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Assessment of Noise Exposure for Indoor and Outdoor Firing Ranges

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The National Institute for Occupational Safety and Health (NIOSH) received an employee request for a health hazard evaluation of a Special Weapons Assault Team (SWAT) in January 2002. The department was concerned about noise exposures and potential hearing damage from weapons training on their indoor and outdoor firing ranges. NIOSH investigators conducted noise sampling with an acoustic mannequin head and 1/4-inch microphone to characterize the noise exposures that officers might experience during small arms qualification and training when wearing a variety of hearing protection devices provided by the department. The peak sound pressure levels for the various weapons ranged from 156 to 170 decibels (dB SPL), which are greater than the recommended allowable 140 dB SPL exposure guideline from NIOSH. The earplugs, ear muffs, and customized SWAT team hearing protectors provided between 25 and 35 dB of peak reduction. Double hearing protection (plugs plus muffs) added 15–20 dB of peak reduction.

Keywords firing range, hearing loss, hearing protection devices, impulse noise

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INTRODUCTION

Noise exposure due to weapons fire has often been cited as a source for noise-induced hearing loss.(1) Coles et al.(2) summarized the findings of several studies with a wide range of impulsive noise exposure. Typically, impulses due to the discharge of a small-caliber weapon exceed peak sound pressure levels (SPL) of 140 decibels (re 20 μPa) and frequently will exceed 160 decibels depending on the caliber and the amount of gunpowder used. Coles et al.(1) reported peak impulse levels of 159 and 160 dB SPL for the American M-14 and British L1-A1 7.62 mm rifles. Plomp and colleagues(3,4) reported incidence of temporary and permanent hearing loss among weapons instructors during routine testing and qualification. These losses may be a result of exposure to multiple weapons and repeated exposure without proper hearing protection.

Peak sound pressure levels exceeding 185 dB can cause pneumatic injury to internal organs. Johnson(5) proposed limits of exposure for nonauditory injuries for blast overpressure for sound pressures substantially above those produced by small arms based on the log of the A-duration and the number of impulses:

$$\text{Maximum peak pressure} = 195 - \log(\text{A-duration}) - 2.5\log(N)$$

for A-durations <10 ms, and

$$\text{Maximum peak pressure} = 185 - 2.5\text{Log}(N)$$

for A-durations greater than 10 milliseconds, where A-duration is the time from the onset of the positive pressure of impulse until the pressure goes negative, and N is the number of impulses. This exposure limit coupled with an analysis of the hearing threshold shifts was suggested as a practical approach to hearing loss prevention for persons exposed to potentially harmful blast overpressures. Kardous et al.(6,7) recently surveyed noise exposures for law enforcement officers with the U.S. Immigration and Naturalization Service. Peak noise exposures ranged from 147 to 157 dB SPL depending on the weapons: Beretta 0.40 caliber pistol, M4 rifle, or Remington 870 12 gauge shotgun.

The National Academies Institute of Medicine recently completed a review of noise and military service.(8) One of the most striking statistics is the cost of compensation to the Veterans Administration for service-related hearing loss that totaled approximately $660 million for hearing loss and an additional $190 million for tinnitus at the end of fiscal year 2004. Fleischer and Muller[9] have proposed that lack of exposure to continuous noises common in industrialized society resulted in an increased susceptibility among nomadic Tibetan populations where their only exposure was apparently impulse noise from guns and fireworks.[9] Exposure to lower levels of continuous noise that do not present a risk of hearing loss can condition the cochlea against damage when exposed to higher levels of impulsive noise.[10–12]

Whereas the risk of hearing loss due to weapon exposure is greater among military personnel than for other occupational sectors, law enforcement officers have similar requirements to maintain proficiency with a variety of weapons, primarily in small caliber pistols, rifles, and shotguns. Consequently, the incidence of service related hearing loss can be expected to be greater for law enforcement officers.

In January 2002, the National Institute for Occupational Safety and Health (NIOSH) responded to a request for a health hazard evaluation (HHE) from the employees and management of a 148-member city police department who were concerned about potential hearing damage from noise generated during weapons training on their indoor and outdoor firing ranges. Questions were also raised about the adequacy of recently purchased custom hearing protection devices (HPDs) for use during training and deployment.

Because a SWAT team member from a nearby jurisdiction incurred a permanent hearing loss after firing his weapon in an enclosed space, the requesting department purchased a number of ESP-Elite in-the-ear assistive listening devices for shooters (Electronic Shooters Protection, Brighton, Colo.) that attenuate sounds whose levels exceed 90 dB SPL and amplifies lower level sounds. ESP manufactures two models that use miniature electronic circuitry in a custom-molded earpiece. The device can be worn either in the ear or behind the ear with a premolded earmold and allows the wearer to still wear standard goggles and helmets without interference. The device has compression circuitry, an attack time of 1 ms, and a release time of 400 ms.

The maximum output saturated sound pressure level (SSPL90) is 93 dB, and the high-frequency average (HFA) output sound pressure level (OSPL90) is 88 dB. The high frequency average maximum gain is 22 dB. Despite the manufacturer's claims, the officers remained concerned about the potential for hearing loss during training and deployment and some complained of increased sensitivity to loud noise after wearing the ESP-Elite for a while.

