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Assessment of firearm moderators (short report)

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CONTENTS

EXECUTIVE SUMMARY

OBJECTIVES

Large calibre rifles are used by the Forestry Commission for the culling of deer. These rifles produce high levels of noise in excess of the peak action level given by the Noise at Work Regulations. Hearing protection is used but the response of hearing protectors is difficult to predict when using firearms. There remains a risk with full-bore rifles that exposure while wearing properly selected hearing protection still exceeds 200Pa (140dB). Fitting moderators to these rifles reduces the peak noise level and the overall noise exposure, and it has also been claimed moderators reduce the recoil.

To assess the benefits of moderators measurements were made during the firing of nine different full-bore rifles and one .22 calibre rifle. Moderator models A, B and C were tested with full-bore rifles, model D on the .22 rifle. Only a limited range of moderators was selected for testing, as the intention was not to validate all the devices available but to find whether any were effective with the chosen rifle types.

MAIN FINDINGS

Without a moderator full-bore rifles gave peak sound pressures levels over 150dB(C). Only the smaller .22 rimfire gave peak levels below 140dB(C). The peak level under hearing protection could exceed the Noise at Work Regulation's 200Pa (140dB) Peak Action level as the effectiveness of hearing protection worn during firing was reduced by the recoil and muff movement.

Moderator A consistently reduced the peak noise level below 137dB(C). With this moderator full-bore firearms could be fired without hearing protection. A similar reduction was obtained in the vicinity of the person firing proving additional protection would be given to a dog, or an observer without hearing protection.

Moderators B and C were significantly less effective than moderator A confirming a wide variation between different designs.

With supersonic ammunition moderators gave little reduction in the noise at a distance in front of the firing point as noise from the bullet flight dominates. A reduction is only possible when subsonic ammunition is used but this is not recommended as a practicable noise control measure.

The recoil of the full-bore rifles was reduced by 20 to 30% with moderators A, B and C.

RECOMMENDATIONS

The highest peak level with moderator A fitted is just at the new Physical Agents (Noise) Directive action level of 137dB(C). Although not essential some lightweight hearing protection should be used in combination with this moderator when firing full-bore rifles, until the effect of age and use on the efficiency of the moderator is known.

1 INTRODUCTION

Large calibre rifles are used by the Forestry Commission for the culling of deer. These rifles produce high levels of noise, with peak levels in excess of 150dB. The peak action level given by the Noise at Work Regulations is 200Pa, equivalent to 140dB. This will also be the upper peak pressure limit in the Physical Agents (Noise) Directive (PA(N)D) (due to be adopted in February 2006), while hearing protection will be required at peak levels above 137dB(C). Under the current Regulations there is a duty to reduce the noise exposure of employees as far as is reasonably practicable by means other than the use of hearing protection.

The response of hearing protectors when using firearms is difficult to predict. There remains a significant risk that even with the use of hearing protection peak sound pressures are in excess of 200Pa at the ear. Moderators reduce the noise level, and it is claimed they also reduce recoil.

At the request of the Forestry Commission and the Health and Safety Executive (HSE), the Health and Safety Laboratory made measurements during the firing of full-bore rifles to assess the benefits of selected moderators. Three models of moderator were tested on full-bore rifles, identified as A, B, and C, and a measurement was made on a .22 rimfire with a fourth moderator, model D. Descriptions of each moderator are given in Appendix A.

Only a limited range of moderators were selected for testing, as the intention was not to validate all the devices available but to ensure a suitable moderator effective with the range of rifles was found. Measurements were made of the noise at the ear, both under and outside the muffs, the noise heard by a dog to the side of the man firing, and the noise heard by the quarry. The relative recoil with and without the moderator was measured with accelerometers fitted to the stock during firing.

2 MEASUREMENT METHOD

2.1 ON SITE RECORDINGS

Firing took place from a raised area, located part way up the side of a sheltered wooded valley that formed the firearms testing area. The raised area consisted of a mound of loose earth with a rough concreted area at the top. Carpet was placed over the concrete during the measurements to give some cushioning to the men firing. The weather was cool, with little wind. Eight professional forestry rangers provided and fired the rifles, five shots with the moderator fitted and five without. They each fired from the right shoulder, in a prone position and wore the earmuffs they normally wear when using rifles. These earmuffs were of a variety of types and ages.

