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Noise Exposure Assessment and Abatement Strategies at an Indoor Firing Range

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Exposure to hazardous impulse noise is common during the firing of weapons at indoor firing ranges. The aims of this study were to characterize the impulse noise environment at a law enforcement firing range; document the insufficiencies found at the range from a health and safety standpoint; and provide noise abatement recommendations to reduce the overall health hazard to the auditory system. Ten shooters conducted a typical live-fire exercise using three different weapons—the Beretta .40 caliber pistol, the Remington .308 caliber shotgun, and the M4 .223 caliber assault rifle. Measurements were obtained at 12 different positions throughout the firing range and adjacent areas using dosimeters and sound level meters. Personal and area measurements were recorded to a digital audio tape (DAT) recorder for further spectral analysis. Peak pressure levels inside the firing range reached 163 decibels (dB) in peak pressure. Equivalent sound levels (Leq) ranged from 78 decibels, A-weighted (dBA), in office area adjacent to the range to 122 dBA inside the range. Noise reductions from wall structures ranged from 29–44 dB. Noise abatement strategies ranged from simple noise control measures (such as sealing construction joints and leaks) to elaborate design modifications to eliminate structural-borne sounds using acoustical treatments. Further studies are needed to better characterize the effects of firing weapons in enclosed spaces on hearing and health in general.

Keywords Firing Range, Noise Abatement, Impulse Noise, Noise-Induced Hearing Loss

The Bureau of Justice estimates there are 738,000 law enforcement officers in the United States.[1] These officers are required to train constantly in the accurate and proficient use of firearms. Indoor firing ranges have gained wide appeal among law enforcement agencies because they offer protection from inclement weather conditions and can be operated around the clock under controlled environmental conditions. They are designed primarily with safety, efficiency, and versatility in mind. However, until recently, most indoor ranges have been operated without the benefits of environmental controls to protect the health of shooters and range personnel from the adverse effects of exposure to airborne lead and noise during live-fire exercises. The discharge of weapons produces impulse noise levels that often exceed the American Conference of Governmental Industrial Hygienists (ACGIH®) 140 dB peak sound pressure limit.[2] Prolonged exposure to impulse noise can lead to noise-induced hearing loss (NIHL).[3,4]

The health hazards from exposure to airborne lead and other contaminants at indoor firing ranges have been widely investigated and documented.[5–7] However, exposure to hazardous impulse noise and the resulting risk of hearing loss at these facilities has received almost no attention. Impulse noise behaves differently in indoor firing ranges because of the reverberation effect when it reflects off hard surfaces. Investigators from the National Institute for Occupational Safety and Health (NIOSH) conducted two site assessment visits to the indoor firing range of a federal law enforcement agency. The purpose of those visits was to identify the salient acoustic parameters associated with typical live-firing sessions and provide noise abatement recommendations.

The NIOSH criteria document states that exposure to impulsive noise shall not exceed 140 dB,[8] but it does not provide any guidance on evaluating impulse sounds such as those generated from firearms that often reach 170 dB. The Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) suggested that in order to fully evaluate the effect of impulse noise on the auditory system, parameters such as peak pressure, duration, rise time, energy, spectral content, number and mixture of impulses, and temporal spacing should be considered.[9] NIOSH developed a technique to measure the various impulse noise