To explore this question, measurements of the noise signature from the department's weapons were made during shooting exercises at both the indoor and outdoor firing ranges. Simultaneous measurements of the protection offered by various HPDs and the noise levels produced by the weapons were collected using an acoustic mannequin.

METHODS

Noise Measurements, Equipment, and Calibration

An external microphone and mannequin were positioned 1 m to the left of each shooter. Acoustic recordings were made with a Tascam (Montebello, Calif.) DA-P1 Digital Audio Tape (DAT) recorder (48 kHz sampling rate and 16-bit resolution). The mannequin, (French German Research Institute de Saint Louis) consisted of a HEAD Acoustics (Brighton, Mich.), acoustic pinnae and ear canals, Brüel and Kjær (Norcross, Ga.) 4157 middle ear simulator, and a Brüel and Kjær 4165, $^1/_2$-inch microphone and was designed to measure impact and impulse noise.[13,14] The maximum measurable peak sound pressure level was 148 dB (dB SPL re 20 micropascals [μPa]). Because the mannequin measurements were performed under hearing protection, the maximum SPL was not exceeded. The sound outside the hearing protector was recorded using a Brüel and Kjær 4136, $^1/_4$-inch microphone (maximum SPL of 172 dB) 6 cm from the right side of the mannequin head. The mannequin's ear canal and external microphone were adjusted to the same elevation as the ear canal of the shooter.

Both the mannequin microphone and the external microphone were calibrated with a piston-phone (Brüel and Kjær 4228) that produced a 124-dB SPL tone at 250 Hz. With the piston-phone running, the recording levels for the right (mannequin) and left (4136 microphone) channels of the DAT were adjusted to approximately 50 dB below the expected maximum signal levels (150 and 170 dB SPL, respectively).

Weapons and Protectors

Table I lists the 10 weapons used during the study. The department helped to select weapons from their inventory: 9 mm, 0.40, 0.45, 0.357 pistols; 12 gauge shotguns; and 0.223 assault rifles. Because several models were available at each caliber, the long- and short-barreled versions were selected to assess the effect of barrel length on the impulse peak level. The number of shots analyzed for each weapon varied between 146 and 160 shots for the indoor range and between 160 and 172 shots for the outdoor range. The variability of the number of analyzed shots was dependent on the quality of the recording of the weapon impulse.

For each protector reported in this article, five shots per condition were analyzed. More protectors were tested than are reported here. Data were also collected for Heckler and Koch (H&K) 53 and 36 assault rifles used by the SWAT team. Because of the expense of the frangible 0.223 caliber H&K ammunition, comprehensive measurements with hearing protectors at the indoor range were not practical. Furthermore, the use of nonfrangible ammunition at the indoor range could have perforated the steel collector plates in the bullet traps due to their higher velocity. At the outdoor range, seven weapons were used (Table II), but only the long-barreled models of the pistols were assessed.

Several types of hearing protectors were used at each firing range, the results for three types will be reported in this

TABLE I. Weapons Tested at the Indoor Firing Range May 2002

Manufacturer	Model	Caliber	Barrel Length (cm)	Weapon Classification	Shots Analyzed
Smith & Wesson	686	.357	6.35	Revolver	156
Smith & Wesson	586	.357	15.24	Revolver	157
Colt	1991-1A	.45	12.70	Semi-automatic pistol	154
Para-Ordinance	P10	.45	8.89	Semi-automatic pistol	154
Glock	27	.40	8.89	Semi-automatic pistol	160
Glock	22	.40	11.43	Semi-automatic pistol	156
Colt	Pocket 9	9 mm	6.35	Semi-automatic pistol	155
Sig Sauer	P228	9 mm	11.43	Semi-automatic pistol	149
Remington	11-87	12 gauge	45.72	Pump shotgun	146
Remington	870	12 gauge	45.72	Semi-automatic shotgun	155

article: the David Clark Company Model 27 (Worcester, Mass.) earmuffs; the Electronic Shooters Protection Elite; and the E •A•R Classic foam earplug (Indianapolis, Ind.). The David Clark Model 27 has a noise reduction rating (NRR) of 27 dB. The ESP-Elite did not have an NRR and was manufactured to fit the mannequin's pinna.

The E•A•R Classic has an NRR of 29 dB. The David Clark earmuffs were tested by themselves, in combination with the E•A•R Classic earplug, and in combination with safety glasses that produced a break in the seal between the earmuff cushions and the wearer's head. The ESP-Elite was tested by itself with three volume settings: Off, Unity gain, and Maximum volume. The E•A•R Classic was tested by itself.

For each hearing protector condition, each weapon was fired five times, at about 2-sec intervals to allow the reverberant response of the range to decay. The recording times on the DAT recorder and any misfires or weapon malfunctions were recorded.

Data Processing and Analysis

The DAT tape recordings were digitally transferred to ".wav" files using a Lexicon Core32 sound card (Bedford, Mass.). Each set of recordings was separated into a .wav file and directory. Next, the five-shot groups were isolated and saved as .wav files for analysis. Calibration tones were edited to select only the final portions of each channel's sample of the calibration signal, and levels were calculated for each microphone for use in the subsequent analysis.