2.1.1 Noise recordings

The noise outside the muffs was recorded with microphones held by the side of the head as shown in Figure 1. The noise under their muffs was recorded with miniature microphones fixed at the ear canal entrance as shown in Figure 2. Noise recordings were also made with tripod mounted microphones 2m to the side of the firing position and at a position 23m in front to assess the noise exposure of a dog and the noise heard by the quarry.

Figure 1 Measurements either side of the ranger's head

Figure 2 Miniature microphone on the ear for measurements under the muffs

The microphones and accessories used are listed below.

By the side of the ranger's head and 2m to the side at the position of a dog:

- Brüel & Kjær 4136 ¼ inch microphones with gooseneck extensions and windshields,
- Brüel & Kjær 2619 preamplifiers
- Brüel & Kjær 2804 microphone power supplies.

Under the ranger's muffs:

- Knowles CA 2832 miniature microphones powered from Brüel & Kjær 2804 microphone power supplies

23m in front of the firing position:

- Brüel & Kjær 4134 ½ inch microphone with gooseneck extension and windshield,
- Brüel & Kjær 2619 preamplifier
- Brüel & Kjær 2804 microphone power supply.

The outputs from the microphone power supplies were taken to two TEAC RD135T DAT recorders. These were set to 4-channel operation and double tape speed to allow recording up to 20kHz. A calibration was recorded for each microphone at the beginning and end of each day with a Brüel & Kjær 4226 sound calibrator set to provide a 1kHz, 114dB calibration tone.

2.1.2 Recoil recordings

Figure 3 Accelerometers fitted on stock

The acceleration associated with the recoil was recorded using two accelerometers fixed firmly to the end of the stock. The primary measurement was in the direction of fire; a second measurement was also made in a perpendicular direction. On the first day this was horizontally across the main axis of the rifle to record the sideways movement; on the second day the vertical direction was chosen.

The force of the recoil is dependent on both the acceleration and the mass of the rifle. The weight of each rifle was noted with and without the moderator fitted.

The recoil instrumentation is listed below:

- Brüel & Kjær 4393 accelerometers
- Brüel & Kjær 2635 charge amplifiers

The acceleration was recorded on the DAT recorders simultaneously with the noise. In addition a calibration for each accelerometer was recorded at the start and end of each day with a Brüel & Kjær 4294 vibration calibrator giving a 160Hz signal, with an r.m.s. acceleration of $10ms^{-2}$.

3 ANALYSIS OF THE RECORDINGS

Noise measurements were analysed by replaying the recordings through a Brüel & Kjær 2260 sound analyser.

3.1 PEAK SOUND PRESSURE

High peak sound pressures are hazardous to the ear. The Noise at Work Regulations aim to reduce the peak sound pressure at the ear to no more than 140dB. The Physical Agents (Noise) Directive sets a limit at this level and also requires hearing protection to be worn at peak levels above 137dB(C). The use of the C-weighting excludes frequencies outside the audible range.

The maximum C-weighted peak level in each series of five shots is reported here.

Above 126dB the miniature microphones under the muffs only measure positive sound pressures. Above 126dB the under muff results may be underestimated by up to 1dB because of this limitation. Below 126dB the microphones measure the full positive and negative pressure variations in the sound.

3.2 SOUND EXPOSURE LEVEL (SEL)

There is also a requirement to control the daily noise exposure arising from the number of shots fired in a day. The Noise at Work Regulations sets a first daily noise exposure ($L_{EP,d}$) action level of 85dB(A), and a second action level at 90dB(A). The Physical Agents Directive has action levels at an $L_{EP,d}$ of 80 and 85dB(A) and a limit at 87dB(A). Measurements are A-weighted to simulate the susceptibility of the ear to the frequency of the sound.

The sound exposure level (SEL) is the equivalent steady level over one second. It gives a measure of the total noise in a shot. The mean SEL of one shot in each five shot series is reported here. The $L_{EP,d}$ is calculated from the SEL using the following procedure.

$$L_{EP,d} = SEL + 10(\log N) - 44.6 \quad dB(A)$$

where N is the number of shots fired in a day.

