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Developing a method to assess noise reduction of firearm suppressors for small-caliber weapons

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Firearm suppressors reduce the muzzle blast of a gunshot through a series of baffles contained in a canister. The American National Standards Institute has no firearm suppressor testing standards. A recent NATO test standard, AEP 4875, ignores the contribution of the ground reflection at the shooter's ears and is not representative of how firearms are typically fired. The aim of this study is to commence empirical development of a standard to assess the noise reduction of firearm suppressors for hearing conservation purposes. Fourteen firearms with and without a suppressor were evaluated with high velocity and low velocity (subsonic) ammunition. Twelve microphones were positioned in a ring 3 meters from the muzzle with 30° spacing and 1.5 meters above the ground. One microphone was positioned at 1 meter to the left of the muzzle and two microphones were positioned at 15 centimeters from the right and left ears of the firearm operator. The suppressors were effective in reducing the peak sound pressure levels between 3 and 28 dB and A-weighted equivalent energy (L_{Aeq}) between 2 and 24 dB.

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1. INTRODUCTION

Firearm noise is potentially hazardous to the hearing of the shooter and bystanders if proper hearing protection is not worn. Depending upon the firearm, the sounds near the ear may range from 140 to 175 decibels peak sound pressure level (dB peak SPL).[1–4] Firearm noise consists of several components including the pull of the trigger, ignition of the primer, combustion of the powder, the exit of the bullet from the muzzle, an N-shaped ballistic shock wave (or N-wave) produced by supersonic projectiles, and the noise of any cycling mechanism for semi-automatic or automatic systems. Firearm suppressors are designed as an engineering noise control to reduce the muzzle blast. Once the bullet exits the muzzle, the gas from the combustion of the gunpowder spherically expands and produces the muzzle blast. When the firearm suppressor is attached to the muzzle, a series of baffles and expansion chambers divert the expanding gases and break up the initial shock wave substantially reducing the sound energy. If the bullet exceeds the speed of sound, then a characteristic N-wave will be formed.[5] However, the N-wave is unaffected by the presence of the suppressor because it is generated by the supersonic bullet. For semi-automatic or automatic firearms, the exhaust gas is sometimes used to cycle the loading of the next cartridge. This exhaust can become the dominant noise source for the shooter when firing a suppressed weapon.

A. PREVIOUS RESEARCH

Several evaluations of firearm suppressors have been reported. In a series of two reports for the U.S. Army, Skochko and Greveris[6,7] developed the theory for predicting the pressure wave in small caliber firearms for subsonic projectiles and evaluated 13 firearm suppressors. Five meters to the side of the guns, they estimated that the suppressed noise levels ranged between 100 and 124 dB peak SPL and the effectiveness of the suppressors ranged between 7 and 35 dB.

In a series of studies, Pääkönen and Kyttälä evaluated several small caliber firearms and suppressor models for the suppressed and unsuppressed condition with high-velocity and subsonic ammunition.[8–11] For some of the firearms they evaluated, the suppressor was integrated into the design of the barrel. They recorded sound levels at the shooter's position and at 1 and 10 m to the side of the shooter. At the shooter's ear, the reduction of the sound exposure levels calculated with 1-second duration ranged between 8 and 25 dB. At 10 meters to the side, reductions between 4 and 32 dB were observed. Pääkönen reported the reduction as a function of the angle around the shooter at a distance of 15 m with an M62 rifle with unsuppressed high-velocity ammunition, suppressed high-velocity, and suppressed subsonic ammunition.[10] Reductions of 30 dB in the peak sound pressure levels were observed for some angles to the side and behind the shooter. Peak sound pressures were not attenuated significantly in the 50-degrees surrounding the axis of fire, presumably due to the ballistic shock wave. Pääkönen reported measurements at the shooter's left ear and on a semicircle of 10-m radius centered on the muzzle to the left of the shooter with 45° spacing. They measured between 18 and 41 dB reduction in peak levels and between 13 and 34 dB reduction in the sound exposure levels for the unsuppressed supersonic and the suppressed super and subsonic conditions.[8]

Lobarinas et al. reported the noise reductions at three positions for five suppressors with a .223 caliber, AR-15 rifle and four suppressors with the .300 caliber, AAC Blackout 300 rifle: 1 meter to the left of the muzzle, at the shooter's right and left ears.[12] They reported unweighted, peak and C-weighted reductions for the suppressors. Depending upon the length of the barrel for the AR-15, the peak level reductions ranged between 20 and 25 dB at the 1-m position, between 15 and 25 dB at the left ear, and between 6 to 9 dB at the right ear. For the AAC Blackout 300, the reductions ranged from about 15 and 27 dB peak at the 1-m position and about 16 and 20 dB for the ear positions. One interesting finding from their study is that the reductions at the right ear were less than the reductions at the left ear for the AR-15 firearm. The gas ejection port on the right side of the weapon was identified as the probable cause of the higher peak sound pressure levels on the right versus left side of the weapon.

Murphy et al.[5] reported measurements from four firearms measured in the suppressed and unsuppressed conditions with high- and low-velocity ammunition. Reductions near the ear of the shooter ranged from 17 to 24 dB peak SPL and reductions in the A-weighted 8-hour equivalent energy ranged between 9 and 21 dB. One of the research gaps identified in their work was specifying the optimal location for assessing the performance of firearm suppressors. Optimally, the location would be robust to changes in the directivity of the firearm noise and the N-wave produced by a supersonic projectile. As Murphy et al.[5] demonstrated in their sound power measurements with a hemispherical microphone array, the high frequency content of the N-wave must be removed to properly analyze the effect of the suppressor on overall sound power/emission. The outward propagation angle of the N-wave in the forward direction, θ, depends upon the speed of sound, c, and supersonic projectile velocity, v_{bullet}, where $\theta = \cos^{-1}(c/v_{\mathrm{bullet}})$, so the

