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Original Article

Measurement of impulse peak insertion loss for four hearing protection devices in field conditions

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Abstract

Objective: In 2009, the U.S. Environmental Protection Agency (EPA) proposed an impulse noise reduction rating (NRR) for hearing protection devices based upon the impulse peak insertion loss (IPIL) methods in the ANSI S12.42-2010 standard. This study tests the ANSI S12.42 methods with a range of hearing protection devices measured in field conditions. ***Design:*** The method utilizes an acoustic test fixture and three ranges for impulse levels: 130–134, 148–152, and 166–170 dB peak SPL. For this study, four different models of hearing protectors were tested: Bilsom 707 Impact II electronic earmuff, E·A·R Pod Express, E·A·R Combat Arms version 4, and the Etymotic Research, Inc. Electronic BlastPLG™ EB1. ***Study sample:*** Five samples of each protector were fitted on the fixture or inserted in the fixture's ear canal five times for each impulse level. Impulses were generated by a 0.223 caliber rifle. ***Results:*** The average IPILs increased with peak pressure and ranged between 20 and 38 dB. For some protectors, significant differences were observed across protector examples of the same model, and across insertions. ***Conclusions:*** The EPA's proposed methods provide consistent and reproducible results. The proposed impulse NRR rating should utilize the minimum and maximum protection percentiles as determined by the ANSI S12.42-2010 methods.

Key Words: Hearing protection devices; impulse noise; noise reduction rating; noise-induced hearing loss

Short duration, high-level impulsive sounds are generated from a variety of sources: impact hammering, pneumatic tools, riveters, punch-presses, air guns and firearms. Some workers claim, "Hearing protection? I only wear it when I know that I am going to be exposed to a lot of noise." The transient nature of impulsive noise contributes to their decision to operate such equipment without hearing protection. Even if workers were to use hearing protection, there is no indication on the packaging that provides guidance for product selection or sets expectations for safety performance related to impulse noise attenuation.

Firing a weapon poses a significant risk of noise-induced hearing loss if hearing protection is not worn. The Veterans Administration pays more than one billion dollars annually to veterans who have auditory dysfunction identified as their primary disability (Fausti et al, 2009). Carpenters, mechanics, and foundry workers experience impulse noise exposures of 130 dB peak SPL and above in daily work duties (Taylor et al, 1987; Starck et al, 2005; Zhu & Kim, 2005). Therefore, it is no surprise that workers in industries where exposure to impulse noise is common, such as construction, mining, manufacturing, and service industries (e.g. law enforcement), suffer hearing loss at a significantly greater rate than other non-noise exposed workers (Hager, 2008; Bureau of Labor Statistics, 2009; Franks, 1996, 1997). The combination of continuous noise exposure and impulsive noise exposure also results in a more hazardous combination than exposure to continuous noise alone (Henderson & Hamernik, 1986; Voigt et al, 1980).

Coles et al (1967) demonstrated that exposure to high-level impulse noise produced by small-caliber weapons caused a significant temporary threshold shift (TTS) in the hearing of humans. Impulsive noise exposure has a greater risk of producing permanent threshold shift than an exposure to continuous noise of an equivalent energy (Dunn et al, 1991; Hamernik et al, 1998; Zhao et al, 2010). Impulse noise, because of its transient nature, is able to affect the ear before the acoustic reflex is able to activate and reduce the transmitted energy to the cochlea (Price, 1982; Price & Kalb, 1991). High amplitude stimulation of the cochlea can excessively fatigue the outer and inner hair cells, mechanically damage the cells of the

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Abbreviations

ATF	Acoustic test fixture
EPA	Environmental Protection Agency
IPIL	Impulse peak insertion loss
NRR	Noise reduction rating
REAT	Real-ear attenuation at threshold
SPL	Sound pressure level

basilar membrane, and initiate apoptotic cell death around the site of greatest stimulation (Henderson & Hamernik, 2007; Davis & Murphy, 2007). The risk of hearing loss due to exposure to firearms and consumer fireworks has recently been investigated by Flamme et al (2009a, 2009b, 2011). The risks are not just limited to the shooter; they extend to the bystanders and other participants at firing ranges and shooting events where such exposures occur. Consistent use of hearing protection devices (HPDs) with adequate attenuation values can reduce the risk of acquiring noise-induced hearing loss (NIHL) secondary to impulse noise exposures.

While this paper does not evaluate various damage risk criteria, the peak pressure level, spectral composition, impulse duration, and number of impulses are the primary factors in predicting hearing damage (Johnson & Patterson, 1997; Hamernik et al, 1998). The reduction of the peak pressure level is an inherent characteristic of the protector and can be measured in the laboratory. The peak pressure and integrated energy are correlated with increased risk estimated by MIL-STD 1474D or the equivalent A-weighted 8-hour exposure level (DOD, 1997; DTAT, 1983). Other proposed methods will yield a similar trend for the range of exposures that are involved in this study; lower peak pressures are correlated with lower risk of incurring temporary or permanent hearing loss (Flamme et al, 2009a, 2009b).

The EPA requires an NRR for hearing protection devices (HPDs) entered into commerce in the United States (EPA, 1979). The NRR is a laboratory measurement that describes the attenuation performance of a hearing protector. The real-ear attenuation at threshold (REAT) measures the unoccluded and occluded noise-band thresholds for a panel of listeners at center frequencies ranging from 0.125 to 8.00 kHz. The REAT attenuation is measured in a low-level continuous noise environment where linear acoustic effects are dominant. The attenuation performance of a hearing protector is assumed to be constant throughout the linear acoustic regime, levels below 140 dB SPL re 20 µPa. Above 140 dB SPL, the attenuation exhibits a small increase by a few tenths of a decibel per decibel increase in peak level (Allen & Berger, 1990; Murphy, 2003). For a hearing protector, with a nonlinear orifice and for earmuffs, the attenuation can increase as much as a 0.5 dB/dB at levels of 140 to 170 dB peak SPL (Dancer et al, 1999; Zera & Mlynski, 2007; Berger & Hamery, 2008).