SEL measurements were not possible under the muffs if the peak level exceeded 126dB due to the absence of the full negative pressure variations.

3.3 MEASUREMENTS FOR ESTIMATION OF HEARING PROTECTOR ATTENUATION

Hearing protector attenuation is frequency dependent. The difference in the C and A-weighted maximum sound pressure level measured with a Fast time constant ($L_{C,\ fast\ max} - L_{A,\ fast\ max}$) is used to estimate the frequency content of gunfire. According to EN 458:1993 the protector M-value is the predicted attenuation if the $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ value is less than 5dB. A revision of EN 458 due for publication in 2004 gives the M value minus 5dB as the predicted attenuation during gunfire.

A and C-weighted r.m.s. maximum levels recorded outside the muffs of the ranger firing were measured and the mean $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ result of each five shot sequence is reported.

3.4 RECOIL RECORDINGS

There is no recognised standard test for assessing the effect of recoil, so measurements have been based on the frequency range between 0.4Hz and 100Hz which is the range defined by ISO 2631-1:1993 for assessing exposure of the whole body to vibration or shock. The acceleration due to the recoil was measured by replaying the recorded signal from the accelerometers on the stock through a Larson Davis HVM 100 vibration meter. The measurements were band limited to the required frequency range but no additional frequency weighting was applied.

Both the maximum peak and maximum r.m.s. acceleration, obtained with a 1 second exponential time constant, were measured. The peak gives the highest instantaneous acceleration, the r.m.s. exponential time average maximum is dependent on both the level and duration.

4 RESULTS

Numbers and letters together with a brief description in the tables identify the moderators, firearms, and hearing protectors in these results. The names have been removed to avoid promotion of any particular device.

4.1 BY HEAD OF THE RANGER FIRING

Table 1 gives the sound levels measured by the side of the head and outside the muffs of the ranger firing.

4.1.1 Peak sound pressure levels

The measured peak level on the right was higher than on the left. Without a moderator all full-bore rifles gave peak levels in excess of 150dB on the right side of the head. The smaller .22 rimfire gave a peak level of 131dB without a moderator.

Moderator A reduced the peak level of full-bore rifles to below 137dB(C), giving a reduction in peak level of between 18 and 27dB. Moderators B and C gave no more than an 8dB reduction in peak level.

4.1.2 Sound exposure level (SEL)

Without a moderator the full-bore rifles gave an SEL between 118 and 124.5dB by the right ear. With Moderator A the SEL was 100.5 to 105.5dB(A). An SEL of 105.5dB(A) corresponds to a daily exposure ($L_{EP,d}$) of 85dB(A) after 257 shots and an $L_{EP,d}$ of 80dB(A) after 81 shots.

Without a moderator the .22 rimfire rifle gave a sound exposure level (SEL) of 91dB(A) at the right ear. 7,000 shots would have to be fired in a day to reach a daily exposure ($L_{EP,d}$) of 85dB(A) at the unprotected ear.

4.1.3 $L_{C,\ fast\ max} - L_{A,\ fast\ max}$

High $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values indicate low frequencies dominate the sound, low values indicate high frequencies dominate the sound. More high frequencies were heard in the shot when the moderator was fitted and low $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values reported for the measurements at a distance confirm this. By the head of the ranger there is a large spread in the $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values which suggest that when the moderator is used sounds from recoil and movement are adding to the measured sound as they are no longer masked by the shot.

4.2 UNDER THE MUFFS OF THE RANGER FIRING

Table 2 gives the results under the muffs of the person firing. Without the use of a moderator peak levels under the muffs sometimes exceed 140dB(C). Peak levels are consistently below 140dB(C) when any of the moderators are used. Table 3 gives the mean and range of the muff attenuation measured for each shot together with the muff M-value.

When a moderator is used the recorded attenuation of the muffs worn by the man firing has reduced. In the case of rifle number 7 the peak level under the muffs has even exceeded the peak level measured outside (shown by negative attenuation values in Table 3). Viewing of the waveform recorded under the muff cups shows frequencies below 50Hz are often dominating when the moderator is used. These low frequencies are due to movement of the muffs with the

recoil, rather than the direct sound of the shot. This movement is also present when no moderator is fitted, but in this case the sound of the gunshot dominates. Analysis of the waveform under the muffs during the firing of rifle number 7 has also picked out a possible low frequency impact on the muffs, immediately following one shot.

