB(C). Therefore, hearing protection should be worn, although the individual may be more interested in sound localisation than protecting their hearing, and would be concerned with greater risks, such as being shot. Hearing protection with talk-through is available and may provide a reasonably practical solution.

Peak levels exceeded 135 dB(C) at 25 m or closer to the side of a person firing, and peak levels exceeded 137 dB(C) at 20 m or less to the side. Hearing protection is therefore recommended for those around the weapon unless they are at least 25 m to the side or behind the closest firer, and hearing protection should be compulsory for anyone closer than 20 m to the nearest firer. At 20 m from the firer, if hearing protection is not worn, the noise exposure of an observer or bystander will reach the upper exposure action value of 85 dB(A) $L_{EP,d}$ after 1440 rounds per day.

Higher peak sound pressure levels were measured at the left ear of the firer compared with the right ear.

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