With the advent of new technologies such as nonlinear orifice or electronic level-limiting protectors, the EPA recognized the woefully outdated state of the 1979 regulation. Nonlinear orifice protectors such as Racal GunFender, Hocks Noise Brakers or EAR Combat Arms exhibit low NRRs, but have increasing attenuation above about 110 dB SPL (Berger & Hamery, 2008). In 2003, the EPA held a workshop to gather input about what elements should be considered in a revised rule. In 2009, the EPA published a proposed rule that updated the measurement methods for conducting the REAT measurement and proposed new rating strategies for active noise cancellation and impulse reducing hearing protectors (EPA, 2009). At the time of proposal, the EPA described a new method for assessing the impulse peak insertion loss (IPIL) of a hearing protection device by evaluating multiple product samples with three ranges of impulse levels, and multiple placements/replacements of the samples on an acoustic test fixture (ATF). In a parallel effort, the Acoustical Society of America Committee on Standards developed a new American National Standard ANSI S12.42 (2010) to define the measurement technique that the EPA was proposing.

This standard describes the use of an ATF and a field probe to measure unoccluded and occluded conditions for impulses with levels of 130 to 134, 148 to 152, and 166 to 170 dB peak SPL. The unoccluded ATF and field probe waveforms are used to calculate the transfer function between the field probe and the fixture. Without moving either device, the hearing protection is placed on the ATF or fitted in the ATF ear canals and a set of impulses are recorded at the same range of impulse levels. The unoccluded field-to-fixture transfer function is used to transform the field measurements made in the ATF-occluded condition to estimate the equivalent unoccluded fixture level. The IPIL is then estimated as the difference between the measured maximum absolute occluded pressure and the estimated unoccluded pressure. Multiple impulses for the same fitting of the protector are averaged; multiple fittings of a given protector sample are also averaged. The resulting dataset has one IPIL value per protector sample at each of the three ranges of impulse levels. The development of the ANSI S12.42 (2010) standard was based upon experience obtained from testing hearing protection performance at multiple testing sites but did not include results from testing multiple protectors at the three recommended levels for multiple insertions. This manuscript reports the results of IPIL measurements from four hearing protectors using gunshot noise as an impulse source.

Methods

This research was conducted as an outgrowth of measurements of impulse noise by firearms during recreational shooting activities. The measurements were conducted at a remote hunting camp near the town of Rudyard in Michigan's Upper Peninsula. A shooting lane was laid out and three measurement positions were identified to yield peak sound pressure levels at the field probe of 130, 150, and 170 dB SPL. The acoustic test fixture and the field sensors were positioned with a direct path to the source and at the same distance from the source.

Acoustic source

Acoustic impulses were generated with a Colt AR-15 rifle firing a 5.56 mm (0.223 caliber) ORM-D Federal Ammunition cartridge with 55 grains of powder and a full metal jacket. The rifle was mounted in a gun stand and one person pulled a lanyard to fire the weapon and was positioned to the left and behind the gun stand (See Figure 1 upper panel). This position minimized acoustic reflections and reduced shadows caused by the body.

Acoustic test fixture

All of the impulses were measured with an acoustic test fixture (ATF) developed by the French-German Research Institute de Saint Louis (Parmentier et al, 2000). The fixture was purchased by the National Institute for Occupational Safety and Health (NIOSH) in 2001 and consists of a solid acrylic head shape containing a capsule for an ear simulator on the right side of the head. The capsule is

Figure 1. Panel A: The Colt AR-15 rifle was mounted in a gun stand and a lanyard allowed the weapon to be fired remotely. Panel B: The acoustic test fixture was mounted on a tripod and is shown with the Bilsom 707 Impact II earmuffs. The PCB Electronics 137A23 blast pressure probe, GRAS 40DP eighth-inch microphone, and Bruel & Kjaer 4136 quarter inch microphone are shown mounted in grazing incidence near the acoustic test fixture. The positions of the sensors are indicated.

shock isolated from the cavity inside the acrylic head and the ear simulator is further shock isolated within the capsule. The model 4157 Bruel & Kjaer (B&K) 60711 ear simulator was outfitted with a B&K model 4136 quarter-inch pressure microphone. The maximum root mean square sound pressure level (RMS SPL) for the microphone is nominally 174 dB and, consequently, the peak level for the test fixture is 177 dB. Above these limits, the electronics of the microphone distort beyond the manufacturer's tolerances. Two channels of the data acquisition system were dedicated to recording the ATF signal, one channel was with 0-dB gain and the other channel applied 20-dB gain to the ATF signal. Both the occluded and unoccluded impulses were recorded without needing to adjust the sensitivities in either the software or the gain settings to prevent peak clipping. For the unoccluded condition, the ATF signal at the 170-dB impulse level clipped the input of the system.

The ATF was positioned to the right and behind the muzzle of the rifle at approximately 0.9, 2.7, and 19.2 metres[1]. The impulse source was level with the ear of the ATF and was 1.26 metres above the ground. The field sensors were placed at the same distance from the muzzle of the rifle as the ear of the ATF (See Figure 1 lower panel). The diaphragms of the pressure microphones and the blast probe were placed in grazing incidence, pointing upward perpendicular to the shock wave's direction of propagation).

Field sensors and data acquisition system

Since these measurements evaluated IPIL for hearing protectors using real-world impulses produced by gunshots, two microphones and a piezoelectric blast probe were used to measure the pressure wave near the test fixture. The eighth-inch pressure microphone was a B&K model 4138 and a B&K 2670 preamplifier connected to a G.R.A.S. Sound and Vibration model 12AN power supply. The quarter-inch microphone was a B&K model 4136 and 2669 preamplifier connected to the second channel of the 12 AN power supply. Finally a PCB Electronics piezoelectric ICP blast pressure pencil probe model 137A23 was used to sample the acoustic blast wave.