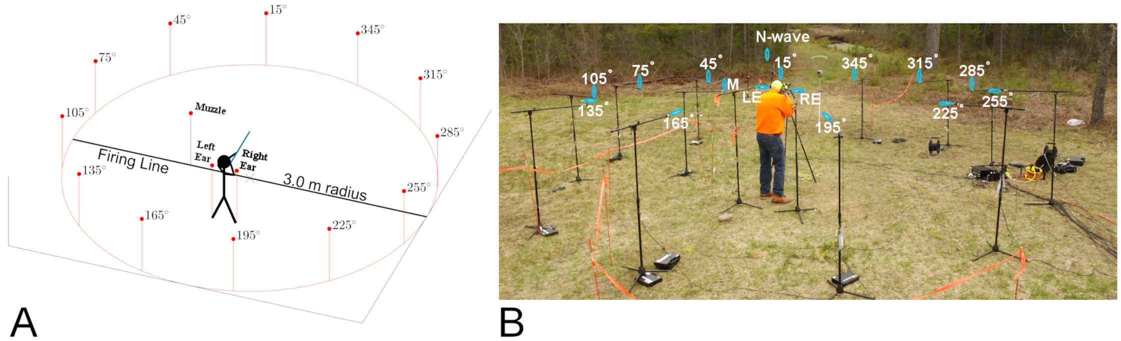

Figure 1: The orientation of the microphones for the ring, muzzle and ear level microphones. Panel A is a schematic arrangement of the microphones and the panel B is a photograph of the actual microphone array with a shooter and chronograph. Twelve microphones were positioned at 3-m radius centered on the muzzle with a 30° spacing at 1.6 m above the ground. Two microphones were positioned 15 cm from the shooter's ears. A trigger microphone was positioned 1 m to the left of the muzzle and a microphone was placed 10 m downrange at 15° off the direction of fire. Each microphone in the photograph is marked with a cyan ellipse. The chronometer to track bullet speed is visible between the 15° and 345° microphones. Photo credit by Donald S. Finan, Univ. Northern Colorado.

N-wave is generally not detected at every microphone position even with supersonic bullets. The noise reduction of supersonic rounds was not as great as it was for subsonic rounds, even when the N-wave was removed (zeroed) in the waveform recording.

The NATO AEP-4875 standard is the only standard to specify a method to assess firearm suppressors.[13] The NATO method specifies that the measurements be made at a minimum of 4 meters above the ground with microphones positioned at the height of the muzzle at a distance of 5 m in a ring. The NATO method mitigates two factors. First the ground reflection is delayed by increasing the path length of the reflected wave relative to the direct path of the muzzle blast and N-wave. Second, having the microphones further away potentially allows the N-wave and its ground reflection to occur before the muzzle blast arrives. The N-wave does not contribute to the hearing hazard for the shooter because it propagates as an expanding cone with its base at the muzzle and apex at the bullet. In some instances where a team is advancing on an objective through a leap-frog maneuver, the forward squad may be exposed to the N-wave if supersonic ammunition is used. Although the NATO method may be sufficient for the purpose of a "pure" comparison of suppressors, that comparison does not include sound sources that are important for determining auditory risk. Ground reflections of the suppressed muzzle blast substantially affect estimates of auditory risk for the shooter. The noise reduction of suppressors tested will depend upon the surface over which they are fired. Asphalt or concrete would tend to reflect more energy than a grassy or sandy surface.

B. PURPOSE

This investigation included several rifles and pistols with firearm suppressors using high- and low-velocity ammunition to understand how suppressors can be included in hearing loss prevention programs as a noise control. The reductions in peak and exposure levels, ΔL_{Peak} and ΔL_{Aeq}, were measured. The angular dependence of suppression from each firearm was evaluated in the suppressed and unsuppressed conditions to determine which positions would be appropriate to use as a performance metric that would inform the development of an acoustic measurement standard.

2. METHODS

A. FIREARMS AND SUPPRESSORS

A convenience sample of four pistols, nine rifles and one shotgun were evaluated with and without suppressors and with low- and high-velocity ammunition (see Table 1). The muzzle velocities of the rounds are listed for each ammunition type. The velocity of the rounds were measured with a chronograph approximately 3 meters in front of the shooter and are reported in Table 1. Four of the "supersonic" conditions were not supersonic, so we will refer to low- and high-velocity ammunition. Each firearm was discharged with two nominal ammunition velocities: subsonic and supersonic, where the speed of sound for that day was nominally c = 338m/s, 1109 fps). Specifically, the .22 long rifle ammunition and the .45 ACP ammunition for the Kimber pistol were not supersonic when measured with a chronograph. The single horizontal line in the tables separates the high-velocity conditions when the rounds were not supersonic. The Daniel Defense Ambush A11 rifle was only fired with high-velocity supersonic ammunition because it was not designed to operate with low-velocity ammunition.

The firearms were shot from a tripod shooting stand. The end of the muzzle was positioned above the center of the 3-m ring with a plumb bob prior to each suppressor and ammunition condition. Masking tape was place on the forestock of the rifles to facilitate positioning the rifle in the same location due to the recoil of the weapons. Nominally, the height of the muzzle was 1.6 m above the ground. Slight variations occurred with the shooter and the weapons. Five shots were fired in each condition. In most cases, the suppressors increased the bullet velocity by a fraction of a percent to as much as 6% (see Table 1). The firearms and suppressors were provided by representatives from the American Suppressor Association and GSL Technology Inc. The representatives had no role in the data analysis or interpretation of the results. The firearms were fired by two of the authors (MS and JL). The suppressors were generally of the same caliber as the rifle or pistol being fired with the exception of the Ambush A11 rifle, where the suppressor's bore was 7.62 mm and the barrel's bore was 6.8 mm. The results for the shotgun will be included in a future report.

B. DATA ACQUISITION AND ANALYSIS

All of the measurements were conducted at a hunting camp near Rudyard, MI. An array of 16 microphones was used (see Figure 1). In panel A, the schematic of the microphone array is provided to facilitate interpretation of the photograph of the actual arrangement. Panel B shows the actual microphone array with each microphone and its orientation indicated by a cyan ellipse. Twelve microphones were positioned in a 3-m radius ring centered on the muzzle of the firearm, 1.6 m above the ground with a 30° spacing. The line of fire was directed between two of the forward microphones. Two microphones were positioned 15 cm from the shooter's right and left ears. One microphone was positioned at 1 meter, 90° from the line of fire to the left of the muzzle at 1.6 m above the ground. The final microphone was positioned 10 m down range, 15° to the left of the direction of fire 1.6 m above the ground (not depicted in the schematic). Microphones in the forward portion of the ring and the muzzle microphone were 1/8-inch G.R.A.S. 40DP or 4138 Brüel & Kjær (B&K) microphones. The microphones at the shooter's ears were B&K 4135 1/4-inch microphones. The microphones in the rear half of the ring were G.R.A.S. 40BE, 40BD or B&K 4135 1/4-inch microphones. The down range microphone was a 1/2-inch 40AO G.R.A.S. microphone. The chronometer is shown in the lower panel of Figure 1. For the rifles and pistols, the chronometer was read by the shooter after each shot was fired and recorded in the log book. It was located at 3 meters from the ring center.