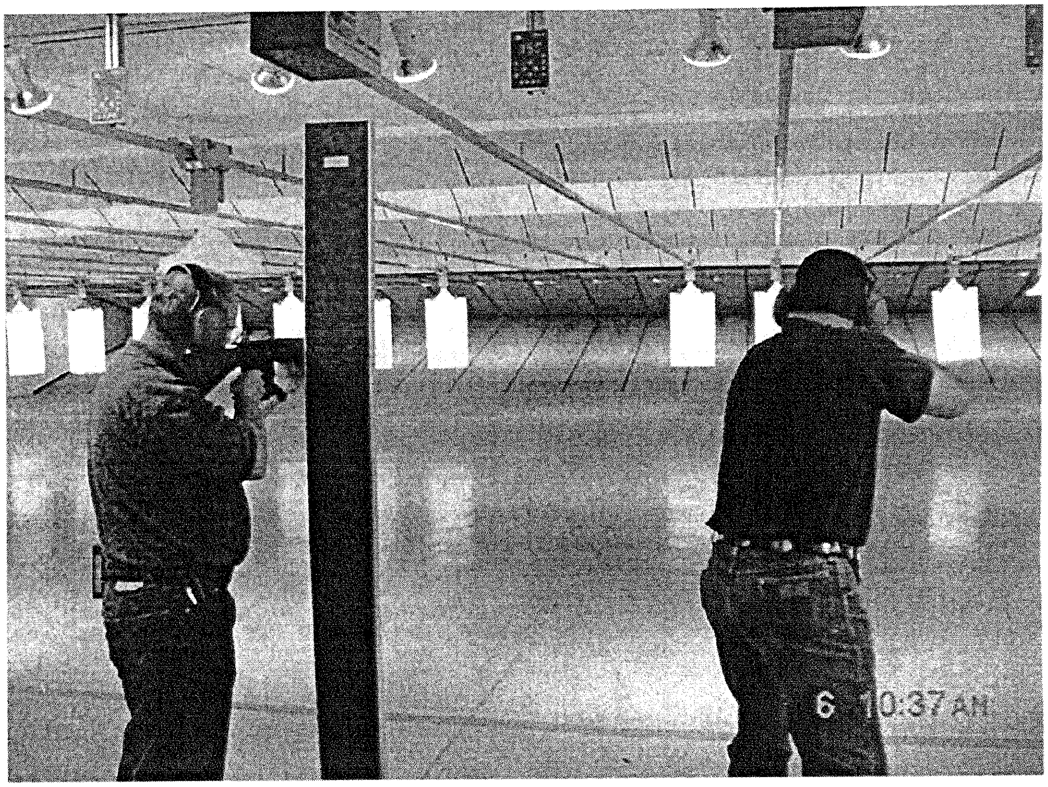

FIGURE 1
Front view of indoor firing range.

parameters highlighted in the CHABA document. The measurement results were used to make appropriate noise abatement recommendations. The recommendations were designed to be compatible with improving the range's ventilation system and reducing the overall lead levels.

METHODS

The noise assessment of the firing range consisted of (1) personal exposure and area noise assessment of officers during a live-fire session, and (2) sound level measurements to determine noise levels in the firing range and the amount of noise reduction in the adjacent areas due to the existing wall structure.

Firing Range

The firing range building structure includes a 20-lane shooting range and adjacent areas consisting of a cleaning room, an observation station, a classroom, and an office area. The range is ventilated by two rooftop heating, ventilation, and air conditioning (HVAC) units that control exposure to lead and other contaminants. The adjacent classroom and office are served by separate HVAC units. The range is maintained under negative pressure. Baffles are installed to protect lighting fixtures, ventilation pipes, and the roof structure from misfire. The bullet trap is directly exhausted by a dust collection unit located outside the building. A motorized target retrieval system is installed for all lanes. Typically, shooters training at the facility undergo one to two hours of indoor range use per day. Figures 1 and 2 show the front view of the firing range and the back view of the adjacent space behind the firing line.

Instrumentation Description

Peak sound levels were measured using a B&K 4136 1/4″ microphone, B&K 2615 pre-amplifier, B&K 2807 power supply, and recorded on a Panasonic SV-255 digital audio tape (DAT) recorder. Area measurements were conducted using a B&K 2260 and Quest 1800 Type 1 sound level meters. Personal and area noise level measurements were also collected using Quest Q400 and the Larson-Davis 706 Type 2 dosimeters.

The dosimeters were set to measure the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) and the NIOSH-recommended exposure limit (REL).[8,10] The NIOSH REL for noise is 85 dBA for an 8-hour time-weighted average (TWA) using a 3-dB exchange rate (equal energy rule). The sound level meters and dosimeters conform to the American National Standards Institute (ANSI) specifications.[11,12] The equipment was calibrated before the visits by the manufacturers. Field calibrations were conducted before and after measurements were taken.

