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Original Article

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Abstract

Objective: This research assessed the reduction of peak levels, equivalent energy and sound power of firearm suppressors. *Design:* The first study evaluated the effect of three suppressors at four microphone positions around four firearms. The second study assessed the suppressor-related reduction of sound power with a 3 m hemispherical microphone array for two firearms. *Results:* The suppressors reduced exposures at the ear between 17 and 24 dB peak sound pressure level and reduced the 8 h equivalent A-weighted energy between 9 and 21 dB depending upon the firearm and ammunition. Noise reductions observed for the instructor's position about a metre behind the shooter were between 20 and 28 dB peak sound pressure level and between 11 and 26 dB $L_{Aeq,8h}$. Firearm suppressors reduced the measured sound power levels between 2 and 23 dB. Sound power reductions were greater for the low-velocity ammunition than for the same firearms fired with high-velocity ammunition due to the effect of N-waves produced by a supersonic bullet. *Conclusions:* Firearm suppressors may reduce noise exposure, and the cumulative exposures of suppressed firearms can still present a significant hearing risk. Therefore, firearm users should always wear hearing protection whenever target shooting or hunting.

Key Words: Hearing conservation/hearing loss prevention, instrumentation, impulse noise, psychoacoustics/hearing science, noise induced hearing loss, firearm suppressors, damage risk criteria

Introduction

Gunfire is noisy. Peak sound pressure levels have been reported for small calibre rifles, pistols and shotguns ranging between 140 dB peak sound pressure level (dB peak SPL) for a 0.22 calibre rifle to well above 175 dB peak SPL for a 0.30 calibre rifle with a muzzle brake (Murphy et al. 2012). The impulses from gunfire present a significant hazard to the hearing of the shooter and nearby shooters or bystanders. The most common approach to protecting the shooter and bystanders from the high-level impulse exposures has been to provide personal protective equipment – hearing protection devices (HPDs). However, the standard for industrial hygiene practice has been to follow a hierarchy of controls, beginning with eliminating or replacing the process that produces the exposure, then moving to engineering or administrative solutions to minimise the exposure, and then finally relying on personal protective equipment as a last resort. Firearm suppressors are an engineering noise control. Limiting the time or number of rounds or the type of ammunition that a person may fire in a given training session is an administrative control.

The pull of a gun trigger initiates a chain reaction of events that result in one or more bullets being fired down range. The trigger releases a firing pin that strikes a cartridge containing a primer, powder and the bullet. The primer ignites and combusts the powder that forces the bullet out of the barrel. After the bullet exits the barrel, the gases and unburnt propellant follow and produce what is called the muzzle blast. Depending upon the ammunition characteristics, the bullet may be accelerated beyond the speed of sound in air thus breaking the sound barrier. If the bullet is accelerated to supersonic speed, the waveform observed down range will include a

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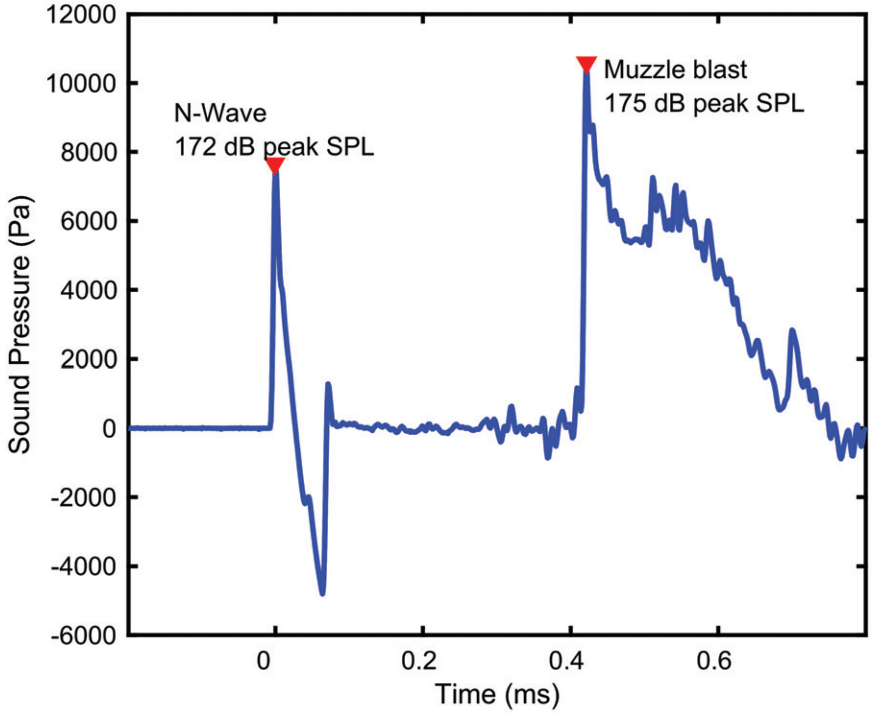

Figure 1. An example of an N-wave preceding the muzzle blast. The peak levels of the N-wave and muzzle blast are indicated with inverted triangles. Figure adapted from data reported in Rasmussen et al. 2009, Figure 9.

ballistic N-shaped wave (N-wave) in addition to the muzzle blast (Figure 1). The N-wave will start at the trajectory of the bullet and radiate conically outwards from that line.

The muzzle blast is characterised by a sharp pressure rise that generally follows an exponentially decaying oscillation as the gases condense at the muzzle blast and then return to their quiescent state. As an engineering noise control, the firearm suppressor minimises the muzzle blast by breaking up the initial wavefront. The shock front can be disrupted by passing through a series of baffles in the suppressor. The peak energy escaping the muzzle is diminished by allowing the expanding gasses to pass through small orifices separating the baffle sections. Thus, the effectiveness of the suppressor will depend upon the length of the suppressor, the number of baffles and orifice dimensions within the suppressor.

Under ideal conditions, the suppressor does not alter the velocity of the bullet. Therefore, if the propellant charge is capable of accelerating the bullet to a supersonic speed, an N-wave will still be produced. This component of firearm noise associated with the bullet is not expected to be altered by the use of a suppressor.

Damage risk criteria for noise exposure

Several noise exposure damage risk criteria (DRC) for small calibre firearms exist to protect persons from hearing hazards. The simplest of these criteria is based on the peak level, wherein peak levels over 140 dB SPL are considered hazardous to adults and peak levels over 120 dB SPL are considered hazardous to children (WHO 1997). Until 2015, the US Department of Defense used the MIL-STD 1474D (1997) as a *de fact*o DRC. The peak sound pressure level of the weapon, the B-duration (the time for the envelope of the gunshot to decay by 20 dB from the peak impulse level) and the number of shots that were expected to be fired were used to estimate the allowable number of rounds that a person could ‘‘safely’’ fire. The MIL-STD-1474D included no limits for impulsive sounds with peaks below 140 dB SPL, and it assumed that all exposed listeners would use hearing protectors above 140 dB SPL. In reference to this standard, some suppressors are labelled as ‘‘hearing safe’’ if they are not expected to allow sound levels in excess of 140 dB SPL.

In related DRC research, Atherley and Martin (1971) first proposed using an integrated A-weighted equivalent energy as a damage risk criterion. Stevin (1982) examined a variant of A-weighted equivalent energy, SEL for a 1-s exposure, and concluded that a 135 dB SEL could provide a reasonable DRC for an impulse exposure with a peak level of 170 dB SPL. Dancer and Franke (1995) also proposed a similar DRC limit value of $L_{\mathrm{Aeq,8h}} = 85$ dB. The $L_{\mathrm{Aeq,8h}}$ criterion is based upon filtering the acoustic signal to approximate the transfer function of the auditory periphery and integrating its energy. The A-weighting curve is derived from the iso-loudness curve at 40 phons and it is implemented into most sound measurement instruments in use today (ANSI/ASA S1.4 2014).