A Matlab program (Natick, Mass.) was developed to examine the average signal level as a function of time, permitting identification of the beginning of each gunshot. Once the start of each gunshot was identified, a window of 42.67 or 170.67 ms was analyzed for the peak protected and unprotected noise levels, the one-third octave band spectra, and the attenuation spectrum of the hearing protector. Because reflections from other objects were largely dissipated, the shorter time window of 42.67 ms was used with the outdoor measurements. The one third-octave unprotected spectra from each weapon were averaged across recordings to estimate the mean spectra for each weapon.

Evaluation Criteria

When evaluating longer time records, the spectral response is often frequency weighted to yield the dB A-weighted response that is meant to approximate the risk of hearing loss as a function of frequency. For this article, the linear unweighted response will be used to report spectra of the gunshot impulse events. Also, the peak impulse level is determined both outside and underneath the hearing protection device. The difference between the unprotected and protected peak levels will be reported as the peak level reduction of the HPDs.

TABLE II. Weapons Tested at the Outdoor Firing Range May 2002

Manufacturer	Model	Caliber	Barrel Length (cm)	Weapon Classification	Shots Analyzed
Smith & Wesson	586	.357	15.24	Revolver	168
Colt	1991-1A	.45	12.70	Semi-automatic pistol	162
Glock	27	.40	8.89	Semi-automatic pistol	165
Sig Sauer	P228	9 mm	11.43	Semi-automatic pistol	167
Heckler & Koch	53	.223	21.59	Automatic rifle	167
Colt	AR-15	.223	50.80	Semi-automatic rifle	170
Remington	870	12 gauge	45.72	Semi-automatic shotgun	167

RESULTS

Peak Exposure Levels

Outdoor range measurements, where there are fewer reflected sound waves, provided a good approximation of expected results in an anechoic environment. The first impulse of the shockwave from the weapon muzzle was extracted for analysis. Because there was a drizzling rain at the time of the test, a fabric tent covered the shooting area. Though the ground, mannequin, tent, shooter, shooter's assistant, picnic table, and weapons were potential reflective surfaces, the side of the mannequin's head reflected the most energy (double peak at 1.82 ms). Figure 1 displays the protected and unprotected waveforms for a .357 Smith & Wesson 586 revolver at the outdoor firing range with a David Clark earmuff. The peaks at 3.58 and 4.23 ms appear to be reflected sound from the tent and the shooter, while the peak at 6.24 ms is consistent with the difference between the direct and ground-reflected paths.

The protected waveform resulting from the David Clark Model 27 earmuffs used when the Smith & Wesson 586 was fired yielded a peak protected level of 137.5 dB SPL, and resulting waveform was less sharply peaked than the unprotected waveform. Earmuffs generally resembled a low-pass filter that smoothed the jagged nature of the waveform. Although earplugs were not uniformly attenuating across frequencies, the increased attenuation at low frequencies resulted in waveforms that resembled a significantly attenuated unprotected waveform.

Figure 2 consists of two bar graphs showing the average and standard deviation of the peak sound pressure level measured at the indoor and outdoor firing ranges. For the indoor range (upper panel), the Smith & Wesson 586 and 686 revolvers produced sound pressure levels of 167.9 and 167.1 dB SPL, respectively. The Colt Pocket 9 and Para-Ordinance P10 pistols produced the next greatest peak pressure levels, 162.3 and 162.4 dB SPL, respectively. The remaining weapons at the indoor range produced peak pressure levels that ranged from 158.6 to 160.8 dB SPL. At the outdoor range (lower panel), the Smith & Wesson 586 revolver and the H & K 53 rifle produced the highest peak pressure levels, 168.6 and 166.8 dB SPL, respectively. The other weapons produced peak pressure levels that ranged from 159.0 to 161.5 dB SPL. For the indoor and outdoor ranges, approximately 160 shots were included in the mean and standard deviation for each weapon.

Weapon Spectra

Figure 3 displays the one-third octave band spectra of the weapons tested on the outdoor range. The horizontal lines represent 10 decibel intervals; the dark bar at the center of each spectrum is the 1000 Hz band. For most of the weapons, maximum sound level occurred between 500 and 800 Hz. With the exception of the Glock 22 and Colt 1991-A1, the SPL in the maximum band exceeded 130 dB SPL. The maximum energy of the Smith & Wesson 586 occurred at 2000 Hz.

The peak impulse sound level is based on the instantaneous sound pressure measured during the gunshot event. The one-third octave band analysis represents the average of the signal over the analysis window (42.67 ms). If a single gunshot is sampled with both a short and long time window, the long window, one-third octave analysis will yield lower estimates of the band levels. The overall energy will increase for a longer time window, but the average level will decrease due to the decay of the impulse with time. For this reason, the peak sound pressure levels are listed on the weapon spectra in Figure 3 rather than the logarithmic sum of the one-third octave bands.