Calibrations of the microphones were performed prior to each data collection session. A B&K 4228 pistonphone was used to generate a 0.250 kHz tone of nominally 124 dB SPL. Temperature, humidity, and barometric pressure were recorded from a NIST-traceable sensor. The calibration level was adjusted for barometric pressure; typically the calibrated level of the pistonphone was adjusted by − 0.15 dB. The NIOSH Sound Power VI sampled the calibration tone and the sensitivity (Pa/mV) was determined and stored. The sensitivity of each channel was measured several times to ensure that the microphone responses were consistent. After all the sensitivities were measured, the digitized microphone voltage signals were converted to a pressure signal. The peak levels at the locations of the field probe and ATF were of primary importance. Temperature affects the speed of sound and both temperature and humidity affect absorption. Absorption effects over the short distances involved in this study would be less than a tenth of a decibel (Harris, 1966).

The data acquisition system was a National Instruments (NI) CompactDAQ chassis (cDAQ 9172) with five CompactRIO modules (cRIO 9215) installed and controlled by the NIOSH Sound Power VI running in LabView. Each module has four input channels and supports ± 10-V signal range, 16-bit resolution, and 100 kHz sampling rate. For the measurements at 170 and 150 dB, the quarter- and eighth-inch microphones triggered the data acquisition. For the 130 dB impulses, a G.R.A.S. model 40BH microphone positioned approximately 1 metre to the left of the impulse source triggered data acquisition. The signal was continuously sampled to identify an impulse event and a 100-millisecond pre-trigger delay allowed capture of the ambient noise prior to the impulse. For each impulse, the computer operator recorded in the logbook the peak level, the sample number, the insertion/placement number of the sample on the ATF, and the data file number. The computer, microphone power supplies, and DAQ chassis were all powered by a portable Honda generator that was placed about 20 metres from the nearest recording station and shielded somewhat by a tool shed.

The weather during the data collection threatened to jeopardize the entire effort. During the afternoon of the first day, the positions for sampling at the three impulse levels were determined, but rain interrupted the IPIL data collection. The weather for the second and third days was better and allowed us to collect the entire matrix of conditions in about 12 hours. On the second and third days (May 14 and 15, 2010), the average wind speeds measured at the Chippewa County International Airport were 11.1 ± 3.0 and 10.9 ± 3.0 miles per hour during the data collection periods respectively. The measurement site was shielded somewhat by the surrounding forest. For the PCB blast probe, the slight breeze or the lack of signal conditioning made its recordings unusable. The analysis was conducted using the ¼-inch microphone in grazing condition. Comparisons of the 1/8 and ¼-inch microphones showed nearly identical pressure waveforms and the better signal to noise ratio for the ¼-inch microphone determined its selection.

Hearing protection devices

Four different models of hearing protectors were selected for impulse testing: Bilsom 707 Impact II electronic earmuff, E·A·R® Pod Express, E·A·R® Combat Arms version 4, and the Etymotic Research, Inc. Electronic BlastPLG™ EB1. The Bilsom 707 Impact II earmuff is an electronic sound amplification earmuff and is now marketed as the Sperian (Honeywell) Impact Sound Amplification Earmuff. The earmuff was purchased on the open market and was tested with the electronics turned off. Similarly, the Etymotic Research EB1 is a sound amplification earplug and was also tested with the device turned off. The Combat Arms earplug utilizes a small orifice that provides increasing acoustic impedance as the pressure differential increases across either side of the valve so that the attenuation of this product increases as the impulse level increases (Parmentier et al, 1994, 2000; Berger & Hamery, 2008). The Pod earplug samples were purchased on the open market. The focus of this study was to evaluate earplugs and an earmuff in the passive (electronics turned off) mode. Five samples of each protector model were tested during this study. The samples of the four styles of protectors were separated into five sets so that at least a complete test of a set of protectors could be conducted in the event of inclement weather. The protectors were sequentially placed on the mannequin by the second author and data were collected over the course of three days in between rain showers and drizzle. The protectors were stored in sealed plastic bags between trials. All five sets of protectors were successfully tested.

Selection rationale

More than 400 hearing protector models are sold in the United States and any number of products could have been used in this study. An earmuff, foam earplug, premolded earplug, and a nonlinear device were chosen. The Impact 707 muffs, Combat Arms, and Pod Express plugs were products which had been previously studied in the NIOSH Impulse Noise Laboratory. The Impact 707 muffs were tested with the batteries installed and with the device turned off. Subsequent laboratory tests of the Impact 707 muff with the electronics turned on were not included in this study. The Pod Express earplugs were chosen because the plugs would fit completely within the ear canal of the ATF. Prior tests with the NIOSH acoustic shock tube exhibited a high degree of consistency of impulse peak insertion loss across samples. The Combat Arms earplugs were provided to NIOSH by 3M/EAR.

The Combat Arms version 4 single-ended earplugs were selected over the version 2 dual-ended plugs and the version 3 with its system to rotate the valve into place. The Combat Arms version 4 features a unique toggle design that allows the wearer to simply open and close the valve with a finger tip without having to remove the plug. In the testing reported in this study, the plug was inserted into the ear canal of the ATF in the closed condition and impulses were recorded first. The valve was opened without removing the earplug and additional impulses were subsequently recorded. Two pairs of plugs were provided to the first author in February 2010 and additional samples to complete the set of five plugs were provided in April 2010. Thus the plugs were likely not from the same production lot, a fact that could be important after the data are presented.

Etymotic Research Inc. provided the second author five EB1 earplug samples which were tested with depleted batteries to maintain the mass of the protector but prevent the electronics from functioning. As a new product specifically designed for impulse noise reduction, the triple flange design should be similar in performance to the Combat Arms earplug when the valve is closed.