Price and Kalb (1991) proposed the use of an electroacoustic model of the auditory system, the Auditory Hazard Assessment Algorithm for Humans (AHAAH). Zagadou, Chan, and Ho (2016) proposed a different electroacoustic cochlear model that purports to represent the integrated energy received by the cochlea (ICE). In 2015, the US Department of Defense promulgated MIL-STD 1474E for noise limits of military materiel. This standard has previously been used as a de facto noise criterion because it defined limits for the use of no hearing protection (peak levels below 140 dB SPL), single hearing protection, and double hearing protection. It also defined exposure limits that should not be exceeded because excessive exposures could produce damage to other parts of the body (e.g. lungs, gut, or other organs). The revised MIL-STD-

1474E (2015) standard includes a modification to the equivalent energy of the $L_{IAeq,100ms}$ and the AHAAH model. $L_{IAeq,100\,ms}$ is derived from the $L_{Aeq,8\,h}$ with an adjustment for the duration of the initial peak overpressure of the impulse.

The choice of a DRC is open to a good deal of interpretation. The peak sound pressure levels and the 8-h A-weighted equivalent energy were selected as the metrics to characterise the suppressor performance because they related to traditional metrics describing exposures and risk assessments of impulse noise. The exposure limit of $L_{Aeq,8\,h} = 85$ dB was used to estimate permissible exposures.

Prior evaluations of firearm suppressors

Suppressor effects have been evaluated by many researchers. Skochko and Greveris (1968) conducted an extensive study of firearms with and without suppressors. While their results are difficult to interpret due to a lack of information about microphone locations, they generally found between 10 and 35 dB peak reductions for the suppressors. They note that the nearfield levels downrange will generally be dominated by the muzzle blast and the supersonic bullet's N-shaped shock wave (N-wave). They also note that low-velocity bullets will generate noise as the bullet displaces air along the trajectory and as the turbulence in the wake produces vortices that are shed at a regular frequency.

Pääkönen (2008) considered the use of firearm noise suppressors to reduce the impact of firing ranges on community noise annoyance. Shotguns produced peak impulse levels that were approximately 65 dBA at 2 km in the direction of shooting and 65 dBA at 1.4 km to the right and left sides of the shooter. Rifles had less of a noise footprint and extended to about 1 km to the sides of the shooter. Pistols produced 65 dBA peak levels at about 1 km in front and 0.4 km to the side of the shooter while small bore rifles (0.22 calibre) produced 65 dBA peaks at about 0.5 km in front and 0.3 km to the side of the shooter. Pääkönen (2008) also found that suppression was largely ineffective beyond 30 m in front of the shooter. At distances of about 10 m to the side of the shooter, the reductions in C-weighted levels due to the suppressor ranged from about 15 to 20 dB.

Lobarinas et al. (2016) considered the performance of several suppressors with semi-automatic rifles of two different calibres: the widely used 0.223 calibre Armalite 15 (AR-15), and the 0.300 calibre Blackout. The attenuation that they reported varied with the suppressor that was used and the measurement location. Generally, they reported between about 20 and 30 dB of peak reduction for the muzzle or the left ear. For the weapons that had a gas ejection port associated with the cycling of the semi-automatic weapons, the reduction at the right ear of the shooter was less, about 10 to 18 dB.

Nakashima (2015) conducted a series of measurements of small-calibre firearms with and without suppressors. For the three firearms evaluated at 0.5–1 m to the side of the shooter, the levels of peak reduction were 22 dB for the 5.56 mm C8 semi-automatic rifle, 29 dB for the 8.6 mm C14 medium range sniper rifle, and 32 dB for the 12.7 mm C15 long range sniper rifle. Nakashima (2015) did not report the reductions in terms of other metrics such as equivalent energy, although they did consider the effects of HPDs on the allowable number of exposures.

In 2015, the North American Treaty Organization (NATO) working group published the NATO AEP-4785 Standard for testing suppressors and measuring the acoustic signature of small arm suppressors (NATO 2015). The purpose of this standard was to accurately measure the far-field acoustic characteristics of a suppressor for small-calibre firearms from a 4 m elevated firing platform. The method focuses primarily on the reduction of the muzzle blast and excludes two components of the acoustic signature, the N-wave and the ground reflection. The elevation of the platform helps to ensure that any reflection from the ground will be separated by about 13 ms from the initial muzzle blast. The NATO method uses a 12.5 ms time window to isolate the muzzle blast from any N-wave that might be present and the arrival of the ground reflection. The NATO method will only characterise the effect of the suppressor on the blast wave. The ground reflection contributes to the acoustic hazard of a firearm. In some conditions where troops or public safety officers might be advancing towards an objective, the N-wave could contribute significantly to the acoustic hazard.

Sound power calculations

In addition to the exposures that might be received at the ear of the shooter, this paper reports the sound power for the suppressed and unsuppressed firearms measured with a 3-metre radius hemispherical array of microphones. The sound power characterises the total energy radiated from a noise source and yields the directivity and power as a function of frequency bands (ANSI/ASA S12.54 2011). Microphones are spaced about the hemisphere and the sound energy passing across each microphone is summed to estimate the total energy radiated through the hemispherical surface. The sound power level is first calculated in one-third octave bands by integrating over the surface, then correcting for the reflections, and lastly summing across the one-third octave bands to obtain the overall sound power level in dB relative to 10^{-12} W. Because the radiation of a gunshot is highly directional, the sound power may provide insight regarding the total energy of noise radiated by a firearm and of the noise reduction afforded by the suppressor because it is integrated over the entire hemisphere and not just a single location of a microphone.

Purpose

Exposure to firearm noise is the leading cause of hearing loss among military, law enforcement and public safety officers (Ylikoski and Ylikoski 1994). The prevalence of hearing loss among youth and adult recreational firearm users who engage in target shooting or hunting is greater than that observed for the general public (Stewart et al. 2002, 2014; Stewart M, Borer, and Lehman 2009; NHCA 2017). Because the hearing loss associated with firearm noise exposure often presents as a precipitous loss of high frequency hearing, the impairment can be difficult to remediate. Audiologists frequently see these configurations among their clients and need to have effective solutions to prevent further hearing loss. Relying upon hearing protection alone does not provide sufficient protection to the shooter because the hearing protection is frequently improperly fit or not worn at all. Hunters do not typically use protection because their ability to hear their quarry is dramatically reduced. Wearing typical earmuffs or earplugs causes the hunter to lose situational awareness. Electronic hearing protection offers the ability to hear environmental cues while still affording protection against the firearm noise. However, Stewart et al. (2014) reported that hunters typically use protection only about 20% of the time. Often the hunters are using larger bore rifles or shotguns with sufficient energy to harvest large game animals such as deer. Because a single shot can produce temporary or permanent hearing loss and hearing protection is typically fit poorly, other protection schemes need to be investigated. Firearm suppressors present a viable solution to effectively reduce the potential noise exposure by more than 20 dB. The use of a suppressor coupled with hearing protection can provide for a more hearing-safe experience.

The purpose of this article was to evaluate the noise reduction of firearm suppressors for high- and low-velocity ammunition with two different microphone configurations. High-velocity ammunition was expected to accelerate the bullet to supersonic speed and therefore produce an N-wave. The first study was conducted with the Michigan Department of Natural Resources (DNR) at the Rose Lake outdoor firing range (Lansing, MI). Microphones were positioned to evaluate the effective reduction of the suppressors on four different firearms. In the second study conducted at a hunting camp in Rudyard, MI, an array of 10 microphones positioned on a 3 m radius hemisphere was used to measure the sound power of two different firearms with and without a suppressor.