4.3 AT A DISTANCE FROM THE RANGER FIRING

Table 4 gives the results for the recordings made 2m to the side and 23m forward of the person firing. Without a moderator peak levels 2m to the side are between 152 to 157dB(C). With moderator A these fell below 134dB(C), with reductions in the peak level of 26 to 29.5dB. Moderator A reduced the A-weighted SEL by between 18 and 22dB.

Moderators B and C were less effective. They reduced the peak sound pressure by 12 and 10dB respectively 2m to the side and gave a reduction of around 10dB in the A-weighted SEL.

The moderators both at 2m and 23m distance reduced the $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values. This confirms the moderators are removing the low frequencies from the sound.

23m in front of the firing point there was little or no reduction in the peak sound level from the full-bore rifles when a moderator was used and no more than a 5dB reduction in the A-weighted SEL.

Moderator D gave a 24dB reduction in the peak level 2m from the ranger firing when used with the .22 rimfire rifle, and a 13dB reduction 23m in front of the firing point.

4.4 RECOIL

Table 5 gives the recoil results in the direction of fire. These include the weight of the firearm, the mean acceleration for the five shots, and a force reduction ratio consisting of the weight times the acceleration with the moderator to the weight times acceleration without. The results show that the recoil is reduced by 20 to 30% when the moderator is used. It should be noted that the actual force could not be calculated because the mass acting with the acceleration is only proportional to the recorded weight.

Table 6 gives the mean acceleration measured in the directions perpendicular to the direction of fire. The force associated with the acceleration in these directions is thought to be proportional to a much lower mass than in the direction of fire, so the measured acceleration is of less significance to the actual recoil force.

5 DISCUSSION

5.1 CAN HEARING PROTECTION ALONE PROVIDE ADEQUATE PROTECTION?

When no moderator is used muffs have sometimes proved inadequate against the peak levels from full-bore rifles. Peak sound pressures at the ear have exceeded 140dB(C). Most muffs gave considerably less protection than the M-value estimate, especially when the moderator was used. This suggests the attenuation is limited by noise produced under the muffs, due to movement of the muffs and impacts on the cups as the firearm recoils.

5.2 IS HEARING PROTECTION REQUIRED WHEN A MODERATOR IS USED?

Hearing protection was required when any of the full-bore rifles were fired without a moderator. Only the .22 rimfire rifle was quiet enough to be used without hearing protection.

With moderator A full-bore rifles could be fired without hearing protection. Moderator A reduced the peak sound pressure levels to below 137dB(C), while hearing protection is required by the Noise at Work Regulations when the peak level exceeds 140dB. Also with moderator A the worse case daily noise exposure ($L_{EP,d}$) would only exceed 85dB(A) if more than 250 shots were fired in one day.

When the Physical Agents (Noise) Directive replaces the Noise at Work Regulations hearing protection will be required when the peak level at the ear exceeds 137dB(C). This value is close to the highest peak level measured with moderator A. There may therefore be a benefit in maintaining the use of some lightweight hearing protection in combination with firearm moderators. Also no measurements have yet been made to determine whether the moderator efficiency reduces with age, so some precautions are advisable.

Someone in the vicinity of the person firing would not need hearing protection under the current Noise at Work Regulations or the Physical Agents (Noise) Directive if moderator A were used as the peak noise level 2m to the side was reduced below 134dB(C).

Moderators B and C did not give sufficient reduction in the peak sound pressure to allow full-bore rifles to be used without hearing protection.

5.3 NOISE EXPOSURE OF A DOG

Peak levels 2m to the side of the ranger firing are between 151 and 157dB for full-bore rifles without a moderator. With moderator A the peak levels were below 134dB(C) and the SEL was reduced by 18 to 22dB. Assuming the frequency weighting for human hearing may be applied to dogs the results show this moderator would considerably reduce the noise exposure of a nearby dog.

The peak level remained above 140dB when moderators B and C were used and the SEL was reduced by just 10dB. These moderators would provide less protection for a dog.