Hearing Protection Device Attenuation

Figure 4 presents the averaged attenuation spectra across weapons for the David Clark earmuff and the E•A•R Classic earplug alone and in combination measured at both the indoor (50 shots) and outdoor (35 shots) firing ranges. For the David Clark muffs, the attenuation below about 500 Hz is less than that observed for the E•A•R Classic earplug. The combined attenuation is considerably improved for the high frequencies but will be practically limited by bone conduction.

Figure 5 presents the averaged attenuation spectra of 5 shots for the David Clark earmuff when used with safety glasses for the selection of weapons fired at the outdoor range. Two effects are observed in the curves. The low frequency (below 500 Hz) attenuation is reduced considerably relative to the about 10 dB of attenuation shown in Figure 4 for the earmuff alone. The high frequency region exhibits lower attenuation compared with the 30–40 dB in the 4000–10000 Hz region for the single muff. The small amount of gain (negative attenuation) between 100 and 250 Hz might be amplification due to the Helmholtz resonance of the volume under the earcup and the mannequin ear canal.

Figure 6 presents the averaged attenuation spectra across all weapons observed for the ESP-Elite on the indoor (50 shots) and outdoor (35 shots) ranges. For the most part there are small differences in the midfrequency region (2000–6300 Hz). The differences between the indoor and outdoor measurements could result from fitting effects (placement and replacement). The earpiece was fit in the mannequin's ear and the gain setting was made without removing the ESP-Elite device.

Figure 7 consists of two histograms. The first presents the maximum SPL output for the ESP-Elite, and the second presents the saturated SPL output. The saturated sound pressure level was the output of the ESP-Elite device based on the average of 1000, 1600, and 2500 Hz bands for a 90 dB input according to the ANSI S3.22-1996 standard for testing hearing aid characteristics.[15]

Figure 8 displays the maximum SPL reductions for the various hearing protection devices on both firing ranges.

DISCUSSION

Noise Measurements Peak Exposure Levels

Several considerations affect these data. First, the mannequin cannot duplicate the transmission paths of acoustic energy that reach the human cochlea. Because the mannequin was designed to have high isolation of the ear simulator, it provides an estimate of the air conduction pathway of the protector.

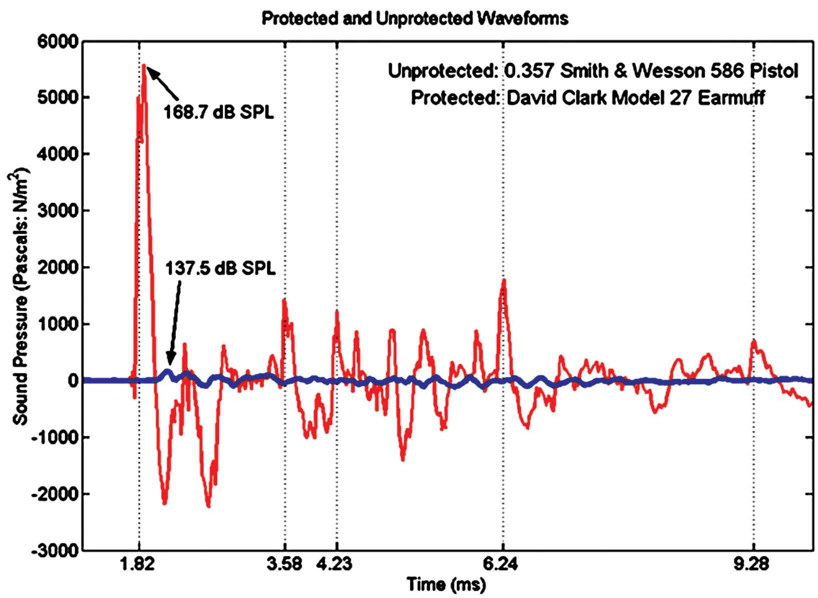

FIGURE 1. Outdoor recording of the unprotected and protected waveforms from the Bruel & Kjaer 4136 microphone and ISL mannequin. The lower amplitude trace is the protected waveform (mannequin) and the higher amplitude waveform is the unprotected (external microphone). The vertical dashed lines indicate the presence of reflected pressure waves from surrounding objects.