Study 1: Rose lake four microphone

Study 1: Methods

For the Rose Lake study, four microphone locations around a right-handed shooter were used to capture the noise at 0.6 m to the left of the muzzle, at 0.35 m to the right and left of the shooter's ears and at approximately 1 m behind the shooter's head where an instructor might be positioned. Two microphones were placed at each position, a polarised pressure (200 V) microphone in grazing orientation (pointed vertically) and a prepolarized free-field microphone (0 V) pointed at the muzzle. The data reported are only from the pressure microphones because the unsuppressed conditions produced an overload of the prepolarized microphone at the muzzle for some of the firearms tested. Table 1 lists the different firearms and suppressors used for the Rose Lake and the Rudyard studies. The GEMTECH HVT-QM 7.62 and G5 5.56 suppressors have a proprietary quick-mount, bi-lock system such that the suppressor slides over the end of the muzzle providing a repeatable and secure mount. The HVT 7.62 and G5 5.56 suppressors have a series of v-shaped cones that fit within the suppressor cylinder can and are welded together to form the baffles that diffuse the muzzle blast energy. The GEMTECH Outback IID threads onto the end of the muzzle and has a series of six K-shaped baffles. At the Rose Lake study, the low-velocity ammunition was not used with the Ruger Charger pistol because it could have jammed the loading mechanism, which relied on a greater volume of gas ejection than was likely to be produced by the ammunition. The Remington 700 rifles and the Savage MK-11 were bolt action rifles. A tripod gun stand was used to steady the forearm or barrel of the gun. The firearms were fired by right-handed shooters from the standing position. Five shots were recorded for each ammunition type and suppressor condition.

The microphones used were a G.R.A.S. Sound and Vibration 40DP ¼th inch pressure microphone at 0.6 m to the left of the muzzle. The right and left ear microphones were Brüel & Kjaer 4136 ¼ inch pressure microphones positioned 0.35 m from the centre line of the firearm and the microphone 1.0 m behind the shooter's head was a Brüel & Kjaer 4136 microphone as well. The height of the microphones above the ground was 1.63 m and the tip of the muzzle was 1.53 m above the ground. When the firearm suppressor was used, the muzzle microphone was moved along the direction of fire so that it was in the plane of the muzzle.

Impulse waveforms were acquired from all microphones with a National Instruments PXIe-4499 series 16-channel data acquisition card, sampled at 200 kHz with a 24-bit resolution and a dynamic range of ±10 V. The software controlling the system was a custom-designed NIOSH Sound Power virtual instrument (VI), which stored results in a MATLAB binary data file for analysis.

Study 1: Analysis

The impulses were processed for peak SPL, the 8 h A-weighted equivalent energy levels ($L_{\mathrm{Aeq,8h}}$). The $L_{\mathrm{Aeq,8h}}$ values were determined as follows:

$$L_{\mathrm{Aeq,\,8h}} = 10\log_{10}\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right) + 10\log_{10}\left(\frac{t_2 - t_1}{T_{8\mathrm{hr}}}\right) + 10\log_{10}(N), \tag{1}$$

where t_1 is a 20 ms pretrigger and the duration, t_2–t_1, is 100 ms. The number of impulses evaluated for the $L_{\mathrm{Aeq,8h}}$ was one impulse. The pressure signal was filtered through an A-weighting filter in MATLAB from Zechmann (2013). The 100 ms duration provided a uniform time window that minimised influence from other sounds.[1]

Study 1: Results

The data were analysed to determine the reductions of the peak impulse levels and A-weighted equivalent energy levels at

Table 1. Firearm, ammunition, calibre, muzzle velocity and suppressor evaluated in Study 1 at Rose Lake. The Savage Mark II rifle and Ruger 22 Charger pistol were evaluated in Study 2 at Rudyard with the sound power measurements.

Firearm	*Ammunition*	*Caliber*	*Rated muzzle velocity, feet/S*	*Suppressor*
Remington 700 rifle	Winchester 168 grain	0.308	2670	GEMTECH HVT-QM 7.62
Remington 700 rifle	Beck WIN 168 grain subsonic	0.308	990	
Remington 700 rifle	Federal FMJBT 55 grain	0.223	3240	GEMTECH G5 5.56
Remington 700 rifle	Beck REM 52GRJHP subsonic	0.223	1000	
Savage Mark II rifle	Winchester 22 Long Rifle 40gr Super-X	0.22	1280	GEMTECH Outback IID
Savage Mark II rifle	CCI 22LR segmented hollow point 40 grain	0.22	1050	
Ruger 22 Charger pistol	Winchester 22 Long Rifle 40gr Super-X	0.22	1280	GEMTECH Outback IID

each position. In Table 2, the peak level results are described for each combination of firearm, ammunition type, and suppressor condition. The reductions at the muzzle microphone and the instructor position were greater than those observed at the ear-level microphones for the Remington 0.308 and 0.223 calibre rifles. For the Savage rifle, the peak reductions were comparable across all of the positions, between 20 and 22 dB. For the firearms and suppressors that were evaluated, the differences in the observed reductions between the left and right ear microphones tended to be 2 dB or less with the exception of the Ruger Charger pistol which was 5 dB.

As shown in Table 3, reductions in $L_{Aeq,8h}$ ranged between 9 and 26 dB across all conditions. The Savage MK-11 exhibited reductions in $L_{Aeq,8h}$ of 12 and 9 dB for the left and right ear, respectively, for the low-velocity condition. The average reductions in $L_{Aeq,8h}$ at the instructor position tended to be slightly greater than the reductions at the right and left ear positions. The average reductions in $L_{Aeq,8h}$ at the left and right ear were not significantly different than one another. Differences between the left and right ears were not expected for the bolt-action rifles because the noise primarily emanates from the muzzle or the end of the suppressor. For the rifles and the pistols, the $L_{Aeq,8h}$ suppressed levels tended to be about 1 dB higher at the right-ear microphone than the left-ear microphone in the suppressed condition. In the suppressed condition, Lobarinas et al. (2016) observed a larger difference between the left and right ear microphones which they attributed to a gas ejection port on the semi-automatic rifle. The Ruger Charger pistol was semi-automatic but does not use a large volume of gas to cycle the action compared to firearms using more propellant.

The reductions in $L_{Aeq,8h}$ provide an indication of the effect of the ammunition and suppressor on auditory risk. When $L_{Aeq,8h}$ is reduced by 3 dB, the risk is reduced by a factor of 2 and the allowable number of rounds double because of the last term in Equation (1), $10\log_{10}(N)$. For example, the 32 dB reduction at the left ear microphone for the 0.308 Remington 700 rifle (Table 3) from $L_{Aeq,8h}$=76 dB for the unsuppressed high velocity ammunition to $L_{Aeq,8h}$=44 dB for the suppressed low velocity ammunition corresponds to a risk reduction factor of nearly 1600.

Study 1: Inferential analyses

Multivariable linear regression models revealed small differences between the signals near the shooter's ears for both $L_{Aeq,8h}$ ($F_{5,64}$=13.4; $p<0.0005$; R^2=0.47) and peak ($F_{4,65}$=3.74; $p=0.009$; R^2=0.23) levels. Controlling for the other factors in the model, the $L_{Aeq,8h}$ values at the right ear were approximately 1 dB greater (95% CI: 0.9–1.6 dB) than the left in suppressed conditions. The $L_{Aeq,8h}$ values were approximately 0.4 dB lower (95% CI: −0.82 to −0.05 dB) at the right ear than the left when high-velocity ammunition was used. Post-hoc comparisons across guns indicated that this exposure asymmetry was greater for the 0.22 calibre pistol (0.89 dB) than the 0.308 calibre rifle (0.02 dB). A similar pattern of results was observed in analyses of peak levels, with the exception that the type of ammunition had no significant relationship with the difference between ears.