5.4 DISTURBANCE OF THE QUARRY

Moderators on full-bore rifles gave no reduction in the peak sound level 23m in front of the firing point and only a reduction between 2.5 and 5dB(A) in the SEL. At this distance the flight

noise of the supersonic ammunition dominates over the gunfire both with and without a moderator.

It is difficult to predict whether the quarry will be less disturbed when a moderator is used as the sound heard is not significantly quieter. The sound from the bullet flight, without the sound of the gunfire may be more difficult to locate. With the moderator the sound contains less low frequencies and this may also alter how the quarry reacts to the sound.

There is a reduction in the gunfire noise at a distance in front of the rifle when subsonic ammunition is used. When moderator D was used with the .22 rimfire, there was a 13dB reduction in the peak and a 16dB in the SEL 23m in front of the firing point. This will be heard as a quieter sound by the quarry.

5.5 MODERATOR EFFECTS ON RECOIL

The peak level of the recoil reduces by 20% when both the moderators A and B are used, and the r.m.s. maximum reduces by 30%. Moderator C gave a 30% reduction in both the peak and rms maximum recoil force.

The acceleration in perpendicular directions has not been added to the recoil assessment because it is assumed this is rotational and associated with significantly less mass than the acceleration in the line of fire.

6 CONCLUSIONS

- Without the use of a moderator hearing protectors are required when firing full-bore rifles. Of the rifles tested only a .22 rimfire could be fired without hearing protectors. Hearing protectors which were predicted to provide adequate protection according to standardised methods, did not always reduce the peak exposure below 200Pa (140dB). Muff movement during firing frequently caused low frequency sound under the muffs and in addition at least one impact on the muff cups was recorded during recoil.

- With moderator A the peak level from full-bore rifles reached a maximum of 136.5dB(C) by the head of the ranger firing. The overall noise level was such that over 250 shots could be fired before the $L_{EP,d}$ exceeded 85dB(A). Under the Noise at Work Regulations hearing protection should to be provided, when the number of shots fired in a day exceeds 250.

- Hearing protection will be required at peak levels of 137dB(C) with the enactment of the Physical Agents Directive. Also whether moderator efficiency changes with age and use is unknown. The use of some lightweight hearing protection in conjunction with moderator A is therefore recommended.

- Moderators B and C did not provide sufficient reduction of the noise when fitted to full-bore rifles to permit use without hearing protection. The performance of different models of moderator is clearly variable. To comply with the Noise at Work Regulations there is a duty to reduce as far as is reasonably practicable the noise exposure of an employee; the more efficient moderators should therefore be preferred.

- Moderator A reduced the peak level by 26 to 29.5dB at the side of the man firing, and the sound exposure level (SEL) by 18 to 22dB. This moderator gives significant protection for a dog or another person in the vicinity. The reduction in level is sufficient to remove the need for a person nearby to wear hearing protection.

- Moderators gave no reduction in noise that arises from the bullet flight when it travels over the speed of sound. There is therefore little reduction in the peak level forward of the firing point.

- With subsonic ammunition moderator D reduced the peak and SEL of the noise forward of the firing point by 13 and 16dB respectively.

- Moderators A, B and C all gave a 20 to 30% reduction in the recoil of full-bore rifles.

7 REFERENCES

The Noise at Work Regulations 1989 Statutory Instrument 1989 No 1790 – Health and Safety

Health and Safety Executive Reducing noise at work – Guidance on the Noise at Work Regulations 1989

Directive 2003/10/EC of the European Parliament and of the Council 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise).

International Organisation for Standardisation ISO 2631-1:1985 Evaluation of human exposure to whole-body vibration

Pääkkönen and Kyttälä (1999) Report of Finnish Sound Suppressor Trials
www.guns.connect.fi/rs/trial1999.html