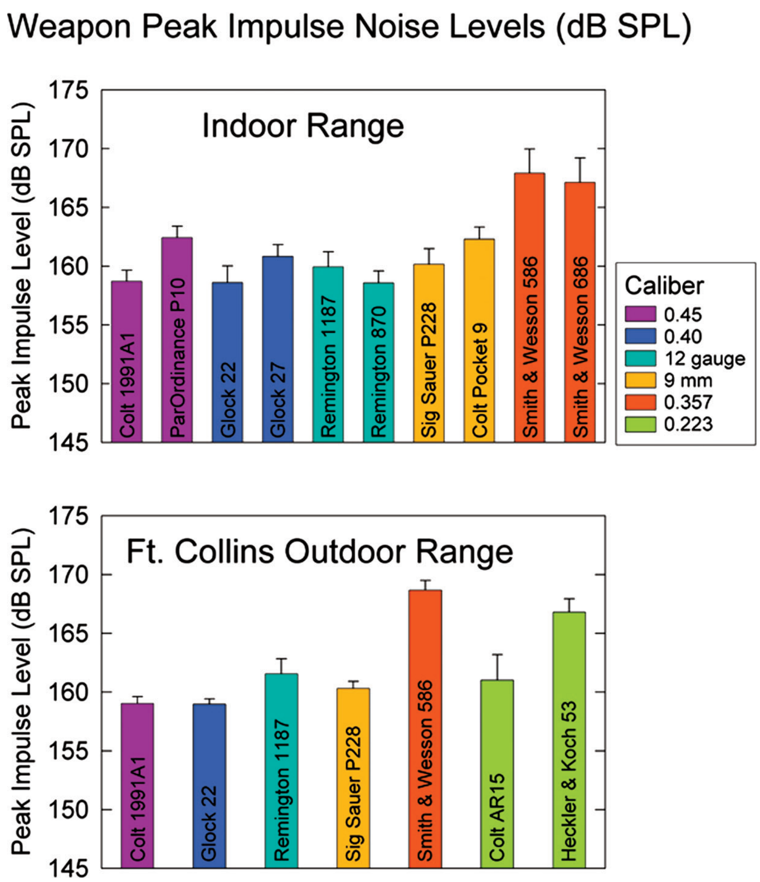

FIGURE 2. Peak impulse noise levels at the indoor and outdoor firing ranges for several calibers of weapons. Each mean and standard deviation was determined from about 160 shots from the same weapon.

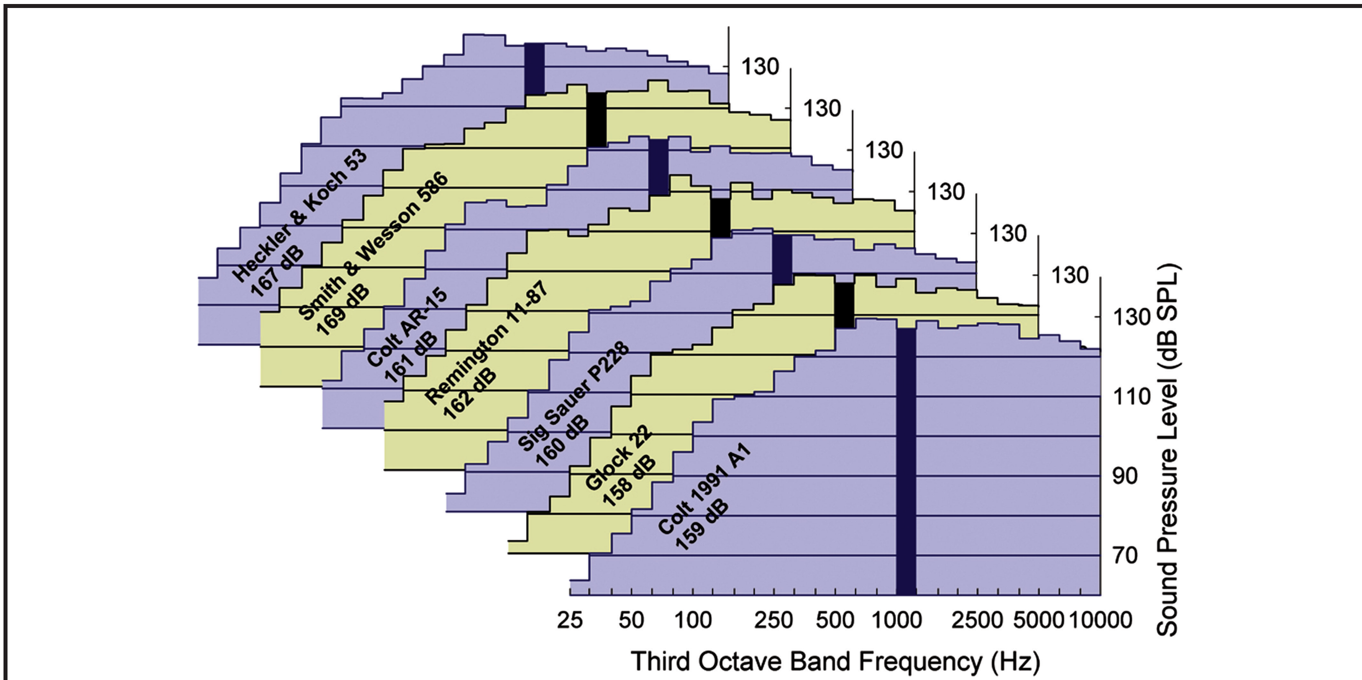

FIGURE 3. One-third octave band spectra for weapons measured at the outdoor firing range. The horizontal lines are spaced in 10-dB intervals. The dark bar in the center depicts the 1000 Hz one-third octave band.

However, transmission into the middle ear via the oral-nasal cavity or direct transmission to the cochlea via bone conduction will not be well characterized by these measurements.(16) Thus, the high frequency attenuation measured using the mannequin is not representative of the attenuation that will be found for humans subjects. Nevertheless, the peak level reductions observed using the mannequin may provide reasonable estimates of the air conduction performance of the protector for human subjects when well fit.