The inferential evaluation of the suppressors, ammunition velocity, and guns yielded statistically significant models at all microphone locations, with each model accounting for at least 91% of the variance in the observed $L_{Aeq,8h}$ values. Both suppressors and low-velocity ammunition reduced sound levels at all microphone locations. In addition, the use of low-velocity ammunition in a gun with a suppressor produced additional reductions in sound levels beyond the simple combination of the individual effects. At the left ear microphone location, for example, the use of a suppressor and low-velocity ammunition each had a main effect on $L_{Aeq,8h}$ by approximately 17 dB (16.9 and 17.2 dB, respectively), and in combined (suppressor and low-velocity ammunition) conditions, the sound levels were, on average, 40 dB lower than in the

Table 2. Average peak impulse levels for five shots and noise reductions for the firearms tested in Study 1 for each condition of suppressor and ammunition velocity. The noise reductions are highlighted with grey shading and are the difference in the averaged peak levels for the unsuppressed minus the suppressed condition.

			Peak sound pressure levels and reductions (shaded) (dB SPL)			
Firearm	*Muzzle velocity*	*Suppressor condition*	*Muzzle*	*Left ear*	*Right ear*	*Instructor*
Ruger Charger		Unsuppressed	160	152	152	135
0.22 caliber	High velocity	Suppressed	138	128	133	113
pistol		Reduction	22	24	19	22
		Unsuppressed	149	140	140	123
	Low velocity	Suppressed	128	118	120	103
Savage MK-11		Reduction	21	22	20	20
0.22 caliber		Unsuppressed	152	141	141	125
rifle	High velocity	Suppressed	131	120	121	105
		Reduction	21	21	20	20
		Unsuppressed	157	140	140	127
	Low velocity	Suppressed	131	122	120	100
Remington 700		Reduction	26	18	20	27
0.223 caliber		Unsuppressed	176	160	160	148
rifle	High velocity	Suppressed	148	134	136	120
		Reduction	28	26	24	28
		Unsuppressed	164	148	149	134
	Low velocity	Suppressed	137	131	132	111
Remington 700		Reduction	27	17	17	23
0.308 caliber		Unsuppressed	176	161	161	150
rifle	High velocity	Suppressed	150	137	136	123
		Reduction	26	24	25	27

Table 3. Average 8 h A-weighted equivalent energy levels, $L_{Aeq,8h}$, for five shots and noise reductions for the firearms tested in Study 1 for each condition of suppressor and ammunition velocity. The noise reductions are highlighted with grey shading and are the difference in the averaged peak levels for the unsuppressed minus the suppressed condition.

			8 h A-weighted equivalent energy levels and reductions (shaded) (dB(A))			
Firearm	*Muzzle velocity*	*Suppressor condition*	*Muzzle*	*Left ear*	*Right ear*	*Instructor*
Ruger Charger 0.22 caliber pistol	High velocity	Unsuppressed	71	63	63	53
		Suppressed	47	48	49	33
		Reduction	24	15	14	20
	Low velocity	Unsuppressed	55	49	48	36
		Suppressed	38	37	39	25
		Reduction	17	12	9	11
Savage MK-11 0.22 caliber rifle	High velocity	Unsuppressed	60	50	50	39
		Suppressed	42	35	36	24
		Reduction	18	15	14	15
	Low velocity	Unsuppressed	66	54	54	44
		Suppressed	41	34	35	21
		Reduction	25	20	19	23
Remington 700 0.223 caliber rifle	High velocity	Unsuppressed	88	75	75	68
		Suppressed	62	54	55	42
		Reduction	26	21	20	26
	Low velocity	Unsuppressed	74	61	61	51
		Suppressed	49	44	45	30
		Reduction	25	17	16	21
Remington 700 0.308 caliber rifle	High velocity	Unsuppressed	90	76	76	69
		Suppressed	65	57	57	45
		Reduction	25	19	19	24

unsuppressed high-velocity conditions, indicating an additional 6 dB (95% CI: 2.5–11 dB) of sound reduction. The combined use of a suppressor and low-velocity ammunition achieved similar benefits at all microphone locations in this study (See Figure 2).

In Figure 2, the average reductions of peak levels for each of the firearms are compared to the reductions for $L_{Aeq,8h}$. Further details are available in Tables 2 and 3. The open symbols indicate the high velocity ammunition and the closed symbols indicate the low velocity ammunition. The different symbols indicate the location of the microphone position around the firearm. The peak level reductions tended to be greater than the reductions observed for $L_{Aeq,8h}$. Except for the muzzle microphone position for the Ruger Charger 0.22 pistol, the reductions for the peak levels were greater than those observed for the $L_{Aeq,8h}$ for the high velocity ammunition. For the low velocity ammunition, the 0.223 calibre Remington 700 at the left ear was the only case where the peak level reduction was less than the $L_{Aeq,8h}$ reduction. This finding suggests that reductions expressed as changes in peak level may not completely represent suppressor effectiveness.

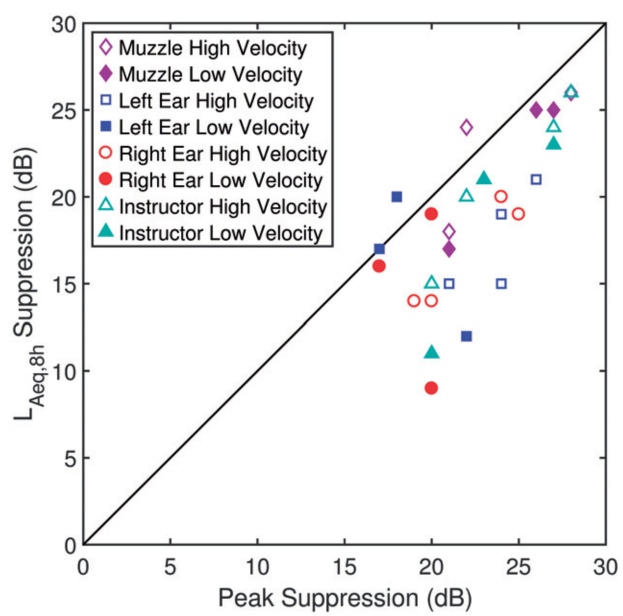

Figure 2. Comparison of suppressors' noise reduction assessed with change in peak level versus change of 8 h A-weighted equivalent energy, $L_{Aeq,8h}$ from Study 1. Open symbols denote the high-velocity rounds and closed symbols are low-velocity rounds. The purple diamonds, blue squares, red circles, and cyan triangles are the reductions measured at the muzzle, left ear, right ear and instructor positions, respectively.

Study 2: Rudyard sound power

Study 2: Methods

As shown in Figure 3, the microphones were placed at the standard locations for sound power measurements (ANSI/ASA S12.54 2011). At each location, a ¼ inch prepolarized microphone and a ½ inch prepolarized free-field microphone pair were located 2.5 cm apart and pointed towards the centre of the hemisphere base. Only the data from the ¼ inch microphones were used since the ½ inch microphones saturated when measuring the unsuppressed conditions. The muzzle was 1.55 m above the centre of the base of the hemisphere.