Analysis

All of the data analysis was performed using methods adapted from the Matlab scripts in Appendix H of the ANSI S12.42-2010 standard. Five calibration impulses were recorded at each impulse level and the averaged complex transfer function between the field microphone and acoustic test fixture was determined. The average transfer function was used to estimate the field microphone level for each recording made with the same configuration of fixture and field microphones. When the fixture was moved to sample a different impulse level, or if the field microphone was inadvertently bumped while changing hearing protectors, then a new set of calibration impulses was recorded and the new transfer function was determined and applied to subsequent impulses.

IMPULSE IDENTIFICATION AND WINDOWING

The field probe and ATF microphones were sampled simultaneously. The sampled signal was buffered for 0.1 seconds before the impulse and 1.0 seconds of data was recorded. The maximum of the absolute value of the signal from the field probe was used to locate the analysis time window. The beginning of the impulse analysis time window was 1 millisecond before the peak sound pressure and the duration of the analysis window was 40.96 milliseconds. In the ANSI S12.42-2010 standard, the analysis window should be at least 300 milliseconds. This deviation from the standard was necessary due to the noise in the data acquisition system. The pre-trigger interval was used to adjust the DC offset for each channel's signal. Because the impulse is asymmetric, an average of the entire sample would be biased. Thus, the first 90 milliseconds of data before the peak sound pressure were averaged and then subtracted from the signal for that channel.

When making measurements at 130 dB, the background noise level of the recording system was plagued by single-sample transient electrical noise with amplitudes comparable to the impulse amplitude. The transients occurred at random times and were reduced through signal averaging. The noise was observed during the data collection, but could not be resolved in the limited time available at the testing site. Therefore, a microphone was placed near the impulse source to trigger sampling with a 100-millisecond pre-trigger interval. The propagation delay from the trigger microphone to the field and fixture microphones (~ 43 msec) was used to locate the analysis time window for 130 dB. For the 150 and 170 dB impulses, the analysis time window was identified directly from the maximum absolute pressure of the quarter-inch field microphone signal which had the best signal to noise ratio. Sample field and unoccluded fixture waveforms are shown in Figure 2 for each range of impulses.

TRANSFER FUNCTION FOR OPEN EAR

The impulse signal analysis as described in ANSI S12.42-2010 is summarized in this section. A unique transfer function exists for each level of impulse source, and physical arrangement of the impulse source, field (FF) microphone(s), and acoustic test fixture (ATF) microphones:

$$P_{ATF,L,n}\,(f) = H_{ATF-FF,L,n}\,(f)\,P_{FF,L,n}(f), \tag{1}$$

where $P_{FF,L,n}(f)$ and $P_{ATF,L,n}(f)$ are the discrete Fourier transforms of the impulse waveforms (n) at a given level, L. The transfer function can be determined by dividing the Fourier transforms of the fixture and field data and averaging the result in the frequency domain.

The averaged transfer function was used to transform subsequent field microphone recordings to estimate the unoccluded fixture waveform level for each impulse,

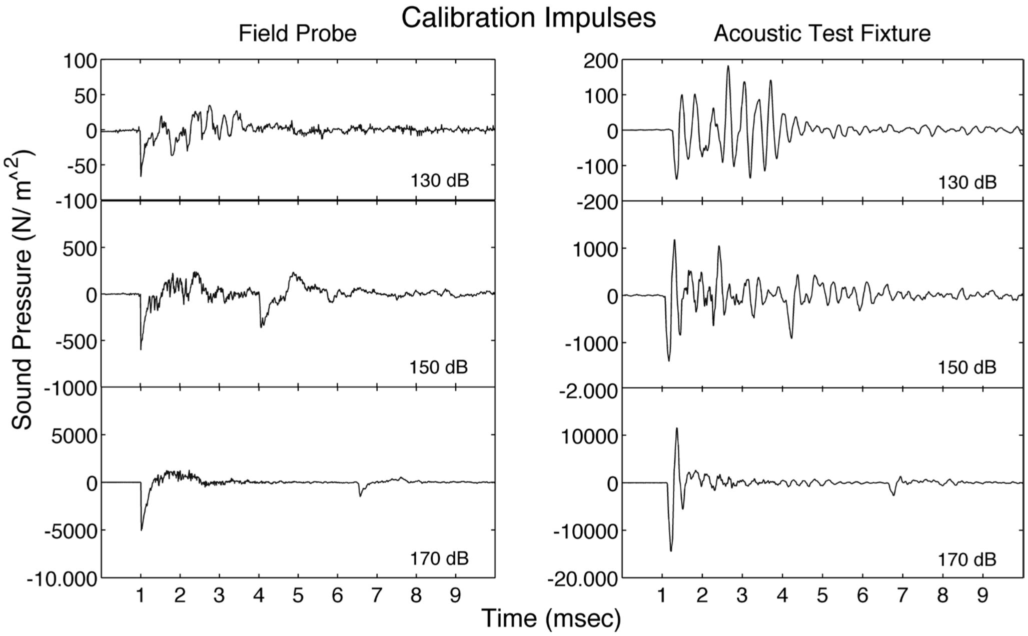

Figure 2. Calibration impulses from each of the three ranges: 130, 150, and 170 dB peak SPL. The panels on the left display the sound pressures in Pascals of the free-field probe microphone (B&K 4136) and the panels on the right display the sound pressures measured by the acoustic test fixture. The ATF filters the signals and produce a ringing following the initial wavefront of the shockwave. Since condenser microphones were used to record the impulses, the negative values correspond to positive pressures.

$$\bar{H}_{ATF-FF,L}(f) = \frac{1}{N}\sum_{n=1}^{N} P_{ATF,L,n}(f)/P_{FF,L,n}(f). \quad (2)$$

$$P'_{ATF,L,i,j,k}(t) = \mathrm{FFT}^{-1}\left(\bar{H}_{ATF-FF,L}(f) \times P_{FF,L,i,j,k}(f)\right) \quad (3)$$

where P′ denotes the estimated ATF pressure waveform for an unoccluded condition.