Second, hearing protectors may not provide the same attenuation for impulse noise as for continuous noise. For a high-level impulse from a weapon, a shock wave is created as the impulse

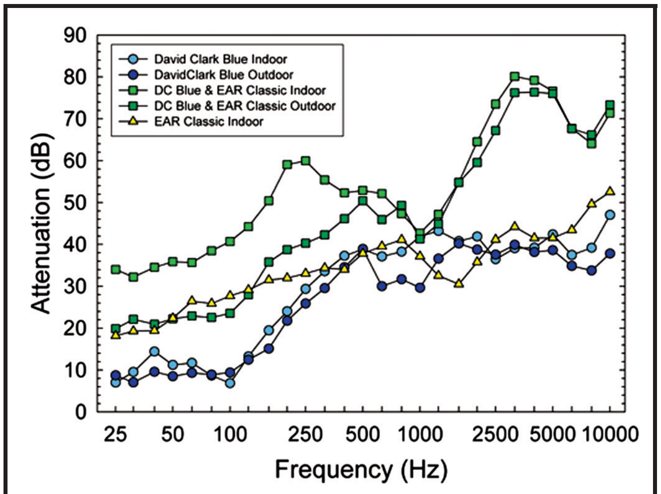

FIGURE 4. One-third octave band attenuation results for the David Clark Earmuff and E•A•R Classic Earplug. The one-third octave band attenuation spectra for the David Clark model 27 earmuff alone and in combination with an E•A•R Classic earplug are shown for the indoor and outdoor ranges

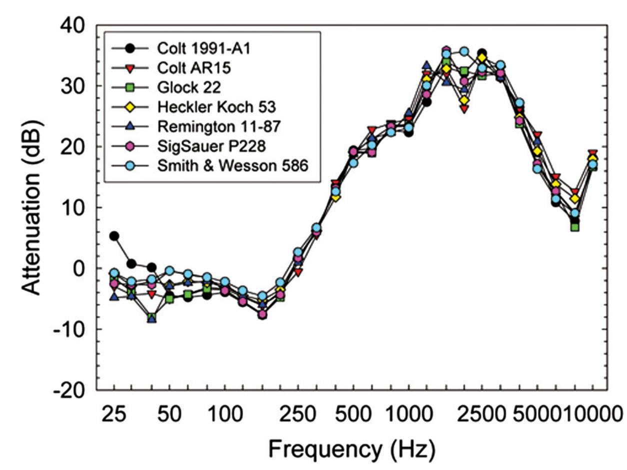

FIGURE 5. One-third octave band attenuation results for the David Clark Earmuff and safety glasses. A pair of safety glasses under the earmuff cushion created a leak for the David Clark model 27 earmuff. The different weapons are depicted with different symbols. The attenuations below 250 Hz are largely negative as a result of the leak. At 2000 Hz, the variation of the attenuations is larger than neighboring frequencies.

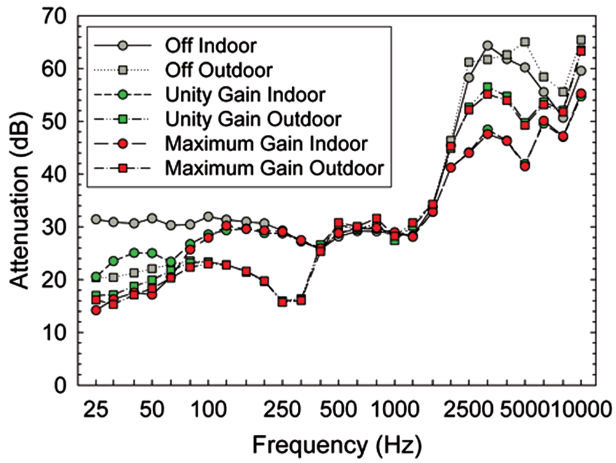

FIGURE 6. One-third octave band attenuation results for the ESP-Elite. The one-third octave band attenuations of the Electronic Shooter Protection Elite hearing protector are shown for three different settings: off, unity gain, and maximum gain. For the off conditions, the indoor and outdoor measurements agree above 100 Hz. For the measurements where the ESP-Elite was turned on, little dependence as a function of the gain setting was observed; however, differences between the outdoor and indoor measurements were evident.

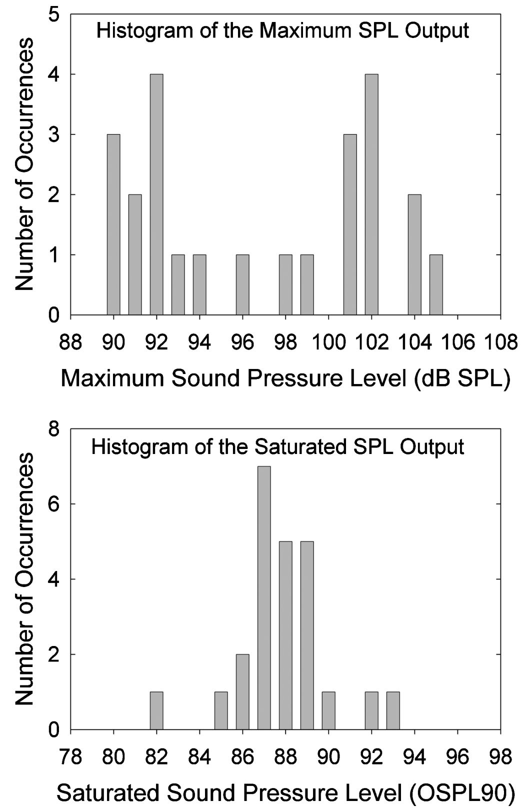

FIGURE 7. One-third octave band attenuation results for the ESP-Elite. Measurements for the ESP-Elite device were collected according to ANSI S3.22-2003. The upper panel displays the histogram of the maximum sound pressure level (dB SPL) along the x-axis for 24 units tested. One unit was for the ISL mannequin, and one officer provided only one ESP-Elite device. The lower panel shows a histogram of the saturated sound pressure level (SSPL) for the same 24 devices. The manufacturer's specifications indicate maximum SPL of 93 dB and SSPL of 88 dB.