The firearms used for the sound power study were the 0.22 calibre Ruger Charger pistol and the 0.22 calibre Savage MK-11 bolt action rifle. The firearms were fired from the standing position by a right-handed shooter for the sound power measurements. Between five and ten shots were taken in each combination of ammunition type and suppressor condition. The impulse

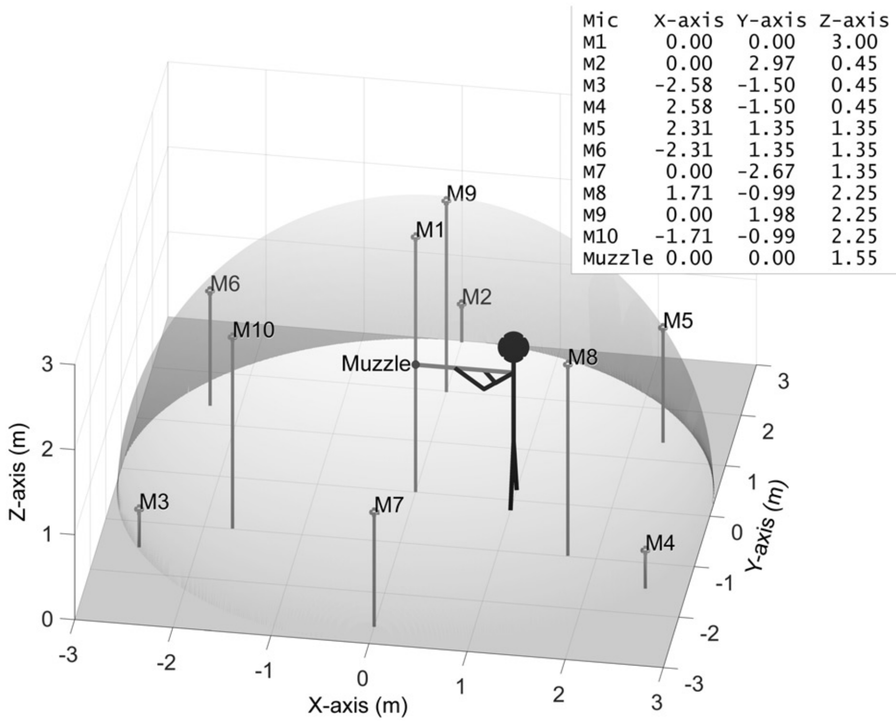

Figure 3. The microphone locations and relative positions on the hemisphere for the sound power measurements in Study 2. The shooter was inside the hemisphere and the muzzle was located over the origin of the hemisphere. The ten microphones are numbered and their corresponding positions are listed in the inset table in metres.

recordings were reviewed and all impulses were used in the analysis.

The data acquisition system collected about 10–15 s recordings that were analysed in multiple stages. The location of each impulse was obtained by identifying the peaks corresponding with the expected number of impulses. A one-third octave-band fifth-order Butterworth filter was applied at each of the one-third octave band centre frequencies from 20 to 20,000 Hz creating 31 bands of data with 10 microphone locations. A time window of 18 ms was applied to the filtered signals centred upon the impulse identified in the first analysis step. The equivalent energy, $L_{\mathrm{Eq},f,i}$, was computed for each band and microphone location. The sound power was estimated using Equations (2) and (3) from ANSI/ASA S12.54 (2011). Finally, the sound power levels, $L_{\mathrm{W},f}$, were averaged across the ten microphone locations assuming equal areas for each microphone location according to the following formula,

$$L_{W,f} = 10\log_{10}\left(\sum_{i=1}^{i=10} 10^{\left(L_{\mathrm{Eq},f,i}/10\right)}\right) + 10\log_{10}\left(\frac{S}{S_0}\right) - K_{1,f} - K_{2,f} \quad (2)$$

where $L_{\mathrm{Eq},f,i}$ is the equivalent energy over the time interval for the sample in the frequency band f = {20 Hz, ... 20 kHz}, i denotes the ith microphone location, S is the area of the measurement surface $2\pi r^2$, S_0 is the reference area 1 m^2, $K_{1,f}$ is the background noise correction of the fth band, and $K_{2,f}$ is the environmental correction of the fth band. The gun blasts had a much higher sound pressure than the background noise, so the $K_{1,f}$ was assumed to be zero. The measurements were made outdoors in an area with sandy-rocky soil at the surface and thin, mowed grass, so the $K_{2,f}$ were assumed to be zero. No correction for absorption was made. The total sound power L_W is calculated by summing over the 31 frequency bands using the formula

$$L_W = 10\log_{10}\left(\sum_{f=1}^{f=31} 10^{\left(L_{W,f}/10\right)}\right) \quad (3)$$

The median unweighted sound power levels are reported for each condition and the error bars were determined as the 25th and 75th quartiles.

Study 2: Results

The sound power level (Table 4) for the high-velocity ammunition was greater than the low-velocity ammunition. The suppressor reduced the sound power level by 23 and 16 dB for the low-velocity ammunition for the pistol and rifle, respectively. The high velocity ammunition was reduced by 15 and 2 dB for the pistol and rifle, respectively.

In Figure 4, the sound power levels for the Ruger Charger pistol are displayed for each one-third octave frequency band, high-velocity/low-velocity ammunition, and for the suppressed/unsuppressed conditions are displayed. The spectra for the unsuppressed conditions are similar to the spectrum for a Friedlander waveform (circles and squares). The suppressed spectrum tended to exhibit the greatest reduction for the frequencies below about 2000 Hz. The high-velocity suppressed waveform has increased spectral energy from 1600 to 6000 Hz (diamonds) and the low-velocity suppressed waveform (triangles) has an increased spectral energy above 6000 Hz. The overall sound power level for the high-velocity ammunition was 150 dB in the unsuppressed condition while the

Table 4. Study 2 median sound power levels noise reductions for each condition of suppressor and ammunition velocity. The sound power level reductions are highlighted with grey shading and are the difference in the median sound power levels for the unsuppressed minus the suppressed condition.

		Sound power level, L_W (dB re 10^{-12} W)	
Firearm	*Suppressor condition*	*Low velocity*	*High velocity*
Ruger Charger	Unsuppressed	145	150
0.22 caliber	Suppressed	122	135
pistol	Reduction	23	15
Savage MK-11	Unsuppressed	130	141
0.22 caliber	Suppressed	114	139
rifle	Reduction	16	2

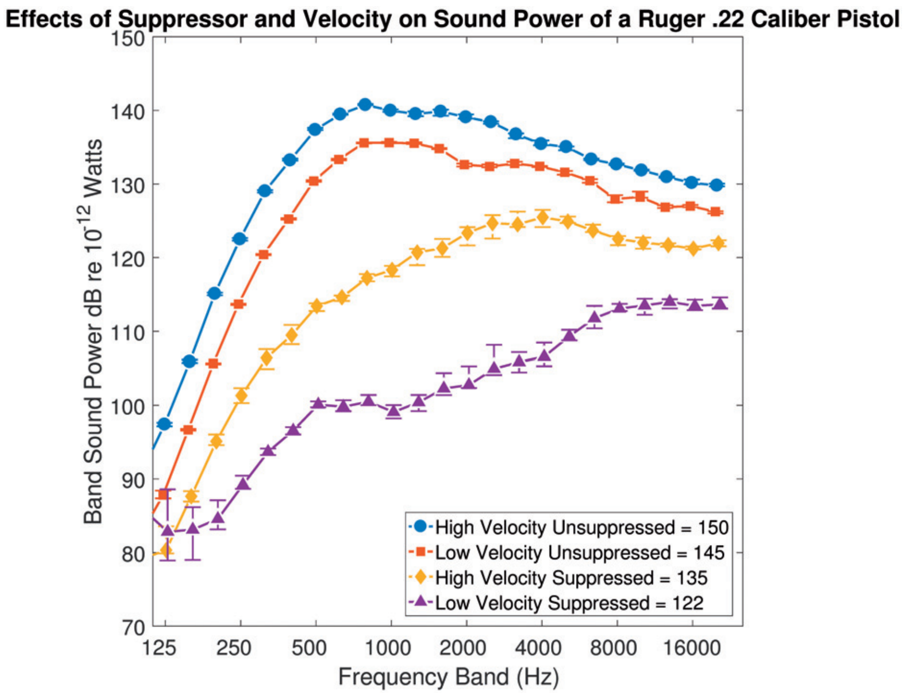

Figure 4. The sound power levels of the Ruger pistol at each one-third octave frequency band, high-velocity/low-velocity ammunition, and for the suppressed/unsuppressed conditions in Study 2.

suppressed was 135 dB, yielding about a 15 dB reduction in sound power level. For the low-velocity ammunition, the unsuppressed sound power level was 145 dB and the suppressed power level was 122 dB, yielding a 23 dB reduction in sound power level.