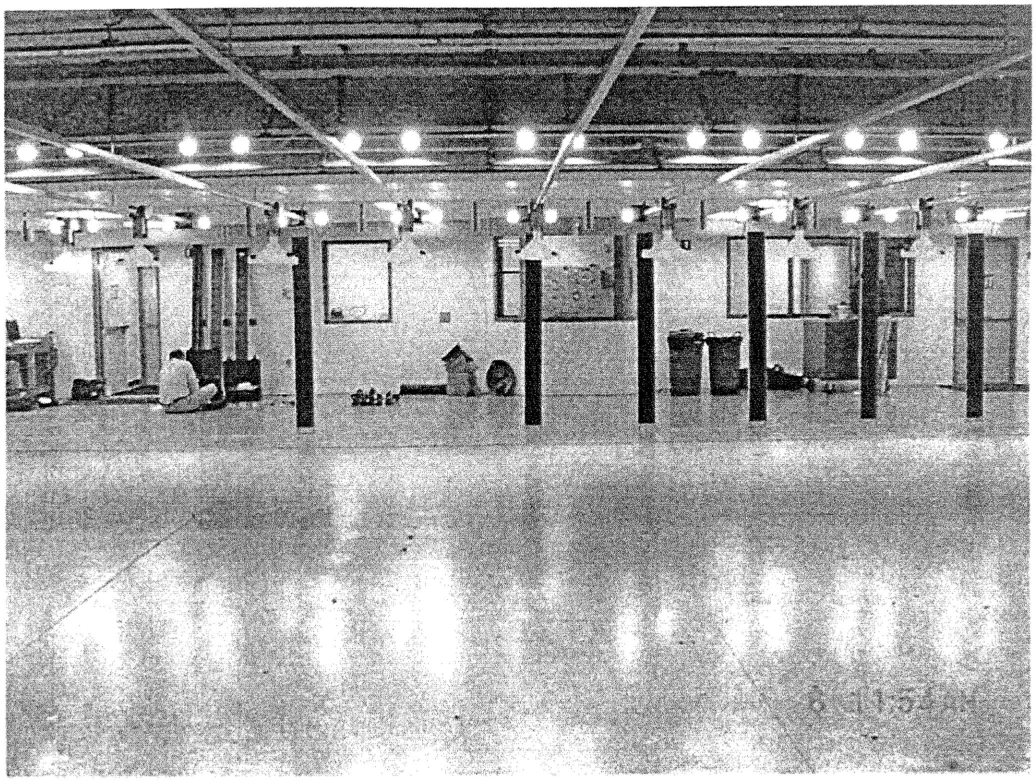

FIGURE 2
Back view of indoor firing range.

Measurement Method

Noise measurements were obtained at twelve different positions throughout the firing range and adjacent areas as outlined in Figure 3. The positions were chosen primarily to measure a typical officer's noise exposure in the firing range and to compute the existing noise reductions afforded by the current building structure in the adjacent areas.

Ten officers conducted a typical firing session that lasted approximately one hour using three different weapons—the Beretta .40 caliber pistol, the Remington .308 caliber shotgun, and the M4 .223 caliber assault rifle. Noise dosimeters were placed throughout the range at each of the measurement positions. Three officers and a range observer also wore dosimeters for personal noise-exposure monitoring. Because noise dosimeters were suspected to overload under such extreme conditions due to their inherent limitations, backup measurements were made using the Bruel & Kjaer (B&K) 4136 microphone and DAT recorder as well as sound level meters. The microphone was positioned at an average officer's ear height (approximately 5.5 ft above ground). Data from the dosimeters were downloaded and analyzed using the QuestSuite 4.0 software. Data from the sound level meter were downloaded and analyzed using the Larson-Davis 824 Utility 3.0 software. Data from the DAT were digitally transferred to a computer as .wav files via a Lexicon-Core2 24 bit audio card and CoolEditPro 6.0 software. Spectral analysis was performed using MATLAB software routines to obtain peak levels, equivalent levels (Leq), time durations, frequency spectrum, octave, and 1/3-octave band spectra.

RESULTS

Area Measurements

Table I shows the measured peak and calculated equivalent sound levels from the B&K 4136 microphone for the firing range, observation station, cleaning room, classroom, and office. Peak levels from the Quest Q400 dosimeters were not included

TABLE I
Measured sound levels at the indoor firing range

Area	Peak sound[A] level (dB)	Equivalent[B] Leq (dBA)	NIOSH REL
Firing range	151	122	6 sec
Observation tower	136	93	1 hr 16 min
Cleaning room	115	90	2 hr 31 min
Classroom	111	79	No hazard
Office	108	78	No hazard

[A]Measured using the B&K 4136 microphone and DAT setup.
[B]Calculated by obtaining the difference in A-weighted equivalent levels: Leq (firing range)—Leq (adjacent area).