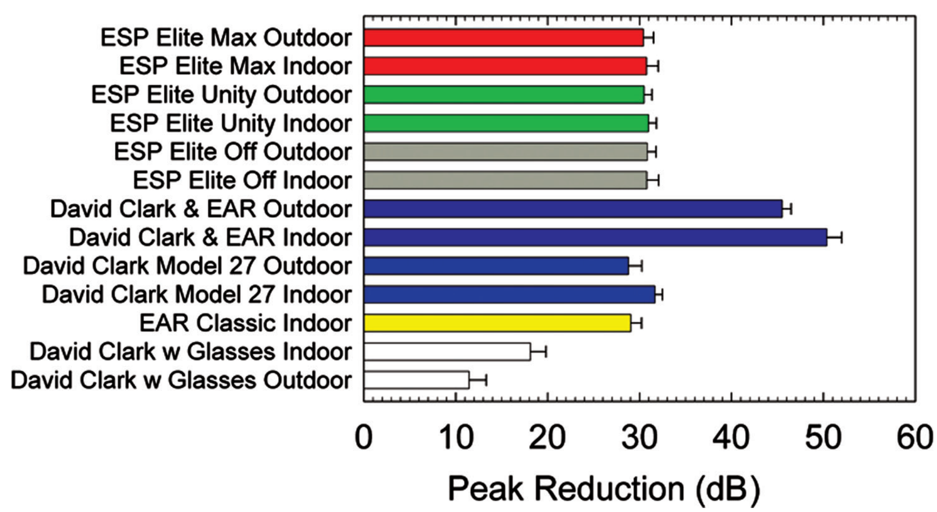

FIGURE 8. Peak reductions for the hearing protection devices. The peak reductions for the protectors measured at both firing ranges. The maximum sound pressure level for the protected waveform was subtracted from the maximum sound pressure level for the unprotected waveform. The resulting difference is the peak reduction.

propagates away from the gun barrel. The flow of acoustic energy from the shockwave into and through the protector may not be representative of lower level continuous stimulation that might be typical of occupational noise exposure.

Third, the audiology, occupational safety and health, and military communities have not agreed on how to evaluate the risk of hearing loss due to impulse noise. High-level impulsive noise presents an increased risk of hearing loss when no hearing protection is provided.[17−19] For example, the U.S. Military Standard 1474D estimates of the daily allowed number of rounds for an M-16 rifle (Colt AR-15 civilian equivalent) with single protection to be 3000 shots.[20] Other calculations based on the Auditory Hazard Assessment Algorithm for the Human ear suggest that only 40 to 1200 are appropriate for single protection.[21] The following formula is derived from the NIOSH Ceiling Limit for impulsive noise:

$$N = 10^{(140-PI)/10} \tag{1}$$

where N = the total number of shots, and PI = the peak sound pressure level in dB.

Using that formula, the peak sound pressure levels in Figure 2, and the peak noise reductions in Figure 8, officers would be exposed to peak sound pressure levels of 130–140 dB SPL. Applying that formula indicates that officers would be limited to firing 1 to 10 shots per day.[22,23] Applying the NIOSH formula to the double-protected data presented for the earmuff-earplug combination increases the allowable number of shots from 100 to 1000. Therefore, properly fitted, double hearing protection should minimize TTS and reduce the potential for permanent threshold shifts.

David Clark Model 27 Earmuff Attenuation

Although the David Clark Model 27 earmuffs yielded peak reductions typical of other earmuffs measured with these methods (about 30 dB), two concerns remain: the use of HPDs with safety glasses, and their use with helmets.

During the NIOSH investigation, measurements were taken using the mannequin with and without safety glasses. As shown in Figure 8, the peak reductions were diminished 10 to 20 dB because the safety glasses disrupted the seal of the earmuff cushion with the side of the head. Based on the peak levels found in this study (Figure 2), officers with a comparable leak could be exposed to 156 to 150 dB peak SPL.