Figure 5 displays the interpolated L_{eq} levels for the Ruger Charger pistol over the hemisphere of the microphone array viewed from above for the 2000 Hz one-third octave band. The 2000 Hz band was selected because the frequency dependent effects first begin to differentiate for frequencies above 2000 Hz. For the suppressed conditions, the energy directed in front of the shooter is significantly greater than behind the shooter.

In Figure 6, the sound power levels for the Savage MK-11 rifle are plotted for the four conditions. Above 2000 Hz, the sound power level spectra of the high-velocity suppressed and the high-velocity unsuppressed conditions are nearly identical. On average, the sound power levels for the high-velocity ammunition were 141 dB for the unsuppressed and 139 dB for the suppressed conditions, yielding a 2 dB reduction in sound power level. In contrast, the low-velocity ammunition had sound power levels of 130 and 114 dB for the unsuppressed and suppressed conditions. The mean reduction of sound power level for the low-velocity conditions was 16 dB. For the suppressed low-velocity ammunition, the noise floor below 400 Hz is elevated compared to the other three conditions. If only the bands at 125 Hz and higher are considered, the suppressor's effect increases to a 17 dB reduction in sound power level.

In Figure 7, the 2000 Hz octave band analysis of the four conditions for the Savage MK-11 rifle are displayed. Comparing the two images in the right column, the sound power levels were effectively identical and the images were also similar. In contrast, the low-velocity ammunition (left column) exhibits a significant difference in the sound power levels and the plots indicate substantial differences with respect to the overall colour and levels. All three plots indicate about a 30 dB difference from front

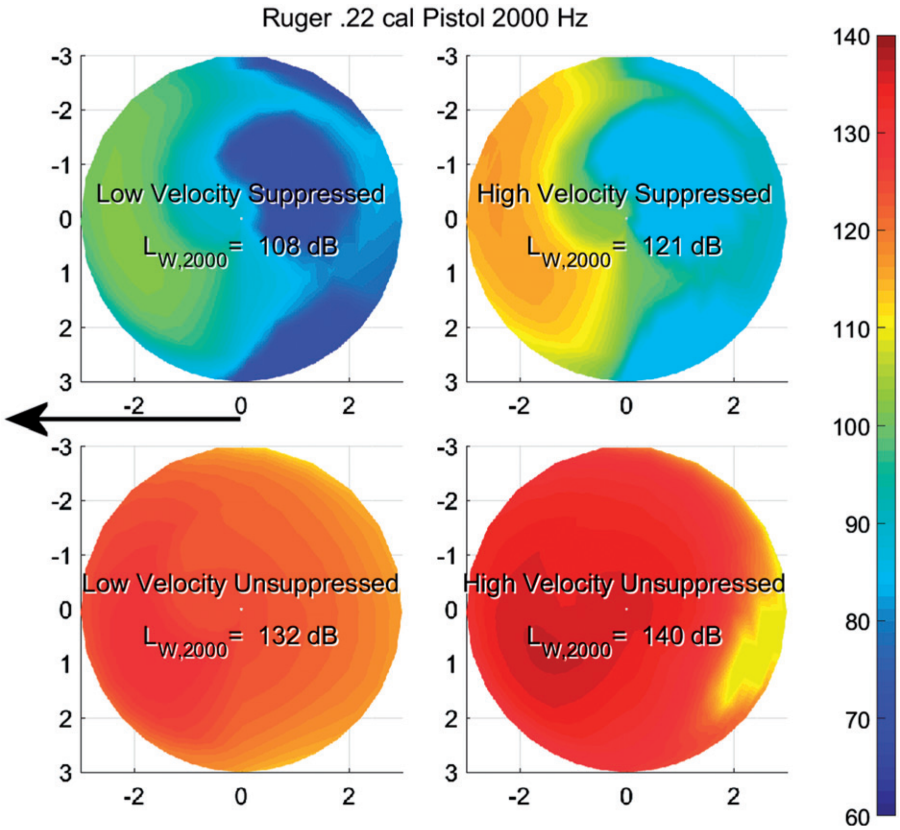

Figure 5. Sound power levels for the 2000 Hz one-third octave band filtered data for the 0.22 calibre Ruger Charger pistol in Study 2. The view is of the microphone array from above and the energy is interpolated over the surface of the 3 m hemisphere. The pistol was in the centre of the hemisphere and the shot was fired towards the left of the hemisphere. The images in the upper row are the suppressed conditions and the images in the bottom row are the unsuppressed conditions. The left column images are for low-velocity ammunition and the right column are the high-velocity conditions. (See Supplemental file for the Ruger Pistol to view the hemispherical plots for all of the frequency bands.).

of the shooter to behind the shooter (left to right in the figure). The suppressed low-velocity condition (upper left) displays some lower levels at the edge of the plot (dark blue), which could be an interpolation artefact associated with microphone locations.

In Figure 8, the waveforms for the microphones in front of the shooter were edited to eliminate the N-wave produced by the high velocity bullet as it passed by the microphones. The N-wave was identified visually and the samples in that time interval were set to zero prior to repeating the analyses. The spectra still exhibit some convergence above about 2000 Hz as was observed in Figure 6. The peak band levels are about 12 dB lower when the N-wave is excluded and the resultant overall sound powers levels were 136 dB and 127 dB for the unsuppressed and suppressed conditions, respectively. The effect of the N-wave on the sound power introduces two analytic complications. First, the microphones in the front half of the hemisphere are contaminated with the N-wave if the bullet is supersonic. Second, substantial sound production by a moving source (i.e. the bullet) is a situation not anticipated in the sound power measurement equations. The source under evaluation is expected to be contained within the reference volume. In this case, the bullet becomes a primary sound source for the frequencies above about 2000 Hz, explaining why the two conditions merged.

Discussion

Noise reduction of suppressors

Two studies were conducted to investigate the benefits of an engineering noise control (i.e. a firearm noise suppressor) and an administrative control (i.e. low-velocity ammunition) to reduce noise exposure from firearms. The results of these studies indicated that firearm noise suppressors tend to reduce peak pressure levels at the shooter's ears by 17–26 dB, reduce equivalent energy levels by 9–21 dB, and reduce overall sound power level by 2–23 dB. Low velocity ammunition uses less propellant than high-velocity ammunition, thus reducing both the muzzle blast and eliminating the N-wave. The larger calibre Remington 700 rifles exhibited greater equivalent energy reductions at the ear microphones for the high velocity ammunition than for the low velocity ammunition. The Savage MK-11 rifle showed almost no difference in the reductions between the high and low velocity ammunition. The levels of the unsuppressed Savage rifle exhibited a 1–2 dB difference as a function of the ammunition, whereas the Remington rifles had between a 12 dB to as much as a 20 dB difference between the two velocities of ammunition.