Signals from the microphones were measured with a combination of National Instruments (NI) PXIe-4464 and PXIe-4499 boards, The forward microphones and the muzzle microphone were sampled with the PXIe-4464 boards since the dynamic range for those devices was ± 42 volts. The ear level and microphones in the rear section of the ring were sampled with the PXIe-4499 board with a ± 10 volt dynamic range. All channels were sampled with 24-bit resolution and 200 kHz sampling rate. The data acquisition software was custom developed in LabVIEW and stored the results to .TDMS format files.

The 90-ms analysis time window with 1-ms rise/fall times was established 5 ms before the onset of the impulse at the muzzle microphone and was applied to all microphones. The impulse at the 10-m microphone was delayed by about 10 ms depending upon the bullet velocity. The N-waves were included in all analyses. Peak levels were identified as the maximum pressure in the recorded signal. The L_{Aeq90ms} levels were obtained after applying a time-domain A-weighting digital filter to the entire recording and then integrating 90-ms samples at each microphone. Similarly, one-third octave band-pass filters with standard center frequencies from 20 Hz to 20 kHz were applied to the recordings and the 90-ms windows were integrated to determine the spectral outputs as a function of angle around the ring and at the other microphones.[14] The one-third octave-band analysis does not facilitate fine-structure spectral analysis of the interaction of the direct and ground-reflected waves. A fast Fourier transform would provide a more detailed spectral analysis. A wavelet analysis is better suited to the transient nature of the firearm impulses. These analyses are beyond the scope of this paper. Other weighting functions (C- and Z-weighting) have been applied, but are not reported. The A-weighted levels are useful for the damage risk criteria estimates in MIL-STD 1474E.[17]

Table 1: The firearms, suppressors, and ammunition velocities of low- and high-velocity ammunition measured with the chronometer used during this study. Four pistols and nine rifles and one shotgun were tested with low- and high-velocity ammunition. For four firearms, the high-velocity bullets were not supersonic ($v_{\text{bullet}} < 1109$ fps or 338 m/s). Firearms tested with supersonic high-velocity ammunition are below the single line in the table. The suppressor manufacturers are listed in the table's footnotes. Firearm type is indicated in the first column and pistols' manufacturer and model are italicized.

Firearm Type	Firearm Manufacturer & Model	Caliber	Suppressor Mfgr	Model	Low Velocity Unsupp/Supp fps	High Velocity Unsupp/Supp fps
Pistol	*Kimber GTSOC Pro*	.45 ACP	GSL[1]	Python	727 / 760	796 / 847
Pistol	*Walther P22*	.22 LR	GSL	Woodland	875 / 886	888 / 903
Rifle	Ruger 10-22	.22	AAC[2]	Element 2	1020 / 1020	1049 / 1045
Rifle	Ruger American	.22	Gemtech[3]	Outback II	1039 / 1060	1073 / 1079
Pistol	*Glock 19*	9 mm	YHM[4]	Sidewinder	911 / 899	1124 / 1126
Pistol	*Sig Sauer MPX-SA*	9 mm	GSL	Stealth	844 / 854	1177 / 1215
Rifle	Colt/Noveske M4 Carbine	.300 BLK	GSL	GT Mag	1005 / 1030	2120 / 2172
Rifle	Daniel Defense MK18	5.56 mm	GSL	GT-556	877 / 894	2554 / 2651
Rifle	DRD Tactical M762	.308	SilCo[5]	Saker 762	1096 / 1100	2572 / 2578
Rifle	Daniel Def. Ambush A11	6.8 mm SPC	SilCo	Saker 762	NA / NA	2617 / 2633
Rifle	Savage Arms 110	.338	GSL	Copperhead	917 / 912	2837 / 2876
Rifle	Savage Arms 10	.223	GSL	SWAT-5	1131 / 1135	2931 / 2998
Rifle	Rock River Arms AR-15	5.56 mm	GSL	Multi Cal	969 / 988	2963 / 3051
Shotgun	Remington Versamax	12 ga slug	GSL	Salvo 8/12	NA	1634*

[1]GSL Technology Inc., Jackson MI; [2]Advanced Armament Co., Huntsville AL;
[3]Gemtech, Eagle ID; [4]Yankee Hill Machine, Easthampton MA;
[5]SilencerCo., Valley City UT
*Estimated slug velocity based upon the relative arrival times of N-wave and blast wave.

3. RESULTS

A. IMPULSE LEVELS BY FIREARM AT THE EAR

The peak impulse levels for the unsuppressed and suppressed conditions for the right and left ears for both low- and high-velocity ammunition are presented in Table 2. The peak levels were averaged across all five shots for a condition to yield the mean and standard deviation. Peak levels for the unsuppressed conditions range from 143 to 166 dB peak SPL for low-velocity bullets and from 143 to 174 for high-velocity bullets. In the suppressed condition, the peak levels ranged between 121 to 150 dB for low-velocity ammunition and between 121 to 151 dB peak SPL for high-velocity ammunition. The four firearm conditions that were not supersonic exhibited almost no difference between the low- and high-velocity conditions. For the Colt/Noveske M4 Carbine and the Daniel Defense Ambush A11 rifles, the right ear in the suppressed conditions was about 8 to 12 dB higher than the left ear position. We attribute this difference to the location of the gas ejection port on the right side of these rifles.

Table 2 lists the A-weighted equivalent energy levels for the 90 ms time window, $L_{\text{Aeq,90ms}}$, at each ear, suppressor condition, and bullet velocity. The conversion factor of $-55.05\text{ dB} = \log_{10}(0.09/(8 * 3600))$ is used between the 90-ms and 8-hour allowable daily doses. To relate these results to the 8-hour exposure limit of 85 dB, any level above 140 dB would exceed the daily allowable exposure per the NIOSH recommendation.[15] With the exception of the high-velocity DRD Tactical M762 rifle, all of the unsuppressed, averaged levels were less than 140 dB, suggesting that one shot might be permitted. However, hearing protection should be worn because the unsuppressed peak levels

Table 2: The peak impulse levels, $L_{\text{Peak,Position}}$, and standard deviations, σ, for each ear, suppressor condition, and bullet velocity.