The second issue concerns the use of earmuffs with the SWAT teams' helmets. The officers used Kevlar helmets with mounting points for face shields but not hearing protectors, and the helmets also covered the upper half of the pinna. Consequently, the helmet could not be used with the circum-aural earmuffs. However, Peltor (East Providence, R.I.) now makes a hearing protection device that permits the use of a helmet with an earmuff (Peltor COM-TAC and SWAT•TAC). The U.S. military currently is conducting research on the use of earplugs with communication capabilities (CEPS, Enterprise, Ala.) for Army aviation, and the ACCES (Colorado Springs, Colo.) earplug for Air Force ground crew personnel) for impulsive and continuous steady-state noise environments.[24]

Performance of the ESP-Elite Devices

The ESP-Elite provided consistent attenuation during use at both firing ranges at frequencies above 500 Hz (Figure 6). Differences between the indoor and outdoor attenuation spectra below 500 Hz seem to be related to the fitting. The data in Figure 7 suggest that the ESP-Elite device yielded a consistent, saturated SPL, in response to a 90-dB SPL input. Maximum sound pressure level output exhibited a wide range of responses across the devices evaluated. Whereas 11 devices were in the 90–94 dB range, 10 devices produced maximum sound pressure levels between 100 and 105 dB, which exceeded the manufacturer's specification of 90 dB maximum output level.

For persons with normal hearing, amplification above 100 dB could exceed the uncomfortable loudness level. For in-the-ear hearing protection, the maximum output levels were quickly measured with a hearing aid analyzer and should be adjusted to limit the maximum to the 90 dB specification. Further research regarding the output of in-the-ear hearing protection needs to be completed to develop recommendations for standards related to such devices.

Consideration must also be given to how well the earpiece fits. Every officer using the ESP-Elite should have the device fit tested to determine whether an effective seal of the ear canal is achieved. Technologies available to test the fit of hearing protection is the FitCheck system from Michaels and Associates (State College, Pa.).[25] FitCheck measures the attenuation of earplugs using narrow-band noise signals presented under circumaural headphones. If the attenuation for a hearing protector is less than 15 dB below 1000 Hz and less than 25 dB at higher frequencies, the device should not be used; it should be remanufactured with a new ear impression.

Performance of the E•A•R Classic

The E•A•R Classic earplug yielded a peak level reduction of 30 decibels, a typical value for a well-fitted protector on the mannequin. The E•A•R Classic also exhibited a consistent performance across subjects and is not as susceptible to acoustic leaks as other earplugs.[26] The peak noise reduction in a human ear canal may vary depending on how far the earplug is inserted. In general, however, studies of hearing protectors have shown that they do not achieve manufacturers' reported attenuation derived from earplugs tested with an experimenter-fit protocol.[27,28]

CONCLUSIONS

Based on the NIOSH recommended exposure level, officers firing weapons should not be exposed to impulse noise above 140 dB for any amount of time.[1] However, the measured unprotected peak noise levels measured just outside the acoustic mannequin ranged from 156 to 171 dB.

Measurements of the protection afforded by the HPDs on the mannequin were consistently in the 30-dB range (Figure 8), unless the earmuff seal was interrupted by the safety glasses. Those peak reduction results, along with the peak noise levels measured for the weapons, indicate that the officers should consider using dual hearing protection during weapons training exercises. To overcome the inability to communicate when double protected, the officers should be provided with electronic level-limiting earmuffs and a choice of earplugs. The earplugs can provide an additional 15–20 dB of peak reduction, while the electronic earmuffs can compensate for the reduced speech intelligibility due to double protection.

If the protected peak levels are in the 120–130 dB range, then the NIOSH formula suggests that 100 to 1000 shots per day would be allowed. This estimate is conservative and officers will not be exposed to an excessive risk of hearing loss if they use double protection. Several hearing protector manufacturers sell combined hearing protector and communication systems that could be adapted for use during weapons training. In the United States, no testing standards or specification for product performance of sound-restoration or communication hearing protection devices currently exist. The European Union has several product standards for different types of hearing protectors and thus may provide some assurance of performance characteristics of the electronics.

The ESP-Elite device appeared to provide sufficient peak level reduction and was comparable to other electronic sound-restoration earmuffs. The ESP-Elite device may not have been correctly fit for a significant portion of the officers due to the excessive saturated sound pressure levels (SSPL) above the 90 dB SSPL published in the manufacturer's literature. Furthermore, the ESP-Elite device does not have an NRR required for hearing protection and/or FDA approval to be sold as a hearing aid. Other devices should be investigated that have been rated as hearing protectors and that allow the use of closed-circuit radio communications, as well as having sound restoration features to enhance the situational awareness of the officers.

RECOMMENDATIONS

Based on the results of this investigation, the following recommendations should be considered against high-level impulses:

- Double hearing protection provides maximum peak level reduction (>40 dB) for the purpose of reducing impulse noise due to small arms fire. Use of double protection can minimize the potential risk of improper fitting of earplugs. However, double protection significantly reduces the ability to localize stimuli, thereby reducing situational awareness.[29] The peak reduction of the double protection is not necessarily additive due to effects of bone conduction. Double protection has the potential to interfere with other protective equipment. Earmuffs are not necessarily compatible with helmets, respirators, or face protection unless specifically designed to be. Low-profile, sound restoration earmuffs with earplugs could provide adequate protection and situational awareness.
- Noise levels generated by the weapons examined in this investigation are intense enough to warrant the initiation of a hearing conservation program that meets the requirements of the OSHA hearing conservation amendment (29 CFR 1910.95).[9] Other sources for defining effective hearing conservation programs are also available.[30–32]

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