TABLES

Table 1 Sound levels measured by the side of the head during firing

Rifle no., calibre, ammunition and moderator	Maximum peak dB(C)		Mean SEL dB(A)		$L_{C,\ fast\ max} - L_{A,\ fast\ max}$ dB	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
Rifle # 1, .243, 100 grain						
Without moderator	149.5	155	114	120	3	1
With moderator A	128.5	131.5	99	100.5	-0.5	-1
Rifle # 2, .25-06, 90 grain						
Without moderator	153.5	155	118	121	3.5	2.5
With moderator A	135.5	136.5	102	105.5	9	-1
Rifle # 3, 6.5 x 55, 156 grain						
Without moderator	151	See	115.5	See	2.5	See note
With moderator A	130	note 1	99	note 1	7.5	1
Rifle # 4, .270, 130 grain						
Without moderator	150	153.5	115	119.5	1.5	4
With moderator A	130.5	131	99.5	101	1	1
Rifle # 5, .270, 150 grain						
Without moderator	153	154.5	119	121.5	3	1
With moderator A	135.5	135	101	103	0	-1
Rifle # 6, .308, 123 grain						
Without moderator	150	153	114	118.5	0.5	1.5
With moderator A	129.5	133	97	100.5	3	0.5
Rifle # 7, .308, 123 grain						
Without moderator	See	158	See	122	See note	1.5
With moderator A	note 2	130.5	note 2	100.5	2	2
Rifle # 8, .22 rimfire, 117 grain low velocity						
Without moderator	See	130.5	See	91	See note	11.5
With moderator D	note 2	127.5	note 2	84.5	2	21.5
Rifle # 9, .25-06, 117 grain						
Without moderator	156	159	122.5	124.5	2	2
With moderator B	151	153	116.5	118.5	1	0.5
Rifle # 10, .270, 130 grain T-mantle						
Without moderator	148	152.5	113.5	118	4	5.5
With moderator C	140	149	103	106	4.5	11

Note 1 Recorded levels were thought to be too low to be correct when compared with measurements in other positions.

Note 2 The microphone showed a drop in sensitivity of 9.6dB when recalibrated at the end of the second day's measurements. The results for these last two rifles tested before calibration have not been reported as the measured level appears effected by the changing sensitivity.

Table 2 Sound levels measured under muffs during firing

Muff, volume, and type	Rifle no., calibre, ammunition and moderator	Maximum peak sound pressure dB(C)		Mean SEL dB(A)	
		Left	Right	Left	Right
Muff N, small volume, passive	**Rifle # 1, .243, 100 grain**				
	Without moderator	142	146		
	With moderator A	121	122.5	82	82.5
Muff T, small volume, sound restoration	**Rifle # 2, .25-06, 90 grain**				
	Without moderator	See note	141	See	
	With moderator A	2	122.4	note 2	84.5
Muff O, small volume, sound restoration	**Rifle # 3, 6.5 x 55, 156 grain**				
	Without moderator	138.5	142.5		
	With moderator A	119.5	124	87.5	87.5
Muff P, large volume, passive	**Rifle # 4, .270, 130 grain**				
	Without moderator	137.5	136.5		
	With moderator A	113	126	72.5	75
Muff N, small volume, passive	**Rifle # 5, .270, 150 grain**				
	Without moderator	143	139		
	With moderator A	125.5	122	90.5	91.5
Muff P, large volume, passive	**Rifle # 6, .308, 123 grain**				
	Without moderator	134	131.5		
	With moderator A	118.5	119.5	71	71.5
Muff Q, large volume passive	**Rifle # 7, .308, 123 grain**				
	Without moderator	139	142		
	With moderator A	123.5	134	-	-
Muff T, small volume, sound restoration in passive mode	**Rifle # 8, .22 rimfire, 117 grain low velocity**				
	Without moderator	110	117.5	73.5	81.5
	With moderator D	102.5	113.5	66	81.5
Muff S, large volume, passive	**Rifle # 9, .25-06, 117 grain**				
	Without moderator	137	140.5		
	With moderator B	129	131.5	-	-
Muff R, large volume, passive	**Rifle # 10, .270, 130 grain T-mantle**				
	Without moderator	135	138		
	With moderator C	127	132.5	-	-

Note 1 Rms values are not quoted where clipping of the microphone signal occurred.

Note 2 The measured peak levels exceeded 140dB when the moderator was fitted. These peak levels are higher than those measured outside the muffs. It is probable the microphone in the left ear was displaced throughout the measurements with the firearm 2.

Table 3 Muff peak attenuation

The mean peak attenuation is shown with the range in parenthesis.