This study did not investigate bullet shapes that might minimise the N-wave nor did it investigate systematic design features of

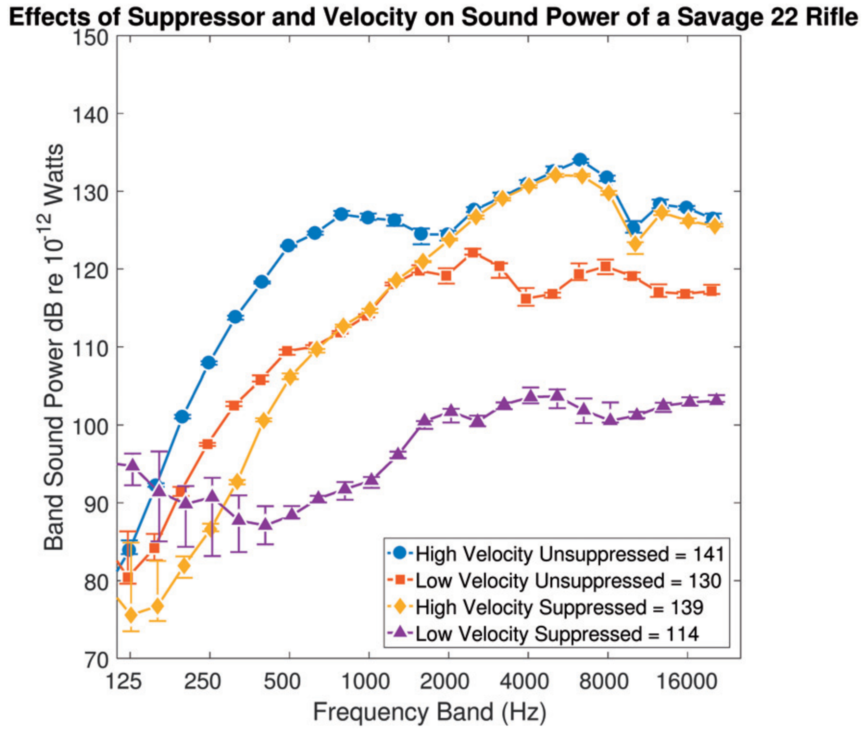

Figure 6. The sound power for each one-third octave frequency band, high-velocity/low-velocity ammunition, and for the suppressed/unsuppressed conditions for the 0.22 calibre Savage MK-11 rifle in Study 2.

suppressors. The suppressors evaluated in this study were a convenience sample of suppressors provided by the Michigan DNR and by one of the authors (MS). Instead, these results can be used to inform a hearing conservation professional about how the evaluation of the suppressor effectiveness can be affected by the location of the microphones as well as the metric used. Typically, suppressor effectiveness has been defined by the change in the peak impulse level. Peak impulse reduction tended to overestimate the reduction of the $L_{Aeq,8h}$ (see Figure 3), which is more strongly related to auditory hazard. As well, the peak sound pressure level is no longer used in the most recent MIL-STD-1474E (2015). An energy-based metric and a computational cochlear damage model are used to assess the noise performance of military materiel. A spectral, energy-based metric for suppressors could be complementary with spectral methods for characterising hearing protector performance in high-level impulse noise (Fackler et al. 2017).

Other damage risk criteria

MIL-STD 1474E includes two metrics that have not been reported in this paper, $L_{IAeq,100ms}$ and auditory hazard units (AHUs). The $L_{IAeq,100ms}$ includes an adjustment correction based upon the pressure wave duration (i.e. A-duration) of the impulse and the correction has a lower limit of 0.2 ms. Since the A-durations for the ammunition were less than 0.2 ms, the A-duration correction was 0 dB. An additional 54.6 dB must be added to the $L_{Aeq,8h}$ to estimate $L_{IAeq,100ms}$. Therefore, the differences between the suppressed and unsuppressed conditions yielded the same reduction as reported above for the $L_{Aeq,8h}$.

AHUs as calculated by the AHAAH model were not reported for several reasons. The AHUs are not readily related to decibel differences. The middle ear muscle contraction (MEMC) and the nonlinear annular ligament result in nonlinear growth of the AHUs which complicates comparisons of measurements at different distances from the muzzle and different angles relative to the direction of fire. Only the microphone positions for the shooter's ears would be relevant. Recent findings have presented additional problems with the assumptions underlying the AHAAH model. The AHAAH model allows for the MEMC to be activated depending upon whether the shooter is warned or not. The warned condition assumes that 100% of persons have a pre-contracted MEMC. Flamme et al. (2017) reported that the prevalence rate of 86% for the acoustic reflex among young 18–31 year olds normal hearing persons based upon a review of the National Health and Nutrition Examination Survey data (1999–2012). The prevalence rates decreased with age and increased hearing loss (Flamme et al. 2017). Zagadou, Chan, and Ho (2016) reported that key parameters of the AHAAH model – namely the stapes dimensions and annular ligament parameters – are not representative of those found in recent studies of the human.

Sound power reduction

Noise in the low frequencies had a small effect in the measurement conditions producing the lowest sound pressures (e.g. suppressed low-velocity). Windscreens are customarily used when measuring continuous noise sources outdoors. However, when making the measurement of high-level impulse noises, the windscreens disrupt the wavefront and dramatically affect the waveform and subsequent results.

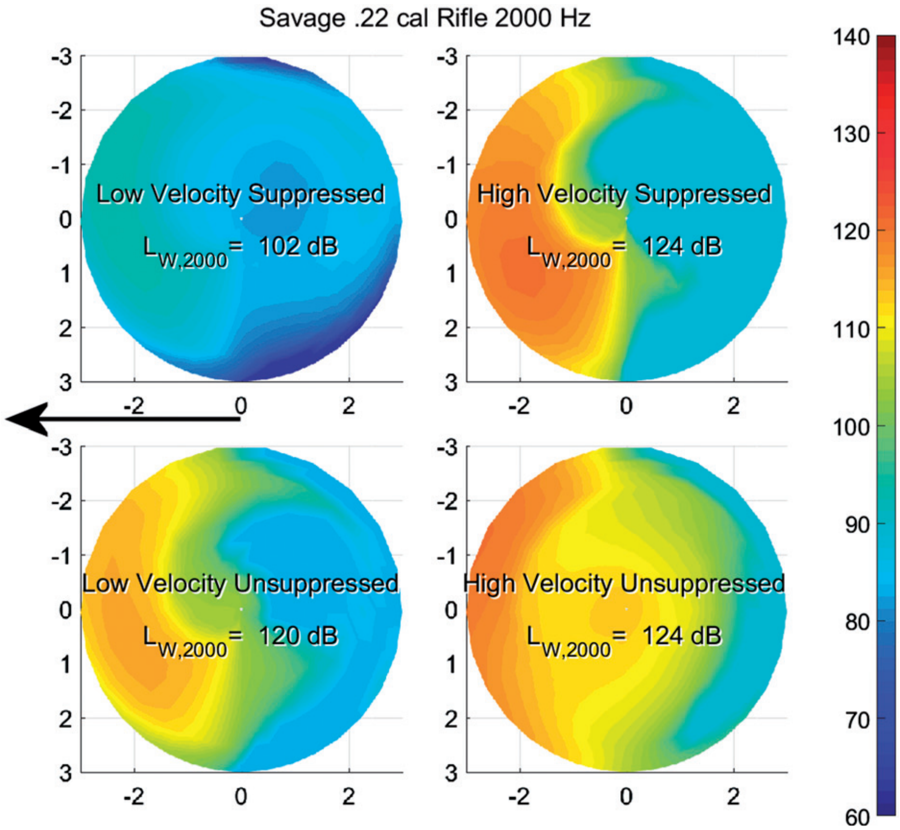

Figure 7. Sound power levels for the 2000 Hz one-third octave band filtered data for the 0.22 calibre Savage MK-11 rifle in Study 2. Figure details are similar to Figure 3. Like the pistol, the sound power levels for the high-velocity conditions are significantly greater than that for the low-velocity conditions. (See Supplemental file for the Savage Rifle to view the hemispherical plots for all of the frequency bands.).

The source directivity was evident in the front of the shooter (left half of the hemispheres) and exhibited a slight asymmetry to the left front of the shooter (lower left quadrant of the hemisphere plots). The shooter aimed along the negative x-axis and microphones 3 and 10 (Figure 3) were to the left and in front of the shooter and microphone 6 was to the right and in front of the shooter. The firearm's directional nature caused the front/back differences. The asymmetry likely resulted from the positions of the microphones and the interpolation of the sound power. The shooter's body may have produced a shadow effect that was more evident in the Ruger Charger than was observed for the Savage MK-11. Murphy et al. (2012) observed an acoustic shadow behind and to the left for a right-handed shooter. Future sound power measurements should use a symmetric array of 20 microphones.