Firearm	Suppression	Low Velocity				High Velocity			
		$L_{\text{Peak,Position}} \pm \sigma$		$L_{\text{Aeq,Position}} \pm \sigma$		$L_{\text{Peak,Position}} \pm \sigma$		$L_{\text{Aeq,Position}} \pm \sigma$	
		Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
Kimber GTSOC Pro	Unsupp	165.6±0.3	165.9±0.2	133.9±0.4	134.0±0.8	167.5±0.2	167.6±0.3	135.0±0.5	136.4±0.5
	Supp	146.6±2.5	146.4±2.2	114.1±1.3	112.5±0.9	148.9±1.1	148.4±1.4	116.2±1.0	115.5±0.7
Walther P22	Unsupp	161.9±0.6	158.5±0.5	125.9±0.3	124.7±0.9	162.7±0.6	159.5±0.9	126.0±0.5	125.4±1.2
	Supp	130.4±1.9	131.7±2.8	100.7±1.0	101.5±2.3	132.6±3.1	132.5±2.0	100.2±1.5	102.4±1.5
Ruger 10-22	Unsupp	145.4±0.4	146.4±0.7	108.8±1.1	107.6±0.7	145.0±0.7	145.2±0.6	109.5±0.6	107.3±0.9
	Supp	126.1±3.4	128.4±4.3	98.9±1.0	97.5±2.4	129.2±4.7	126.9±3.6	99.1±2.9	98.7±3.1
Ruger American	Unsupp	143.8±1.0	143.2±0.6	106.0±0.7	104.6±1.1	144.5±1.0	143.1±1.2	106.3±1.2	104.6±1.0
	Supp	123.6±2.1	128.7±1.5	93.6±0.3	92.7±0.7	120.6±1.8	120.7±2.5	90.8±1.7	89.8±0.8
Glock 19	Unsupp	163.9±0.6	163.2±0.4	130.7±0.8	129.1±0.2	167.0±0.5	165.9±0.6	133.7±0.6	131.6±0.7
	Supp	140.4±1.9	138.1±1.8	104.4±1.0	103.1±0.7	146.1±2.3	146.3±1.3	113.7±1.0	118.8±0.8
Sig Sauer MPX-SA	Unsupp	163.2±0.7	161.6±0.4	127.4±0.5	127.3±0.9	164.7±0.5	161.2±0.6	130.1±0.2	129.0±1.0
	Supp	140.9±1.4	141.3±2.5	113.9±0.5	114.3±1.7	147.9±1.2	149.7±0.8	119.4±0.5	118.8±0.6
Colt/Noveske M4 Carbine	Unsupp	155.8±0.5	156.8±1.2	123.1±0.3	122.4±0.5	161.3±0.1	160.9±0.9	130.2±0.8	129.1±0.5
	Supp	137.4±1.0	149.6±2.9	110.4±0.7	114.9±0.6	139.8±0.9	151.3±1.1	114.5±0.4	122.0±0.8
Daniel Defense MK18	Unsupp	151.6±1.5	149.1±1.0	119.8±0.1	117.8±0.4	168.0±0.4	165.8±0.5	136.9±0.2	135.8±0.2
	Supp	127.9±1.8	120.9±2.0	95.1±1.2	92.4±0.6	149.8±0.9	149.6±2.1	117.3±0.5	120.1±0.9
DRD Tactical M762	Unsupp	163.1±0.4	164.0±0.5	132.9±0.3	130.5±0.1	173.1±0.3	174.2±0.2	143.8±0.1	142.7±0.2
	Supp	134.5±0.7	131.2±1.6	100.9±0.5	100.0±0.9	144.0±1.0	149.5±2.2	117.7±0.4	119.6±0.9
Daniel Def. Ambush A11	Unsupp	NA	NA	NA	NA	162.7±0.3	162.5±0.6	133.2±0.5	131.4±0.1
	Supp	NA	NA	NA	NA	142.8±1.7	150.3±1.9	114.5±0.1	118.4±0.8
Savage Arms 110	Unsupp	153.4±1.5	151.4±2.0	123.7±1.0	121.5±1.5	163.3±0.7	161.8±0.4	134.2±0.2	133.9±0.6
	Supp	133.9±1.4	130.5±2.0	103.0±0.5	99.2±0.9	141.0±1.5	138.6±2.9	116.3±0.8	113.9±0.8
Savage Arms 10	Unsupp	150.8±1.8	150.3±2.1	115.8±2.2	114.3±2.7	161.2±0.5	160.3±0.7	131.3±0.8	130.6±1.1
	Supp	126.6±1.5	123.1±1.9	93.1±1.2	93.3±1.0	135.9±0.9	134.7±0.8	108.8±0.5	106.9±1.2
Rock River Arms AR-15	Unsupp	144.2±1.5	144.4±2.2	111.3±0.9	110.4±0.6	163.4±0.5	161.8±0.4	132.7±0.4	132.1±0.3
	Supp	124.0±1.2	123.7±2.1	94.5±0.5	93.4±0.4	147.8±1.0	150.9±2.2	116.2±0.4	117.1±0.7

Table 3: The means and standard deviations, σ, of the reductions of peak sound pressure levels at locations relative to the muzzle for low- and high-velocity ammunition conditions. The eight microphone positions on the 3-meter ring 15° in front of the firing line and the six positions behind the firing line were averaged to yield $\Delta L_{\text{Peak,3m}}$. The $\Delta L_{\text{Peak,Muzzle}}$ is the microphone 1 m to the left of the muzzle. The right and left ear positions 15 cm from the shooter's ears were averaged to yield $\Delta L_{\text{Peak,Ear}}$.