Rifle no., calibre, ammunition and moderator	Peak attenuation dB		Muff M value dB	Muff, volume, and type
	Left	Right		
Rifle # 1, .243, 100 grain			Not available	**Muff N, small volume, passive**
Without moderator	7.5 (6, 9)	8.5 (7, 9)		
With moderator A	8 (5, 12)	10 (9, 10)		
Rifle # 2, .25-06, 90 grain			28	**Muff T, small volume, sound restoration**
Without moderator	-	14 (12.5, 16)		
With moderator A	-	13.5 (12, 15)		
Rifle # 3, 6.5 x 55, 156 grain			22	**Muff O, small volume, sound restoration**
Without moderator	12.5 (11, 14)	-		
With moderator A	9.5 (8, 11.5)	-		
Rifle # 4, .270, 130 grain			28	**Muff P, large volume, passive**
Without moderator	12.5 (11, 14)	16.5 (15, 17)		
With moderator A	9.5 (8, 11.5)	9.5 (4.5, 16)		
Rifle # 5, .270, 150 grain			Not available	**Muff N, small volume, passive**
Without moderator	10 (9.5, 11.5)	16 (15.5, 16.5)		
With moderator A	9 (6.5, 11)	14 (9, 17)		
Rifle # 6, .308, 123 grain			28	**Muff P, large volume, passive**
Without moderator	15.5 (14.5, 16.5)	21 (21, 22)		
With moderator A	11.5 (9.5, 15)	16.5 (14, 21)		
Rifle # 7, .308, 123 grain			28	**Muff Q, large volume passive**
Without moderator	-	16 (15, 18)		
With moderator A	-	-4 (-7, -2.5)		
Rifle # 8, .22 rimfire, 117 grain low velocity			28	**Muff T, small volume, sound restoration in passive mode**
Without moderator	-	13		
With moderator D	-	14		
Rifle # 9, .25-06, 117 grain			27	**Muff S, large volume, passive**
Without moderator				
With moderator B	19 (18.5, 20)	18.5 (17, 20)		
	22.5 (21, 23.5)	21 (20.5, 21)		
Rifle # 10, .270, 130 grain T-mantle			31	**Muff R, large volume, passive**
Without moderator	13 (12.5, 14)	15 (14.5, 15.5)		
With moderator C	13 (6, 17)	11.5 (6, 18.5)		

Table 4 Sound levels 2m to side and 23m in front of ranger firing

Rifle no., calibre, ammunition and moderator	2m to side			23m in front		
	Max peak dB(C)	SEL dB(A)	$L_{C, fast\ max} - L_{A, fast\ max}$ dB	Max peak dB(C)	SEL dB(A)	$L_{C, fast\ max} - L_{A, fast\ max}$ dB
Rifle # 1, .243, 100 grain						
Without moderator	154.5	117	1	142.5	108.5	2
With moderator A	125.5	95	-1	142.5	103.5	-1.5
Rifle # 2, .25-06, 90 grain						
Without moderator	157	119.5	2	145	110	3.5
With moderator A	133.5	101	-0.5	143.5	105	-1.5
Rifle # 3 6.5 x 55, 156 grain						
Without moderator	154.5	116.5	1	143.5	108.5	2.5
With moderator A	128.5	97.5	-1	143	105	-1.5
Rifle # 4, .270, 130 grain						
Without moderator	153.5	116	1.5	145	110	4.5
With moderator A	129	98.5	-1	145	105.5	-1
Rifle # 5, .270, 150 grain						
Without moderator	153.5	116.5	1.5	See note 1	See note 1	See note 1
With moderator A	129.5	97.5	-1.5			
Rifle # 6, .308, 123 grain						
Without moderator	151.5	114	1.5	147	110	3
With moderator A	126	94.5	-1	147	107	-0.5
Rifle # 7, .308, 123 grain						
Without moderator	153	116.5	1	146.5	109.5	3
With moderator A	124.5	95.5	-1.5	146.5	107	-0.5
Rifle # 8, .22 rimfire, 117 grain low velocity						
Without moderator	133	91.5	-1.5	131.5	96	-1.5
With moderator D	109	Too low	Too low	118.5	79.5	-1
Rifle # 9, .25-06, 117 grain						
Without moderator	153.5	116	1.5	See note 1	See note 1	See note 1
With moderator B	141.5	106.5	0			
Rifle # 10, .270, 130 grain T-mantle						
Without moderator	152.5	116	1	145.5	110	4
With moderator C	143	106	-1	145.5	106	-0.5

Note 1: The signal from the microphone 23m in front was lost on the first day during firing of the last two rifles, numbers 9 and 5.