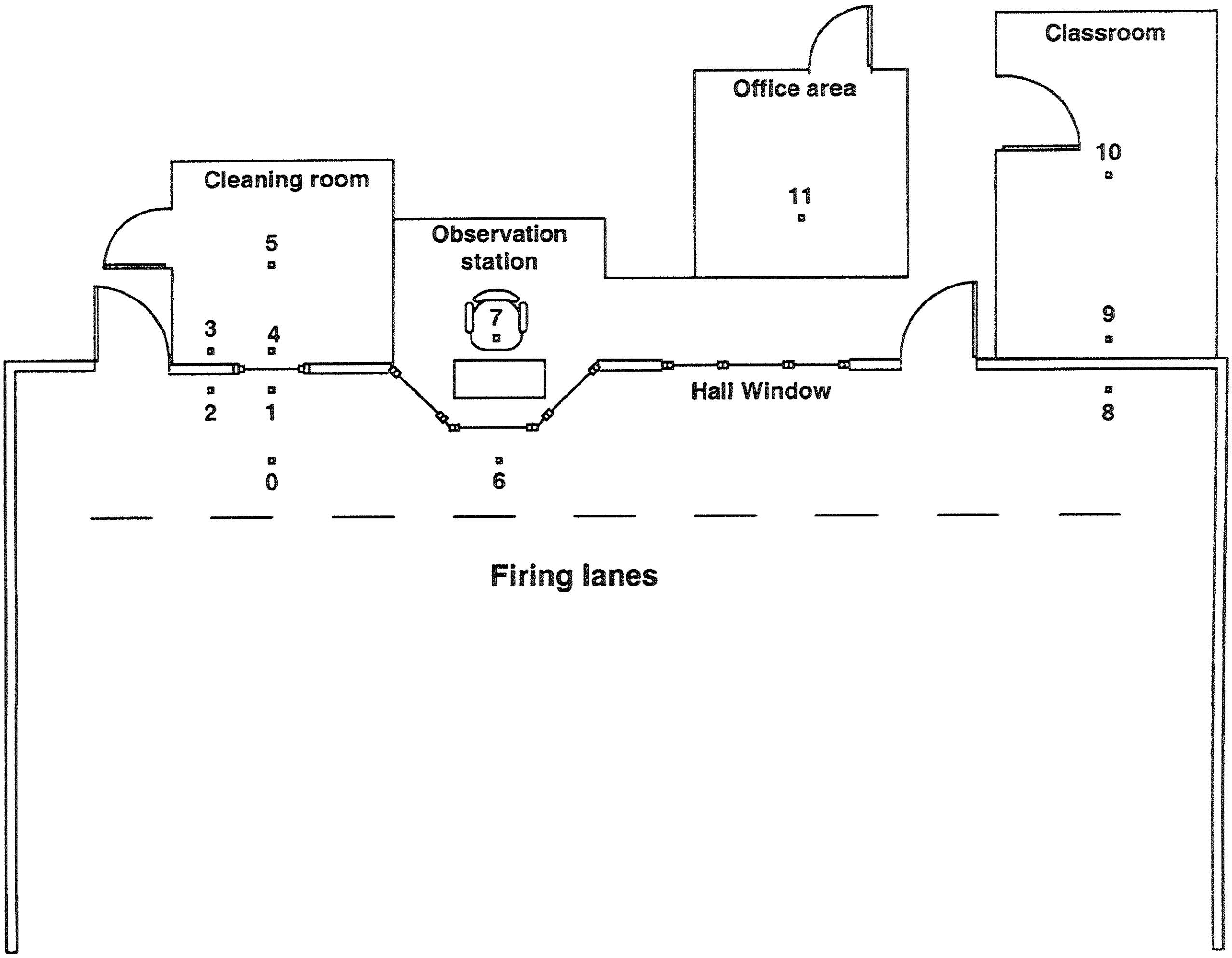

FIGURE 3
Measurement positions at the indoor firing range.

in this article because these units clipped peak levels greater than the instrument range of 146 dB.(13) The limitations associated with the use of dosimeters in impulsive noise environments are discussed elsewhere.(14)

Figure 4 shows noise reductions in full octave bands for the cleaning room, observation station, classroom, and office. The noise reductions are presented in octave bands since noise control materials are normally specified according to their octave-band transmission losses. They were calculated by obtaining the difference in octave bands between the firing range and each of the adjacent areas. They ranged from 29 dB in the observation station to 44 dB in the office area.

Personal Exposure Measurements

Table I also shows the maximum allowable exposure duration for personnel in the firing range and adjacent areas during the shooting session. According to the NIOSH criteria document, shooters exceeded their exposure limit within seconds of the start of shooting.

Table II shows personal noise exposure response for three shooters and an observer who oversaw the firing exercise. Typically, aside from the shooters, only the shooting instructor is present in the firing range during training. The maximum allowable daily dose according to NIOSH criteria was exceeded

TABLE II
Personal exposure response

Personnel[A]	TWA (dBA)	Dose (%)	Maximum level (dBA)	Leq (dBA)
Shooter X	115	94,436	137	123
Shooter Y	111	41,631	133	119
Shooter Z	113	69,178	134	122
Observer	108	19,282	131	116

[A]Each shooter fired three different weapons during the exercise. Dosimeter microphones were placed on the opposite shoulder of the firing arm.