Firearm	Low Velocity $\Delta L_{\text{Peak,Position}} \pm \sigma$ (dB)			High Velocity $\Delta L_{\text{Peak,Position}} \pm \sigma$ (dB)		
Microphone Positions	3m ring 8 mics	Muzzle	Ear L & R	3m ring 8 mics	Muzzle	Ear L & R
Kimber GTSOC Pro	16.6±2.0	17.2±0.8	19.2±1.8	14.7±0.7	17.4±2.0	18.9±0.9
Walther P22	29.8±2.6	28.7±4.2	29.2±2.2	29.5±3.3	28.0±4.2	28.5±2.4
Ruger 10-22	22.1±1.5	21.2±1.6	18.7±2.6	21.7±0.9	22.2±1.3	17.0±3.8
Ruger American	22.1±1.1	18.6±1.8	17.3±1.9	22.4±2.3	19.6±1.6	23.2±2.3
Glock 19	24.5±0.5	25.2±2.6	24.3±1.5	23.4±0.6	25.1±2.2	20.3±1.5
Sig Sauer MPX-SA	21.5±2.9	20.9±2.0	21.3±1.7	17.4±0.7	19.3±2.3	14.1±0.9
Colt/Noveske M4 Carbine	18.6±0.5	22.2±2.0	12.8±1.5	20.3±0.8	21.9±1.5	15.6±0.8
Dan. Def. MK18	25.4±1.0	28.2±1.9	25.9±1.5	24.4±0.4	24.2±1.1	17.2±1.4
DRD Tactical M762	26.5±0.8	23.7±1.9	30.7±1.0	25.0±0.9	18.5±1.3	26.9±1.2
Dan. Def. Amb. A11	NA	NA	NA	21.4±0.9	22.5±0.9	16.1±1.3
Savage Arms 110	18.0±0.7	18.7±0.9	20.2±2.0	19.8±1.4	18.7±0.9	22.8±1.3
Savage Arms 10	22.8±1.5	24.1±0.9	25.7±2.2	22.1±0.5	20.9±1.8	25.5±0.8
Rock River AR-15	23.3±1.2	23.9±1.9	20.5±2.4	19.9±0.9	18.3±1.3	13.2±1.5

were all above 140 dB, an accepted ceiling limit for peak impulse levels. Most of the suppressed equivalent energy levels were less that 120 dB and all were less than 125 dB SPL. Because the suppressed peak impulse levels were not all less than the 140 dB ceiling limit, hearing protection should still be used when firing a suppressed weapon.

B. SUPPRESSION EFFECTS BY FIREARM AND MICROPHONE POSITION

In Table 3 the reductions of peak levels provided by the suppressors at various positions are reported. The microphones from 75° to 285°, 15 degrees in front of the firing line and all of those behind the firing line, do not receive an N-wave. The suppression of peak levels tended to be the least at the ear-level microphones. One potential confounder in the ear-level microphones is the presence of gas ejection ports for the Daniel Defense MK18, Ambush A11, and Rock River Arms AR-15 rifles. The suppressor does not reduce any of the noise produced by the gas ejection port. The microphones on the ring and the muzzle microphone yielded very similar results. In some cases the averaged peak reductions at the ring microphones were more than the muzzle microphone. With the exception of the DRD Tactical M762 rifle, the values at the ring and the muzzle were within a few dB.

In Table 4, the reductions of A-weighted equivalent energy are presented ΔL_{Aeq}. Similar differences are observed in the change in energy as were observed for the reduction of peak levels. The ear-level microphones tended to exhibit less reduction than the muzzle or the average of the ring microphones from 75° to 285°. More reduction was observed at the ear for the Kimber, DRD Tactical M762, and Savage Arms 10 (high-velocity) firearms than for the other reported positions. The muzzle and ring microphone average reductions of equivalent energy for the low-velocity ammunition agreed within two to three decibels except for the Ruger 10-22, Savage Arms 10, and Colt/Noveske M4 Carbine rifles. The reduction of the equivalent energy at the ear was markedly lower for the Ruger 10-22, Ruger American, Sig Sauer MPX-SA, Daniel Defense MK18, and Rock River Arms AR-15 firearms. Again, this difference is likely due to the presence of gas ejection ports on these firearms.

Table 4: The means and standard deviations, σ, of the reductions of A-weighted equivalent sound pressure levels at locations relative to the muzzle for low- and high-velocity ammunition conditions. The eight microphone positions on the 3-meter ring 15° in front of the firing line and the six positions behind the firing line were averaged to yield $\Delta L_{\mathrm{Aeq,3m}}$. The $\Delta L_{\mathrm{Aeq,Muzzle}}$ is the microphone 1 m to the left of the muzzle. The right and left ear positions 15 cm from the shooter's ears were averaged to yield $\Delta L_{\mathrm{Aeq,Ear}}$.

Firearm	Low Velocity $\Delta L_{\mathrm{Aeq,Position}} \pm \sigma$ (dBA)			High Velocity $\Delta L_{\mathrm{Aeq,Position}} \pm \sigma$ (dBA)		
Microphone Positions	3m ring 8 mics	Muzzle	Ear L & R	3m ring 8 mics	Muzzle	Ear L & R
Kimber GTSOC Pro	19.2±1.8	19.6±2.3	20.6±1.1	17.9±0.9	19.1±0.8	19.8±0.8
Walther P22	28.4±1.6	31.5±2.4	24.2±1.7	28.6±1.7	31.7±2.4	24.3±1.4
Ruger 10-22	15.4±1.4	19.2±0.9	10.0±1.2	16.1±1.9	20.0±0.8	9.5±3.0
Ruger American	17.6±0.9	20.7±0.8	12.2±0.9	17.1±3.1	20.5±1.8	15.1±1.6
Glock 19	29.2±1.0	28.3±1.9	26.2±0.9	21.7±0.8	27.5±2.2	16.5±0.9
Sig Sauer MPX-SA	18.8±1.2	19.3±1.9	13.3±1.2	14.6±0.4	15.4±0.8	10.4±0.6
Colt/Noveske M4 Carbine	18.2±0.5	22.5±0.8	10.1±0.4	17.2±0.6	20.3±1.1	11.3±0.8
Dan. Def. MK18	29.3±0.4	31.4±0.7	25.1±0.8	22.6±0.5	24.2±0.9	17.7±0.6
DRD Tactical M762	27.2 + 1.4	26.0±0.7	31.2±0.6	23.0±0.4	18.3±0.4	24.6±0.6
Dan. Def. Amb. A11	NA	NA	NA	20.4±0.4	21.7±0.4	15.9±0.5
Savage Arms 110	20.4±0.7	20.1±0.7	21.5±1.4	17.2±1.0	16.8±0.9	18.9±0.8
Savage Arms 10	18.2±1.0	23.1±0.6	21.9±2.6	21.1±0.6	20.2±0.5	23.1±1.1
Rock River AR-15	21.1±0.7	22.2±0.6	16.9±0.8	18.0±0.8	17.6±1.3	15.8±0.6