Note 2 The rms sound pressure levels 2m from the firing point are not recorded for the Bruno fitted with the moderator as the noise from movement and rapid reloading masked the sound of the shot.

Table 5 Weight, acceleration, and relative recoil reduction with the moderator

Rifle no., calibre, ammunition and moderator	Weight kg	Peak ms^{-2}	Relative recoil	r.m.s. max ms^{-2} (1s time constant)	Relative recoil
Rifle # 1, .243, 100 grain					
Without moderator	4	590	0.8	33	0.7
With moderator A	4.7	390		20	
Rifle # 2, .25-06, 90 grain					
Without moderator	4	680	0.7	38	0.6
With moderator A	4.5	420		21	
Rifle # 3 6.5 x 55, 156 grain					
Without moderator	5.5	580	0.9	32	0.8
With moderator A	6	470		22	
Rifle # 4, .270, 130 grain					
Without moderator	4.5	overload		overload	
With moderator A	5	560		33	
Rifle # 5, .270, 150 grain					
Without moderator	4.5	760	0.8	45	0.7
With moderator A	5	550		28	
Rifle # 6, .308, 123 grain					
Without moderator	5	580	0.8	32	0.7
With moderator A	5.5	420		21	
Rifle # 7, .308, 123 grain					
Without moderator	5.8	380	1.1	23	0.8
With moderator A	6.3	370		16	
Rifle # 8, .22 rimfire, 117 grain low velocity		Recoil indistinguishable from movement between shots			
Without moderator	4				
With moderator D	4				
Rifle # 9, .25-06, 117 grain					
Without moderator	5.5	530	0.8	30	0.7
With moderator B	6	380		19	
Rifle # 10, .270, 130 grain T-mantle					
Without moderator	4.8	720	0.7	42	0.7
With moderator C	5.3	470		26	

Table 6 Acceleration perpendicular to direction of fire

Horizontal sideways motion

Rifle no., calibre, ammunition and moderator	Peak ms^{-2}	r.m.s. max ms^{-2} (1s time constant)
1 .243		
100 grain		
Without moderator	94	7.4
With moderator A	59	4.1
2 .25-06		
90 grain		
Without moderator	65	7.0
With moderator A	110	18
3 6.5 x 55		
156 grain		
Without moderator	40	5.5
With moderator A	28	4.2
5 .270		
150 grain		
Without moderator	64	7.5
With moderator A	38	5.9
9 .25-06		
117 grain		
Without moderator	58	6.0
With moderator B	29	4.9

Vertical motion

4 .270		
130 grain		
Without moderator	120	10
With moderator A	120	5.8
6 .308		
123 grain		
Without moderator	140	4.2
With moderator A	93	2.9
7 .308		
123 grain		
Without moderator	170	2.9
With moderator A	120	2.6
8 .22 rimfire	Recoil indistinguishable from movement between shots	
117 grain low velocity		
Without moderator		
With moderator D		
10 270		
130 grain T-mantle		
Without moderator	180	14
With moderator C	150	9.2

APPENDIX A MODERATOR DESCRIPTION

Moderator A - A sealed unit comprising a cylindrical steel sleeve containing an expansion chamber and a series of baffles. The expansion chamber is sleeved over the barrel and secured at 2 points; on a threaded area at the end of the muzzle and on bushing at the rear of the unit. The baffles extend slightly beyond the end of the muzzle.

Moderator B - A sealed steel cylinder containing a series of baffles. The unit is secured to a threaded area at the end of the muzzle and extends beyond the end of the muzzle.

Moderator C - A sectional unit comprising a cylindrical steel sleeve containing an expansion chamber and a series of baffles. The expansion chamber is sleeved over the barrel and secured at 2 points; on a threaded area at the end of the muzzle and on bushing at the rear of the unit. The baffles extend slightly beyond the end of the muzzle.

Moderator D - A .22 rimfire moderator comprising a sealed steel cylinder containing a series of baffles. The unit is secured to a threaded area at the end of the muzzle and extends beyond the end of the muzzle.