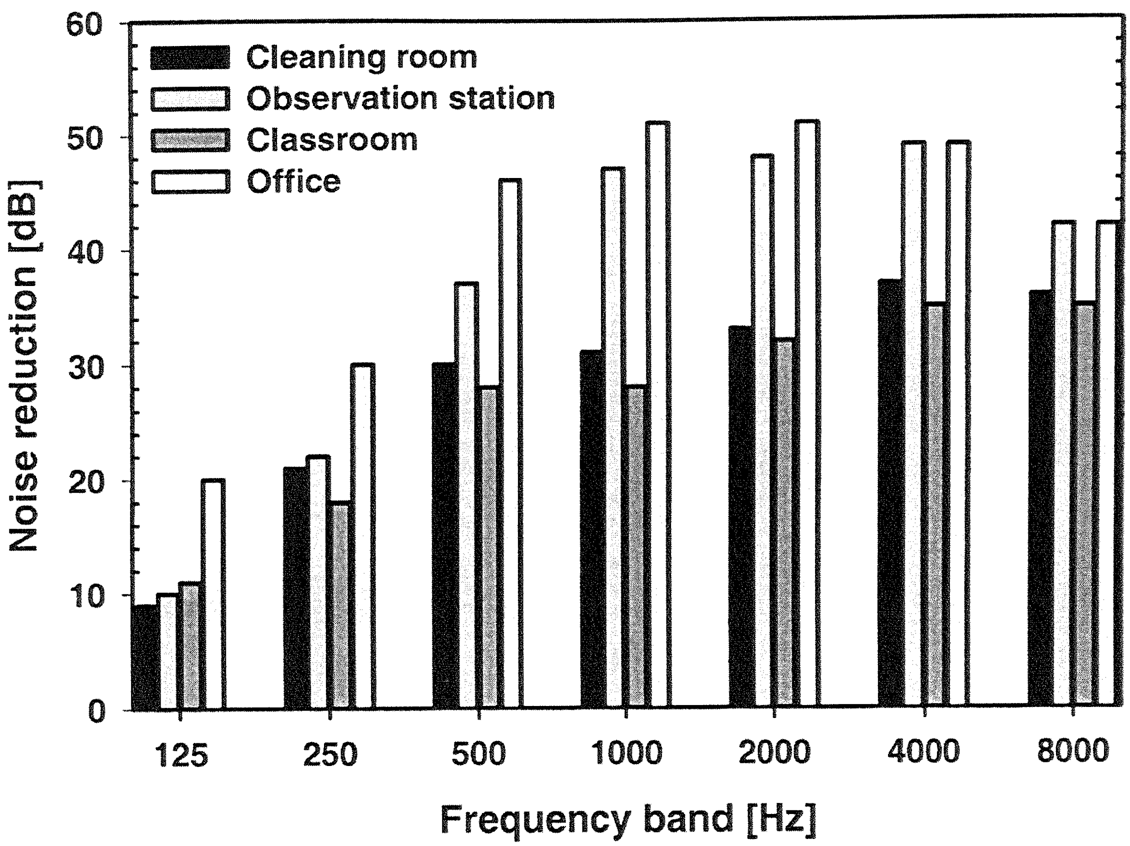

FIGURE 4
Calculated noise reductions in adjacent areas.

within the first few seconds. Although the accuracy of the results is questionable since the dosimeters tend to clip all levels above 146 dB, shooters' Leq matched those obtained by the SLM and B&K 4136 measurement setup inside the firing range (within the tolerances of Type 2 dosimeters).

Although occupational safety and health professionals continue to rely primarily on time-averaged (integrated) measurements to quantifying noise exposure, recent studies have shown that the spectral distribution of the impulse waveform is critical to predicting the ear susceptibility to impulse noise hazards.[15,16] Figure 5 shows the octave-band spectra for the three different caliber weapons used in training. In addition, the understanding of the spectral content produced by the various weapons allows industrial hygienists and noise control engineers to provide noise control measures based on appropriate acoustical treatments that reduce the most prominent spectral peaks.

DISCUSSION

The data show peak levels that exceed the NIOSH and ACGIH maximum allowable exposure level of 140 dB for unprotected ears inside the firing range. Although studies have shown that exposure to impulse noise can produce noise-induced hearing loss, the scientific, occupational, and military communities have not reached a consensus regarding the extent of hearing hazard from exposure to impulse noise.[17,18] The dose-response relationship that applies to continuous noise exposure does not apply in impulse noise environments. In-depth analysis of hearing loss hazards associated with impulse noise generated by firearms are beyond the scope of this article and have been addressed elsewhere.[19]

Sound levels inside the observation station and cleaning room warrant the constant use of hearing protection while the range is in use. However, the range observation officer and shooters using the cleaning room to prepare the weapons often operate without the benefit of hearing protection because they cite concerns about personal safety and the ability to communicate. Although the noise levels in the classroom and office are considered acceptable according to NIOSH criteria, these areas cannot be used successfully for their intended purposes because of the sound leaks that render them ineffective.