The IPIL is determined as the difference between the unoccluded and occluded peak pressure levels for the fixture,

$$IPIL(L,i,j,k) = \max\left(\left|P'_{ATF,L,i,j,k}(t)\right|\right) - \max\left(\left|P_{ATF,L,i,j,k}(f)\right|\right), \quad (4)$$

where L is the nominal peak level (170, 150, 130) and i, j, k, are the sample, insertion, and impulse numbers, respectively. The IPIL(L, i, j, k) are averaged first over the impulse number and then insertions to yield an average IPIL for each sample. The IPIL results are presented in the next section.

Results

Impulse peak insertion loss

Five samples of each of the different protectors were evaluated in this study. The different samples of a protector were placed on the ATF or were fitted in the simulated ear of the ATF five times and the three impulses were measured for a given fitting at each range of levels. In Table 1, the IPILs were averaged across fittings and impulses yielding the average and standard deviations for each protector and impulse range.

E·A·R® Pod Express

The E·A·R® Pod Express earplug (NRR = 25 dB) has a hemispherical foam cap and a stiff plastic stem that aids insertion and removal. When the foam was rolled down, the entire earplug could be inserted into the ear canal of the test fixture.

The mean IPIL values for the Pod Express exhibited a small increase in insertion loss as the external peak level increased (see Figure 3). At 130 dB the mean IPILs were between 32 and 35 dB. The mean IPILs were between 35 to 37 dB at 150 dB. At 170 dB the mean IPILs were between 36 to 38 dB. The Pod earplug exhibited excellent agreement across the five samples. The mean IPIL values increased 4.2 dB over the range of impulse levels and the standard deviations were between 0.4 and 1.1 dB (See Table 1)

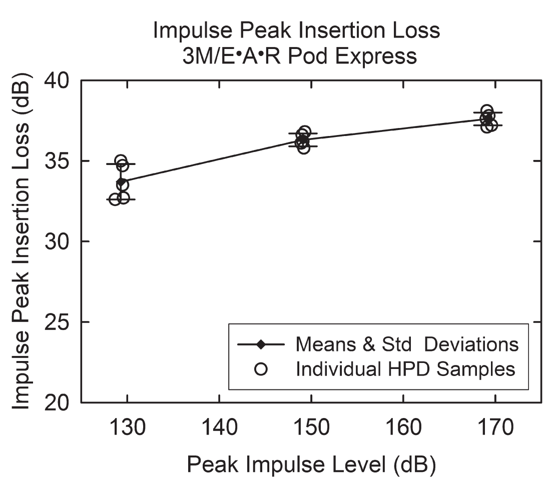

Figure 3. Impulse peak insertion loss for the E·A·R® Pod Express earplugs. At each impulse level, five samples were fitted five times on the acoustic test fixture and three impulses were measured per fitting. Each circle symbol represents the averaged IPIL measured for the repeated fittings and shots for the respective levels for one sample. The means and standard deviations are shown at each level as a diamond symbol with error bars.

Table 1. The means and standard deviations of the impulse peak insertion loss at each range of impulse level. The IPIL values were determined from the average of five hearing protector samples fitted five times to the acoustic test fixture and three impulses for each fitting of the samples. The IPIL was calculated as the difference between the maximum absolute pressures measured in the occluded condition and the estimated pressures for the unoccluded condition using the transfer function between the field and fixture microphones.

	Impulse peak insertion loss at different impulse peak levels (dB SPL)		
Protector	*130 dB*	*150 dB*	*170 dB*
Pod Express	33.5 ± 1.1	36.0 ± 0.4	37.7 ± 0.4
Etymotic Research EB1	33.3 ± 0.8	35.6 ± 1.5	36.8 ± 0.9
Bilsom 707 Impact II	29.3 ± 2.4	32.0 ± 2.8	35.9 ± 2.7
EAR Combat Arms open	20.7 ± 0.6	25.7 ± 1.1	30.9 ± 1.8
EAR Combat Arms closed	28.9 ± 1.7	31.1 ± 2.4	33.2 ± 2.3

Etymotic Research, Inc. Electronic BlastPLG™ (EB1)

The Etymotic Research, Inc. Electronic BlastPLG™ EB1 electronic blast protector is a sound amplification earplug that utilizes the high-fidelity K-AMP· integrated circuit to compensate for the attenuation effects of the earplug (Etymotic Research, 2010). When sounds were below a given threshold of compression this device can be configured to provide amplification. Above the threshold, a compression circuit prevents overexposure of the person wearing the device. Although some tests were conducted with the circuitry turned on, the results reported in this paper only examined the device's passive performance as a hearing protector.

Like the E·A·R® premolded earplugs (e.g. Ultrafit, Hi-Fi, and Combat Arms), the EB1 has three flanges that increase in diameter. The first and second flanges could be inserted fully into the ear canal of the test fixture. The third flange was touching the outer peripheral edge of the ear canal, but was unable to be fully inserted due to the short length of the ATF ear canal. Furthermore, if the earplug were inserted further, the largest flange would begin to exhibit some folding as it was inserted. Subsequent investigation of the second flange found that the outer edge of the flange might also be folded, but that the seal could maintain integrity. At the 130 dB levels, the mean IPILs for the passive EB1 were between 32 and 34 dB (Figure 4). The mean IPILs at 150 dB were between 33 and 37 dB, and at 170 dB the mean IPILs were between 35 and 38 dB for the five samples. The standard deviations for the data were between 0.8 and 1.5 dB and the average IPILs increased 3.5 decibels over the range of levels tested (See Table 1).