C. DEPENDENCE OF SUPPRESSION BY FREQUENCY

In Figure 2, the noise reduction spectra for the Savage Arms 110 rifle with the .338 caliber Lapua, low-velocity ammunition. A color bar indicates the amount of suppression in each band, ranging from 0 (dark blue) to 40 dB (dark red). The twelve microphones on the 3-m ring are displayed in a circular array. The frequency bands range from 20 to 20,000 Hz progressing from the low frequencies at the center to the highest frequency band at the outside. Three dashed white lines indicate the 100, 1000, and 10,000 Hz bands. For the low-velocity condition, the greatest reductions were observed for the bands between 250 and 2000 Hz. In the forward direction, the greatest reduction was below about 1000 Hz. The noise reductions for the other four microphones are shown on the vertical stacked bars on the right of the figure. The 1-m muzzle microphone to the left of the firearm exhibits strong similarities with the 3-m microphones at 75° and 105°. Similarly, the microphones at the left and right ears exhibited strong similarity to the 165° and 195° microphones, respectively.

In Figure 3, the noise reduction spectra as a function of angle are shown for the Savage Arms 110 rifle with the .338 caliber Lapua, high-velocity ammunition. The amount of noise reduction is markedly less than what was observed for the low-velocity ammunition. The reductions of equivalent energy in the forward directions (45°, 15°, 345°, and 315°angles) are significantly lower due to the presence of the N-wave. The muzzle microphone appears to have the closest similarity to the 105° microphone. The left and right ear microphones have very similar noise reduction patterns to the 165° and 195° microphones, respectively. A formal test of correlation has not been performed at this time.

D. MARGINAL EFFECTS FOR SUPPRESSORS

In Figure 4, the average (marginal) equivalent levels across the rifles and pistols were determined with a multilevel linear regression model accounting for correlated observations associated with each discharge. In the left panel, the red line is the unsuppressed average equivalent A-weighted level and the blue line is the suppressed average equivalent

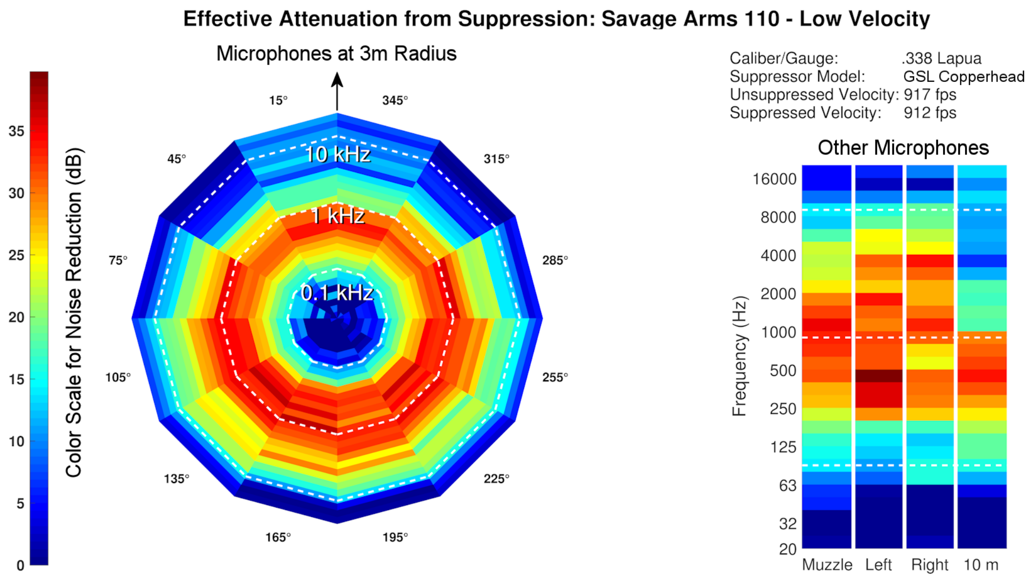

Figure 2: The frequency dependent response of the suppressor as a function of angle and four additional microphones for the Savage Arms 110 rifle .338 caliber Lapua, low-velocity ammunition. The impulse signals were filtered with one-third octave band filters to yield the spectra for the unsuppressed and suppressed conditions. The noise reduction spectra are plotted in color where blue is the least suppression and red is the greatest suppression. The direction of fire is towards the top of the circle. The muzzle, left ear, right ear, and 10-m downrange microphones have separate bars on the right of the figure.

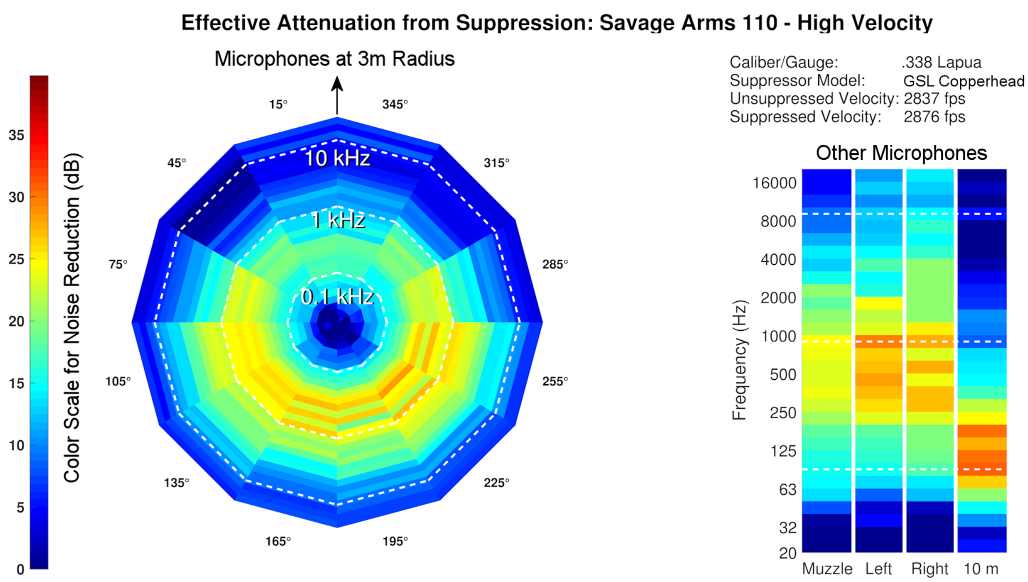

Figure 3: The frequency dependent response of the suppressor as a function of angle and four additional microphones for the Savage Arms 110 rifle .338 caliber Lapua, high-velocity ammunition. The impulse signals were filtered with one-third octave band filters to yield the spectra for the unsuppressed and suppressed conditions. The noise reduction spectra are plotted in color where blue is the least suppression and red is the greatest suppression. The direction of fire is towards the top of the circle. The muzzle, left ear, right ear, and 10-m downrange microphones have separate bars on the right of the figure.