Additionally, airborne lead exposure is considered to be one of the most common health hazards associated with firearms, especially at indoor firing ranges. Some studies have shown an association between lead exposure and hearing loss.[20] Further studies are needed to quantify the cumulative effect of exposure

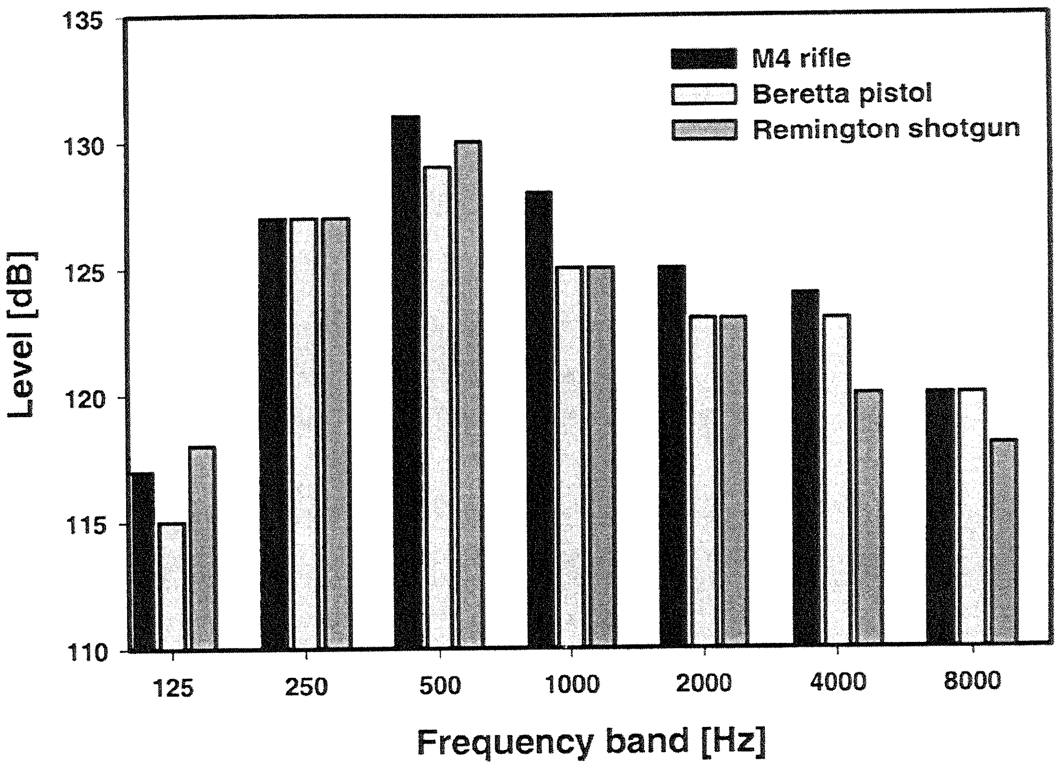

FIGURE 5
Octave-band spectra from three firearms.

to lead and weapons noise. Non-auditory noise effects such as physiological changes, fatigue, increased reaction time, reduced concentration, and irritability have also been attributed to exposure to high levels of noise and can compromise the safety of the exposed individuals.[21–23]

The cleaning room, classroom, and office areas share common weak points with regard to noise intrusion: The transmission loss through the existing wall structure is too low, and the leakage and flanking paths other than the wall are significant. The noise levels resulting from shooting activities have rendered the classroom unsuitable for training because the acoustic isolation is substantially below what is typically required to provide an adequate environment for instruction.[24] Although the office is farther away and does not share a common wall with the actual range, it is still essentially unusable as an office during firing, since telephone conversation and concentration are difficult. The observation station has high noise levels because the bulletproof glass does not provide sufficient transmission loss, the roof is a single layer of sheet metal with no absorption, and the door is not acoustically rated. The observation station presents a special problem in that the range officer is currently required to wear hearing protection while inside the station.

The construction of the firing range did not take into account the many sound leakage and flanking paths that detract from the acoustical performance of the present block wall. Eliminating these noise leakages and flanking paths would definitely improve the performance of the block wall and observation station glass during firing sessions. To achieve the NIOSH-recommended exposure limit of 85 dBA TWA in the cleaning room and observation station, substantial additional noise reductions (5 dB–8 dB) will be needed. Although the classroom and office area measurements show levels below the NIOSH REL, measured peak levels reached 110 dB. Since the number of rounds fired during typical training sessions varies, the risk of hearing damage from these impulses cannot be accurately determined.

NOISE ABATEMENT RECOMMENDATIONS

The following recommendations will reduce the overall noise levels and improve the sound isolation between the range and adjacent areas so that the cleaning room, classroom, and office areas can be used for their intended purposes. The recommendations for noise abatement should be compatible with HVAC/air flow changes to reduce airborne lead concentrations and should comply with fire protection regulations. Some of the noise control strategies are specific to the studied firing range; however, most are applicable to indoor firing ranges in general.