Sound power does not seem to be an optimal means of characterising the reduction of typical auditory risk because the N-wave contributes to the overall power and is only relevant to exposures of personnel in the front of the firearm. For the low-velocity ammunition, the Ruger Charger had a reduction of 23 dB and the Savage MK-11 had a reduction of 16 dB. For the high-velocity ammunition, the reduction in sound power levels were 15 and 2 dB for the Ruger and Savage firearms, respectively.

N-wave effects

In recordings containing supersonic bullets, assessments of suppressor effects may require waveform modifications to extract the N-wave prior to sound power calculations. However, the N-wave is an integral part of the noise emission from gunfire, and extraction of the N-wave should only be undertaken in cases where the sound power from the muzzle blast is the sole interest of the analyses. For the Savage rifle, removing the N-wave from the waveform increased the reduction in the sound power level from 2 dB for the unedited waveform to 9 dB for the edited waveform.

The separation of the N-wave and muzzle blast depends upon the speed of the bullet. The velocity of the 0.22 calibre high-velocity ammunition was not as great as that for the 0.223 and 0.308 calibre ammunition. The N-waves were not clearly evident in the Ruger Charger sound power recordings, whereas the N-waves were evident in the Savage MK-11 recordings. In the NATO AES 4875 standard, the microphones are located 5 m from the muzzle which increases the separation between the N-wave and the muzzle blast. Changing hemisphere's radius from 3 to 5 m would have increased the separation of the N-wave 1.1–1.9 ms, assuming the bullet's velocity was 390 m/s (1280 fps) and speed of sound was 340 m/s. The amplitude of the N-wave obeys a power law relationship of $b^{-3/4}$ where b is the distance from the trajectory to the nearest microphone (Stoughton 1997). A 5 m versus a 3 m

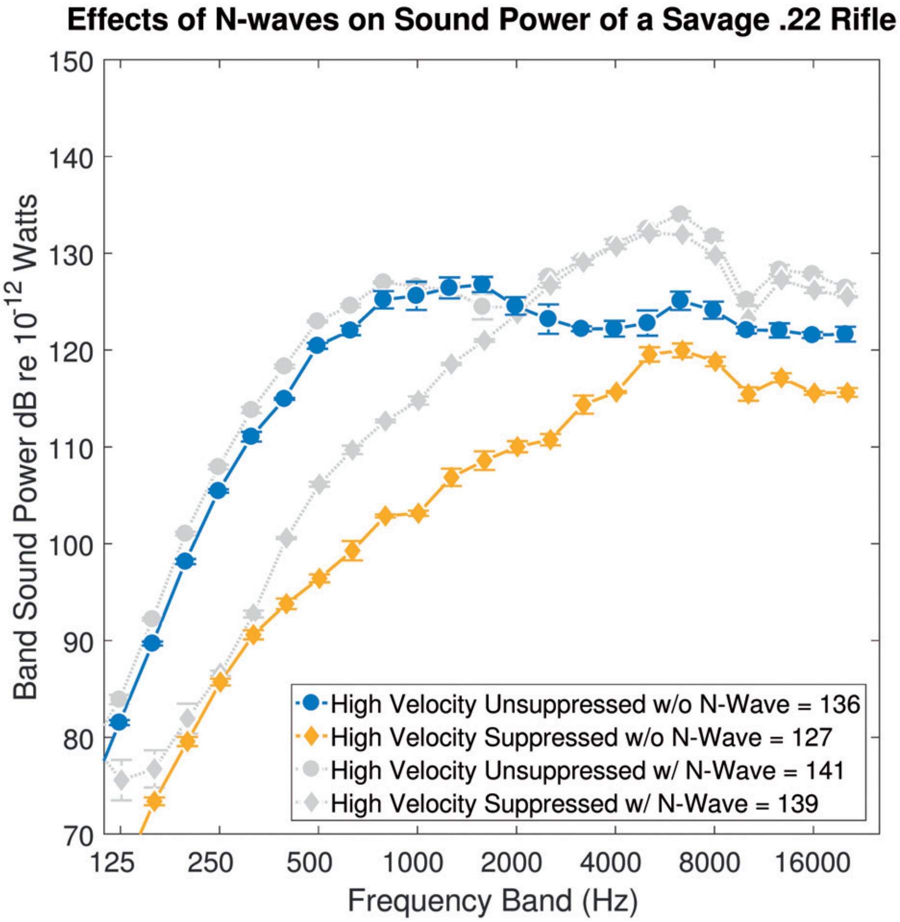

Figure 8. Sound power as a function of the one-third octave bands after the N-wave was extracted. The N-wave contributed substantially to the energy measured at the microphones in the front half of the hemisphere in Study 2.

hemisphere would increase the distance to the nearest microphone and result in about a 3.3 dB reduction in the amplitude of the N-wave.

Biases and limitations

Although the use of a suppressor and/or low-velocity ammunition yielded significant reductions in auditory risk to the unprotected shooter in Study 1, hearing protection is still recommended while firing any gun. The guns selected for Study 1 do not necessarily represent many guns commonly used in recreational or occupational settings. All guns but the Ruger Charger pistol used a bolt-action loading mechanism, which forces all combusted gas out of the muzzle. Semi-automatic loading mechanisms capture the energy in the combusted gas to eject the spent cartridge and load a new cartridge into the chamber. This gas is then released through ports located midway down the gun. Prior work (e.g. Lobarinas et al. 2016) have shown substantial declines in suppressor effectiveness at the right ear position of a right-handed shooter firing from the shoulder, and it is probable that these declines are due to sound energy accompanying the gas ejection. Analyses with a larger number of guns and suppressors are necessary before definitive statements about the elimination of auditory risk can be made.

The Rose Lake recordings were made in open field conditions and cannot be generalised to conditions where reflective surfaces are nearby. The reduction of the peak impulse levels would be expected to be the same whether measured indoors or outdoors. For some police and military tactics where personnel progress in single file towards an objective, persons may be positioned in front of personnel firing from behind to provide cover fire. Blast waves and N-waves from a gun fired in an enclosure (e.g. a firing range with walls or other surfaces, a hunting blind, or a tactical training facility) would reflect from nearby surfaces and reach the ear by multiple paths. The additional reflected energy reaching the listener's ears via these paths will increase the hazard relative to the open field recordings obtained in this study. Suppressors and low-velocity ammunition can be expected to reduce the sound exposure in these settings, but the overall amount of reduction is likely to differ from the results obtained in this study.

Conclusions

The measurements described in this paper are in general agreement with those reported previously. The suppressors reduced exposures at the ear between 17 and 26 dB peak sound pressure level and reduced the 8 h equivalent A-weighted energy between 9 and 21 dB depending upon the firearm and ammunition. Noise reductions observed for the instructor's position about a metre behind the shooter were between 20 and 28 dB peak sound pressure level and between 11 and 26 dB $L_{\mathrm{Aeq,8h}}$. Although these results imply a substantial risk reduction, the limited numbers of firearms, suppressors and environmental conditions evaluated in this study are insufficient to consider any combination of gun and suppressor ''hearing safe''. Thus, hearing protection should be worn whenever firing a gun. For more energetic firearms when target shooting double protection is warranted for the unsuppressed gun and single protection is needed for a suppressed gun.

Note

1. Other equivalent energy metrics could have been used, Sound Exposure Level (SEL) or the new $L_{\mathrm{IAeq,100ms}}$. To convert $L_{\mathrm{Aeq,8h}}$ to SELA, add 44.6 dB. To convert $L_{\mathrm{Aeq,8h}}$ to $L_{\mathrm{IAeq,100ms}}$, add 54.6. All of the unsuppressed A-durations were less than 0.2 ms, which in turn requires no correction for the A-duration (MIL-STD 1474E, 2015, p 45, Eq. 3a).

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Supplementary material available online