Bilsom 707 Impact II

The Bilsom 707 Impact II ear muff was an electronic sound restoration hearing protector and has an NRR of 23 dB. The amplification circuit sampled the external sound level and shut off whenever the level exceeded 82 dB(A). In previous investigations of similar products (Murphy & Tubbs, 2007), the high amplitude of the firearm impulse saturated the input circuit and the signal was effectively attenuated as if the device were turned off. For this study, the batteries were installed but the device was turned off so that the passive performance of the protector could be evaluated.

At 130 dB (Figure 5) the mean IPIL values for the ear muff were between 25 and 32 dB. At 150 dB the mean IPILs were between 27 and 35 dB. At 170 dB the mean IPIL values were between 31 and 38 dB. Although the sample number is not indicated in the plots, the third sample's mean IPIL values across the range of impulse levels were consistently lower than the other four muffs' IPILs by about 3 to 4 dB. Since only one of the authors was conducting the placement and replacement of the samples on the fixture and since the measurements were conducted over two days of testing, the source of the discrepancy must be attributed to that particular sample. In the preliminary analyses, this trend was evident in a comparison of the five fits for the five samples. The IPIL for the third sample was not only less, but it exhibited more variability than the other four samples.

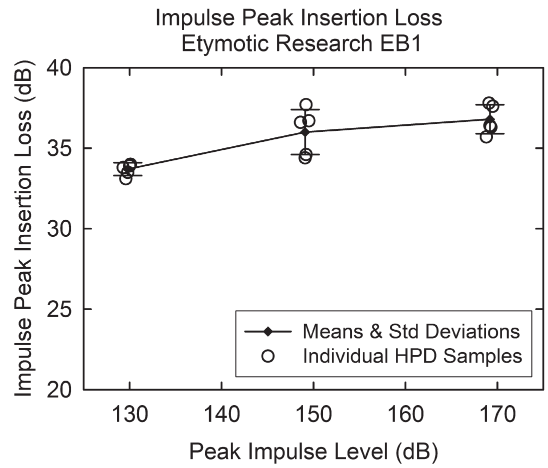

Figure 4. Impulse peak insertion loss for the Etymotic Research Inc., Electronic BlstPLG™ EB1 earplugs. At each impulse level, five samples were fitted five times on the acoustic test fixture and three impulses were measured per fitting. Each circle symbol represents the averaged IPIL measured for the repeated fittings and shots for the respective levels for one sample. The means and standard deviations are shown at each level as a diamond symbol with error bars.

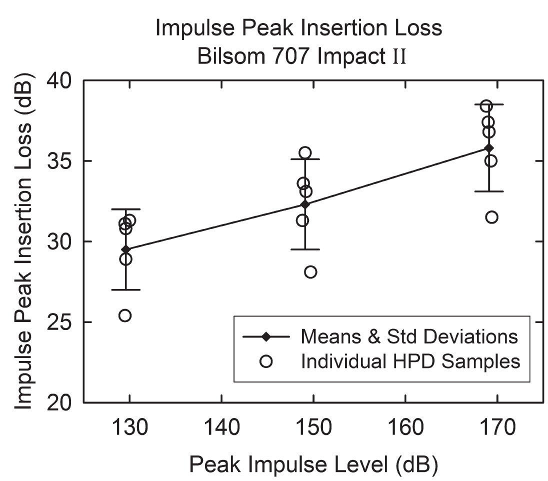

Figure 5. Impulse peak insertion loss for the Bilsom 707 Impact II earmuffs. At each impulse level, five samples were fitted five times on the acoustic test fixture and three impulses were measured per fitting. Each circle symbol represents the averaged IPIL measured for the repeated fittings and shots for the respective levels for one sample. The means and standard deviations are shown at each level as a diamond symbol with error bars.

E·A·R® Combat Arms version 4

The E·A·R® Combat Arms version 4 earplug has an NRR of 7 dB for the valve open condition and an NRR of 23 dB for the valve-closed condition. As described above, the earplug has three flanges that are similar to but not the same as the Etymotic EB1. Like the EB1, the first two flanges could be inserted completely into the ear canal of the test fixture, but the third flange would exhibit some folding if it were pushed in too far. Consequently, the plug was inserted such that the third flange was in contact with the ear canal, but not so far as to produce a wrinkle.

Nonlinear valve open. The results from the Combat Arms earplug are shown in Figure 6. The mean IPIL values from four of the samples agreed within about 4 decibels across the range of impulse levels. However, the fifth sample consistently had mean IPIL values that were 2 to 4 dB higher than the IPILs from the other samples. For the 130 dB impulse range, the mean IPILs ranged between 20 and 22 dB. At 150 dB the mean IPILs ranged between 25 and 28 dB. At 170 dB the mean IPIL values ranged between 29 and 35 dB. The mean values exhibit a significant increase in the peak insertion loss over the 40 dB range of impulses, approximately 0.25 dB/dB.

Nonlinear valve closed. The results for the same samples of the Combat Arms earplug with the valve closed are shown in Figure 7. In this graph, the differences in the mean IPIL values between the fifth sample and the other four samples can be more easily discerned as being 4 to 5 dB greater. At 130 dB, the mean IPILs are concentrated around 28 dB. At 150 and 170 dB peak impulse level, the mean IPIL values are clustered tightly around 31 and 34 dB, respectively. Since only one person fitted the protectors and the data were collected during two days, the differences between the fifth sample of the Combat Arms and the other four protectors must be due to the protector.