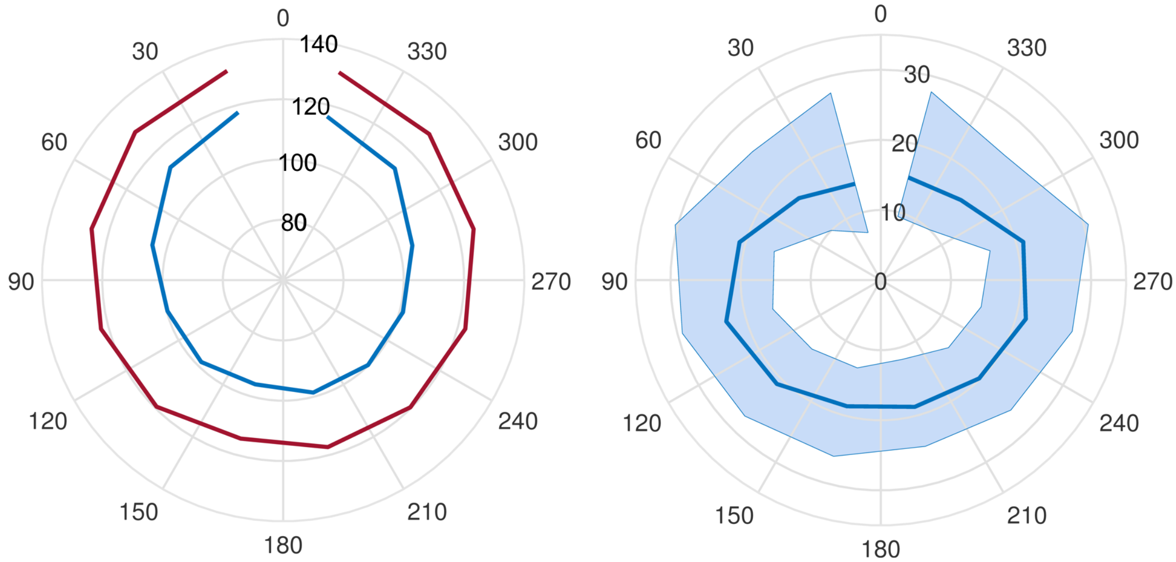

Figure 4: The average levels of the unsuppressed and suppressed A-weighted equivalent levels as a function of angle (left panel) and the marginal reduction in the equivalent levels (right panel). The red line is the unsuppressed average equivalent A-weighted level and the blue line is the average suppressed level in the left panel. In the right panel, the differences between the unsuppressed and suppressed level are shown with the thick blue line as a function of angle. The shaded region of the image depicts the range of effective suppression measured in this study. No distinction has been made between low- and high-velocity ammunition.

A-weighted level. In the right panel, the marginal influence of the suppressors on the equivalent A-weighted level is represented after controlling for the main effects of ammunition velocity, and the main and interactive effects of firearm and suppressor model as a function of angle relative to the line of fire. The shaded region of the image depicts the range of effective suppression measured in this study. Generally, greater reductions are observed to the side of the weapons than in the rear direction. The range in the forward direction (top of the figure) is larger due to the N-wave. Predictive marginal values such as those represented in the right panel of Figure 4 generalize beyond the conditional combinations of firearm, suppressor, and ammunition obtained in this study (see Korn and Graubard, p. 126 for a more detailed discussion of predictive margins[16]). These marginal effects are intended to represent the mean and range of reductions to equivalent A-weighted levels that might be expected across widely-varying combinations of firearm and suppressors relying on similar design principles to those used in this study. With the exception of a small range of angles near the line of fire, the predictive margins suggest that suppressors of this type can provide between approximately 11 and 30 dB of reduction to equivalent A-weighted levels.

4. DISCUSSION

As noted in the introduction, firearm suppressors represent an engineering control that reduces the noise exposure for the firearm user and also for bystanders. Conservation, safety, law enforcement, and military personnel typically have a requirement to demonstrate firearm proficiency on an annual basis. Proficiency is maintained through practice, often involving firing hundreds of rounds. A reduction of 20 to 30 dB substantially reduces the noise dose. Murphy et al. reported that as much as a 40-dB reduction in the peak level could be achieved between a combination of firing with a suppressor and the use of subsonic ammunition.[5] Figure 2 exhibits greater reduction at the lower frequencies between about 160 to 1000 Hz. The suppressed high-velocity round has a similar spectrum to the unsuppressed low-velocity round. For that particular example, the suppression of the total energy was about 30 dB.

Currently only the NATO standard describes a method to characterize the performance of a firearm suppressor.[13] This method does not however provide a noise reduction rating like that reported for hearing protection devices.[17,21] Instead, it computes the sound exposure level for a 12.5 ms window and removes ground reflections and N-waves from the analysis. Our left and right ear data can be compared to positions on the 3-m ring to identify the best match to the ear positions. In the suppressed condition, gas ejection ports for semi-automatic firearms may increase the exposures at the ear on the same side of the weapon. The position of the muzzle relative to the ear microphones required constant adjustment of the ear microphones for each firearm and suppressor condition due to the different lengths. In our method, the muzzle was always located at the center of the ring. Well-defined positions for the muzzle and the measurement microphones will facilitate creating a standard that minimizes the potential for different results due to the microphones being moved between shots. The suppression measurements at the 3-m ring can be compared with those measured at the ear to determine which position yields the best correlation with the ear-level measurements. A standard location near the weapon, but less affected by the near field effects due to the gas ejection port or shadow effects of the shooter could facilitate comparisons of the same suppressor on different weapons.