Shooting Range

No opportunity exists to lower the noise in the firing range to acceptable levels through the application of sound absorption techniques to current surface areas. Double hearing protection is still required for each shooter and anyone else in the range area. NIOSH investigators recommend installing absorptive "septum" barriers between these firing lanes. Although this will reduce a shooter's indirect exposure to sound from other shooters, it will have limited effect in protecting the shooter from the direct sound of his/her own weapon in the firing range. If barriers are used, care must be taken when placing them to ensure a clear and unobstructed view of each shooter from the observation station. Such a design change should consider a number of alternative arrangements to allow the selection of a barrier arrangement that provides acceptable visibility from the station.

Adjacent Areas

In order to provide significant improvement in noise reduction from the firing range into the adjacent spaces, it is necessary to treat both the direct sound paths and all flanking paths. To improve the transmission loss of an existing wall structure, a second wall must be built with an air gap between both walls. This will reduce sound transmission through three different principles: increasing the mass in the sound path, breaking vibration paths, and adding cavity absorption.

The following recommendations are suggested to reduce noise levels in the cleaning room, classroom, and office:

1. Construct a nominal 6″ stud wall on the cleaning room and classroom side of the existing common block wall, including the hallway area leading from the station door to the classroom hallway. The stud wall should be set apart from the existing concrete block wall by a minimum of three inches. The stud wall construction should be a double layer, unbalanced wall of 2″ × 6″ metal stud framing, 6″ acoustical sound insulation batts, resilient channel, and a drywall double layer finish (5/8″ type X Gypsum, two thicknesses on the quieter side). This measure provides noise reduction that will increase the sound transmission class (STC) of the existing wall to an STC 72 rating.[25,26] The added stud wall should be non–load-bearing and extend up to the roof of the building, including the area over the observation station. The top edge of the new wall should be sealed against the corrugated roof system in the same manner as the existing concrete block wall (filled with acoustic fiberglass, drywall piece fit to roof). The windows in the cleaning room wall and in the short hallway leading to the observation station door should be replaced with the same block construction as for the rest of the wall. Windows present special problems in sound reduction, and the likelihood of achieving the intended improvement will be much higher than if these windows are removed.
2. Remove or relocate 110-V outlets that back onto each other in the common wall. The existing outlets on the common wall are placed in such a manner that they form a direct acoustic path for the noise.
3. Place 6″ acoustical absorption batts in the plenum over the ceiling area of the range (over a distance of approximately 22 ft) to reduce noise by a major flanking path. Adding absorption materials above the dropped ceiling over the classroom and office will also be necessary to reduce sound through this flanking path.
4. The roof structure over the observation station is made of a single layer of sheet metal and should be replaced with a new roof that offers significant improvement in sound transmission loss. The roof structure should be specified to provide a minimum of at least STC 60 performance.
5. The existing doors are fire-rated doors without any special acoustical properties. Replace existing doors with acoustic-rated doors having an STC 50 rating.
6. To make the observation station useable without the need for hearing protectors, double bulletproof glass should be installed with the maximum air gap possible (three inches minimum is suggested). In addition, to minimize vibration transmission from one pane of glass to the next (known as interpanel resonance effect), the first and second glass layers should differ in thickness by 30 percent–50 percent, and the two panes should be mounted in resilient channels and inclined slightly (not parallel) to reduce objectionable reflections.

CONCLUSION

The noise assessment of the firing range showed peak sound levels that exceed the ceiling limits for safe exposure. Law enforcement officers were exposed to noise levels that reached 163 dB during a live-fire session. Current damage risk criteria lack the empirical data to establish a quantitative relationship between these levels and hearing damage. Two significant findings have been identified as a result of this study. First, personal noise dosimeters are incapable of producing accurate measurements in impulsive noise environments nor are they suitable to characterizing the impulse noise hazard. Second, other parameters such as peak pressure, time duration, rise time, energy, spectral content, number and mixture of impulses, and temporal spacing must be considered in order to understand the full extent of the hazard to hearing. Hearing protection should be worn throughout the facility, and dual hearing protection must be worn inside the range during firing sessions. Noise abatement techniques addressed reducing airborne sounds by sealing leaks and airtight insulation around doors, windows, and ventilation ducts. Structural-borne transmission and vibration were limited by applying acoustical treatment to walls, windows, doors, and the roof structure.