Impulse noise reduction rating

The primary reason for measuring and computing the impulse peak insertion loss is to inform the consumer of the potential performance

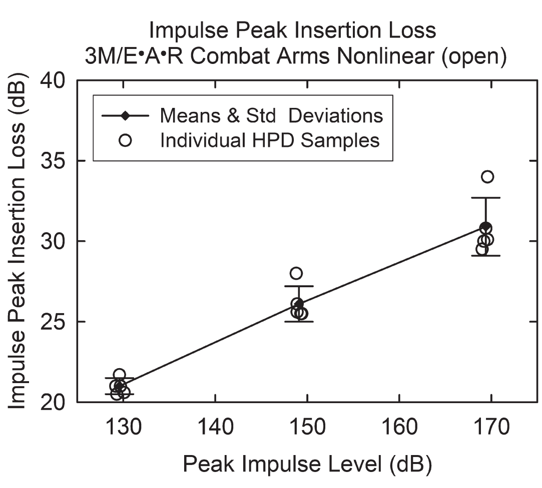

Figure 6. Impulse peak insertion loss for the E·A·R® Combat Arms earplug with the valve open. At each impulse level, five samples were fitted five times on the acoustic test fixture and three impulses were measured per fitting. Each circle symbol represents the averaged IPIL measured for the repeated fittings and shots for the respective levels for one sample. The means and standard deviations are shown at each level as a diamond symbol with error bars.

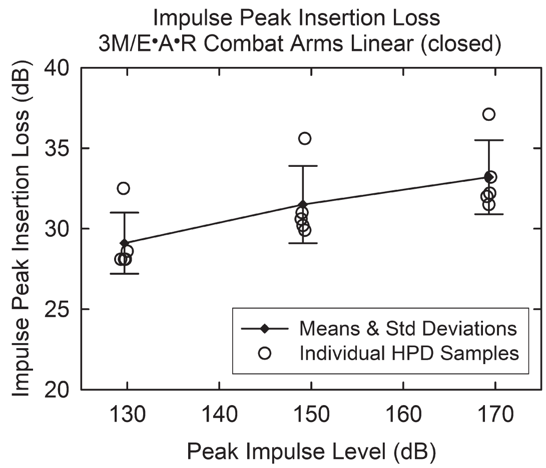

Figure 7. Impulse peak insertion loss for the E·A·R® Combat Arms earplug with the valve closed. At each impulse level, five samples were fitted five times on the acoustic test fixture and three impulses were measured per fitting. Each circle symbol represents the averaged IPIL measured for the repeated fittings and shots for the respective levels for one sample. The means and standard deviations are shown at each level as a diamond symbol with error bars.

of the hearing protection device through the noise reduction rating on the packaging. For devices that have a nonlinear valve or an electronic sound restoration circuit, the REAT measurement does not provide attenuation results that are meaningful at higher exposure levels. Testing must occur at a level where the impulse attenuation becomes effective for the user and must be conducted at levels that provide a consistent basis for comparing the performance of different protectors. The range of impulse levels (130, 150, and 170 dB peak SPL) was selected by EPA because these levels can be produced by commonly used tools, weapons, and recreational exposures (EPA, 2009). Continuous noise levels above 130 dB occur frequently near turbine jet engines, air sirens, and steam whistles, however creating such levels in the laboratory is difficult. The scientific community agrees that levels above 140 dB peak SPL have the potential to produce immediate hearing loss (NIOSH, 1998). U.S. regulatory agencies such as OSHA and MSHA prohibit exposures with time-weighted averages above 115 dB(A) and stipulate ceiling limits for peak levels of 140 dB. In the subsequent section, several approaches to characterizing the performance over the range of impulse levels are reported.

Proposed EPA rating

The EPA proposed using the range of the IPIL measurements for the impulse NRR. If the minimum and maximum of the IPIL tests were used, then outlier data points would unduly influence the rating. In the EPA's public comments received following proposal of the revised rule, several commenters suggested that the rating be determined from mean and standard deviation of the IPIL measurements. In the ANSI S12.68-2007 rating standard for continuous noise, the ratings estimate the percentiles of protection from the mean plus or minus a standard deviation assuming that the values represent the integrated area underneath the distribution of attenuations. For a normal distribution with mean μ and standard deviation σ, the integrated area yielding 90% protection is $\mu - 1.2816\ \sigma$. Similarly the integrated area for 10% protection is $\mu + 1.2816\ \sigma$. Assuming the

Table 2. The protection percentiles computed from three different methods. The protection percentiles for the normal assumption treated all the data as being from a single distribution disregarding the change in IPIL as a function of level ($\mu \pm 1.2816\ \sigma$). The 150-dB protection percentiles were computed from the IPIL values measured from the 150-dB data: $\mu_{150} \pm 1.2816\sigma_{150}$. The minimum/maximum (Min/Max) protection percentiles were derived from the maximum and minimum protection percentiles across the three levels: [minimum($\mu_{Level} - 1.2816\ \sigma_{Level}$), maximum($\mu_{Level} + 1.2816\ \sigma_{Level}$)].

	Protection percentiles		
Protector	*Normal assumption*	*150 dB*	*Min/Max*
EAR Pod Express	(32.3, 38.1)	(35.8, 36,8)	(32.3, 38.1)
Etymotic Research EB1	(33.2, 37.9)	(34.2, 37.8)	(33.2, 37.9)
Bilsom 707 Impact II	(26.3, 39.3)	(28.7, 35.9)	(26.3, 39.3)
EAR Combat Arms open	(20.4, 33.2)	(24.8, 27.5)	(20.4, 33.2)
EAR Combat Arms closed	(26.6, 36.1)	(28.4, 34.5)	(26.6, 36.1)

IPIL values are representative of a normal distribution, the 90% and 10% protection was calculated from the fifteen IPIL values measured across the three levels. The five fittings for each protector and three shots for each fitting were averaged before computing the protection percentiles. In Table 2, the numerical ranges for the impulse NRR are reported for each protector.

In Figure 8, the dashed lines depict the numeric ranges compared to the mean IPIL values at each level and the standard deviations for the various levels. For most of the products, the dashed lines intersect the error bars and thus do not describe the range of performance at the lower or higher impulse levels. A larger coverage factor could be used to increase the range from 90% and 10% to 95% and 5% coverage. Estimating the protection percentiles becomes problematic for small sample sizes and when outlier data are encountered. For the Bilsom 707 earmuff and the Combat Arms earplug, four of the five protectors were clustered and one sample yielded different IPILs. Furthermore, this approach to estimating protection percentiles mixes the IPIL data across the three impulse levels. For a product such as the Combat Arms earplug, the improvement of attenuation with increased level clearly shows that the data should not be mixed in a computation. Other nonlinear and electronically enhanced protectors would likely exhibit similar behavior across levels.