Fackler et al. demonstrated the single number impulse peak insertion loss fails to capture the spectral variations of hearing protection devices and impulses.[21] A spectral impulse noise reduction metric resolved differences across sources and levels for hearing protection. The spectral noise reductions given in Figures 2 and 3 provide information that is compatible with the hearing protector noise reduction data. The noise spectra of the weapon can be measured, combined with the noise reduction spectrum of the firearm suppressor and then the noise reduction for the hearing protector can be applied to estimate suppressed, protected exposure levels.

The dependence of suppression effectiveness with angle is a factor that must be considered in future studies. Suppressor manufacturers need a standard procedure that characterizes the performance of their product and which provides for validation and comparison with other products. Firearm suppressors are sometimes tested by the manufacturer according to MIL-STD 1474.[17] Although both MIL-STD 1474D and MIL-STD 1474E describe measurements of impulse noise, neither version describes how to assess a firearm suppressor.[17,18] MIL-STD 1474E describes microphone placement 15 cm from the subject's ears. Several heights are indicated: prone 0.33 m, sitting 0.80 m, kneeling 1.24 m, and standing 1.60 m. This study only examined the standing position. A lower height would reduce the delay of the ground reflection relative to the peak due to the shorter path length difference. It would also introduce changes in the spectral fine structure due to the comb filter effect.[19]

Nearly every unsuppressed firearm tested by this research group produced impulses at the ear in excess of 140 dB peak SPL.[1,2,4,5] Hearing protection should be worn regardless of the firearm. If the impulse levels are below about 150 dB peak SPL, then single protection may afford adequate protection to the shooter. Most rifles, shotguns and some pistols can produce levels in excess of 160 and 170 dB peak SPL.[1,2,4] A properly worn earplug or earmuff can yield 25 to 35 dB of noise reduction. Thus for a limited number of shots (< 10), the dose might not exceed a daily limit. Unfortunately, numerous studies have identified that hearing protection is frequently worn improperly if at all. Murphy et al. found that about 50% of hearing protector users achieved less than 25 dB of noise reduction for a range of earplugs.[20] If a firearm suppressor were combined with hearing protection, the risk of hearing loss would be significantly reduced. The suppressor may provide 20 to 30 dB of noise reduction and the hearing protection and additional 10 to 30 dB reduction. Unfortunately reducing the single shot peak level below 140 dB or integrated energy to less than 85 dBA does not make the use of a firearm inherently "hearing safe." The damage risk criteria include the contribution of multiple shots (e.g. $10\log_{10}(N)$). Firearm users need to be aware of how many rounds they expect to fire during training. Big game hunters may only fire one or two rounds, whereas a police officer may fire hundreds of rounds. The additional impulse reflections within a typical indoor firing range increase the exposure for the shooter.

The noise reduction of suppressors is frequency dependent. The greatest reductions occur in the low to mid range frequencies, 160 to about 1000 Hz. Small caliber firearm discharges tend to peak in the 800 or 1000 Hz bands, but the resonance of the outer and middle ear can amplify the spectral content in the 2000 to 4000 Hz region. Thus, the spectral performance of a suppressor combined with the noise reduction of a hearing protector and the spectrum of the firearm all need to be included in the determination of the risk for noise exposure. Fackler et al. developed an impulse spectral insertion loss method that can be directly applied to the suppressor's spectral reduction.[21] The unsuppressed spectrum should be adjusted by both the suppressor's response and the response of any hearing protector to determine the noise exposure for the shooter or bystanders.

The suppressors and firearms used in this study represented a range of commonly used calibers and firearms. The Saker 762 suppressor was tested on two rifles (DRD Tactical M762 and Daniel Defense Ambush A11) with different caliber ammunition. The .308 caliber rounds for the M762 match the 7.62 mm diameter of the suppressor's bore, but the 6.8 mm rounds used with the Ambush A11 are smaller than the suppressor's bore and yielded less effective noise reduction. Similarly, the SWAT-5, GT-556 and GSL Multi-Cal (.300 bore) were used with 5.56 mm and .223 caliber ammunition. The GT-556 and SWAT-5 suppressors have the same internal baffle design, but the GT-556 screws onto the barrel while the SWAT-5 is a quick connect design. The GT-556 tended to have more noise reduction at the average of the ring microphones and muzzle, but not at the ear. This difference may be due to the bolt action of the Savage Arms 10 rifle. The Multi-Cal suppressor with its larger bore size exhibited less suppression for the 5.56 mm ammunition when compared to the GT-556 suppressor. This difference could result from the mismatch in the bore of the suppressor and the caliber of the bullet.

The analysis of the shots for this paper included all of the shots for each firearm and suppressor. Suppressors that have not been recently fired often exhibit a louder impulse on the first shot than for subsequent shots referred to as *first pop*. No effort was made to distinguish between first shots and subsequent shots to minimize the *first-pop* effect reported for suppressors. When a shooter fires the weapon, they are not typically going to fire one practice round to eliminate the *first pop* and then make all other shots in short succession. If the firearm doesn't cycle the next round(s) effectively, the delay allows air exchange in the internal volume of the suppressor between shots. The oxygen-depleted gases within the suppressor canister are thought to diminish the combustion of powder within the can, leading to reduced levels after the first shot. The standard deviations for the peak levels in Table 2 tended to be higher for the suppressed conditions than the unsuppressed conditions across the microphone positions. The exposure levels, L_{Aeq}, do not exhibit a consistent trend of suppressed levels having greater variability, which could be due to integrating the energy versus measuring a peak level.

5. CONCLUSION

This paper provides preliminary analysis of the data collected at the Rudyard, MI hunting camp. Many of the items identified in the discussion are potential topics for future analysis and research. The effectiveness of firearm suppressors varies with the weapon and load of the ammunition. Where one is located relative to the discharge and the direction of fire can drastically affect the noise reduction of the suppressor. For an acoustic standard that suppressor manufacturers could use on an ongoing basis, the microphone location that seems to yield the greatest noise reduction might be to the side. The shooter's ears are not in that location. This study would agree with the MIL-STD 1474E that the microphone(s) be positioned near the shooter's ears to best characterize the risk. An alternative that would be more easily configured might be two microphones positioned 2 or 3 meters behind the muzzle at an angle comparable to the 165° or 195° positions used in this study.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

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