REFERENCES

1. Law Enforcement Statistics. [Online] Available at http://www.ojp.usdoj.gov/ Bureau of Justice Statistics. U.S. Department of Justice, Washington, DC (1996).
2. American Conference of Governmental Industrial Hygienists (ACGIH®): TLV®s and BEIs: Threshold Limit Values for

Chemical Substances and Physical Agents, Biological Exposure Indices. ACGIH, Cincinnati, OH (1997).
3. Patterson, J.H., Jr.; Hamernik, R.P.: An Experimental Basis for the Estimation of Auditory System Hazard Following Exposure to Impulse Noise. In: Noise-Induced Hearing Loss, A. Dancer; D. Henderson; R.J. Salvi; R.P. Hamernik, eds., pp. 336–348. B.C. Decker, Philadelphia (1992).
4. Chan, P.C.; Ho, K.H.; Kan, K.K.; et al.: Evaluation of Impulse Noise Criteria Using Human Volunteer Data. J Acoust Soc America 110(4):1967–1975 (2001).
5. Harney, J.M.; Barsan, M.E.: Health Hazard Evaluation Report No. HETA 97-0255-2735, Forest Park Police Department. National Institute for Occupational Safety and Health. Cincinnati, OH (1997).
6. Barsan, M.E.; Miller, A.: Health Hazard Evaluation Report No. HETA 91-0346-2572, FBI Academy. National Institute for Occupational Safety and Health. Cincinnati, OH (1991).
7. Novotny, T.; Cook, M.; Hughes, J.; et al.: Lead Exposure in a Firing Range. Am J Pub Health (77)9:1225–1226 (1987).
8. National Institute for Occupational Safety and Health: Criteria for a Recommended Standard—Occupational Noise Exposure (revised criteria 1998), DHHS (NIOSH) Pub No. 98–126. NIOSH, Cincinnati, OH (1998).
9. Committee on Hearing, Bioacoustics, and Biomechanics: Hazardous Exposure to Impulse Noise. CHABA, Washington, DC (1992).
10. Occupational Safety and Health Administration: Code of Federal Regulations. 29 CFR 1910.95. U.S. Government Printing Office, Washington, DC (1992).
11. American National Standards Institute: Specification for Sound Level Meters, ANSI S1.4-1983. ANSI, New York (R2001).
12. American National Standards Institute: Specification for Personal Noise Dosimeters, ANSI S1.25-1991. ANSI, New York (R1997).
13. Quest Technologies. Instructions for Q400 and Q500 Noise Dosimeters. Quest Technologies: Oconomowoc, WI (1997).
14. Kardous, C.A.; Willson, R.D.: Limitations of Integrating Impulse Noise When Using Dosimeters. Submitted for publication. AIHA J (2002).
15. Price, G.R.: Impulse Noise Hazard as a Function of Level and Spectral Distribution. In: Basic and Applied Aspects of Noise-Induced Hearing Loss, R.J. Salvi; D. Henderson; R.P. Hamernik; and V. Colletti, eds., pp. 379–392. Plenum, New York (1986).
16. Patterson, J.H., Jr.; Carrier, M., Jr.; Bordwell, K.; et al.: The Hazard of Exposure to Impulse Noise as a Function of Frequency, vols. I & II, USAARL Report No. 91-18. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL (1991).
17. Committee on Hearing, Bioacoustics, and Biomechanics: Proposed Damage Risk Criterion for Impulse Noise (Gunfire). CHABA, Washington, DC (1968).
18. Department of Defense: Design Criteria Standard, Noise Limits, DOD, Washington, DC US MIL-STD-1474D (1997).
19. Kardous, C.A.; Willson, R.D.; Murphy, W.J.: Personal Noise Exposure Assessment from Small Firearms. J. Acoust. Soc. America. Submitted for publication.
20. Frost, L.S.; Freels, S.; Persky, V.: Occupational Lead Exposure and Hearing Loss. J Occup Environ Med 39:658–666 (1997).
21. Kjellberg, A.; Skoldstrom, B.: Noise Annoyance During the Performance of Different Nonauditory Tasks. Percept Mot Skills 73:39–49 (1991).
22. Belojevic, G; Ohrstrom, E; Rylander, R.: Effects of Noise on Mental Performance with Regard to Subjective Noise Sensitivity. Int Arch Occup Environ Health 64:293–301 (1992).
23. Heslegrave, R.J.; Furedy, J.J.: Anticipatory HR Deceleration as a Function of Perceived Control and Probability of Aversive Loud Noise: A Deployment of Attention Account. Biol Psychol 7:147–166 (1978).
24. American National Standards Institute: Criteria for Evaluating Room Noise, ANSI S12.2-1995. ANSI, New York (R1999).
25. Warnock, A.C.C.: Developments in Noise Control. Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario (1990).
26. Warnock, A.C.C.: Sound Transmission Through Concrete Block Walls. Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario (1985).