Prediction interval for 150 dB

A second treatment to estimate the impulse NRR was considered based upon the prediction interval derived at a single range of impulses, 150 dB. The 90th and 10th protection percentiles are shown in Figure 8 (solid line) and Table 2. This method could be attractive to testing labs and manufacturers seeking to reduce testing costs, if it worked. Instead, the protection percentiles estimated for the Pod, Combat Arms, and EB1 protectors do not span the mean IPIL values at all three levels. The use of the impulse NRR derived solely from the 150-dB data would underestimate or overestimate the performance at other impulse levels. Thus the 150-dB approach is unacceptable for estimating the impulse NRR.

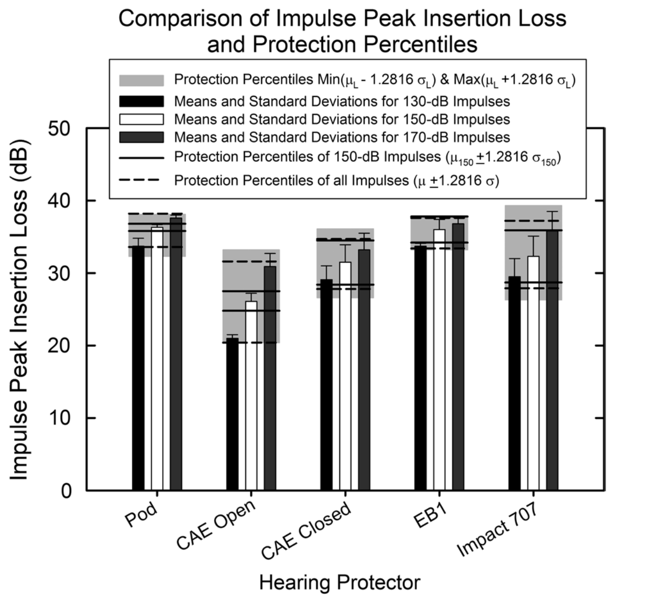

Figure 8. Impulse peak insertion loss values for each protector at each level and the 90th and 10th percentiles of protection from three different methods. The mean IPIL values measured with 130, 150, and 170-dB impulses (black, white, and dark gray bars, and error bars respectively) and standard deviations (error bars) are shown for each protector. The light gray box in the background depicts the range of IPIL as determined from the minimum and maximum of the protection percentiles for each impulse range: [minimum($\mu_{Level} - 1.2816\sigma_{Level}$), maximum($\mu_{Level} + 1.2816\sigma_{Level}$)]. The solid lines represent the 150-dB protection percentiles, $\mu_{150} \pm 1.2816\sigma_{150}$. The dashed lines represent the percentiles of $\mu \pm 1.2816\sigma$.

Maximum and minimum prediction intervals

The third approach estimates the protection percentiles at each of the three impulse levels and then selects the minimum and maximum values across the three levels. In practice, the 90th and 10th percentiles of protection should result from the 130-dB and 170-dB IPIL data, respectively. EPA proposed that the minimum and maximum be determined at each level. This method does not average across the three levels and reduces the influence of outlier data. In Figure 8, the light gray boxes encompass the means and standard deviations. For the Combat Arms and Pod protectors, the variance of the IPIL data changed slightly with the impulse level and the width of the extent of the rating captures that change. For the Bilsom 707, the product exhibited larger standard deviations and the box is somewhat larger.

Other methods for estimating protection percentiles

Other methods of deriving the protection percentiles were investigated. For instance, a line was fit to the fifteen IPIL values (See Figures 3–7). The confidence interval of the line was computed and the upper and lower limits described the limits about the mean at the 130 and 170 dB impulses. Also, the prediction interval was calculated and the interval produced reasonable results for some protectors (e.g. Combat Arms closed valve and Bilsom 707) because the variance was fairly constant over the range of impulse levels. However for other products, the prediction intervals resulting from a linear regression were seemingly too wide. Numerical simulations demonstrated that the impulse with the greatest variance dominated the estimation of the prediction interval. Another approach was to pick the 90th and 10th protection percentiles from the cumulative distribution directly. If a larger sample size were used, then this method could be a reasonable means to assign the impulse NRR. Otherwise, selection for the percentiles of the cumulative distribution may be influenced by the performance of one sample.

Discussion

The impulse portion of the ANSI S12.42-2010 standard was developed to characterize the insertion loss of hearing protection devices when worn in high-level impulsive noise environments. Heretofore, impulse waveforms have been evaluated with damage risk criteria using waveform parameters (e.g. peak and duration), energy (equivalent A-weighted energy, sound exposure level), and model-based methods (Auditory Hazard Assessment Algorithm for Humans: AHAAH) (Coles et al, 1967; Price & Kalb, 1991; Hamernik et al, 1998; Flamme et al, 2009a). Whereas these metrics are intended for assessing the risk of a particular exposure, they provide no guidance that simply describes the performance of hearing protection devices when used in conjunction with such exposures. The impulse peak insertion loss was expected to increase with increasing sound pressure and could be significantly affected by the frequency content of the impulse (Parmentier et al, 2000; Berger & Hamery, 2008). The impulses used in this study were generated by a Colt AR-15 weapon and therefore may only be useful for other gunshot-like noises with similar initial blast overpressure durations (A-duration between 0.3 and 0.8 milliseconds).

Data acquisition and analysis

Data acquisition

The data acquisition presented several challenges during this study. First of all, the remote location did not have electrical service and all of the measurements were conducted outdoors. Since electricity for the computer, DAQ chassis, and microphone power supplies was supplied by a portable generator, there were no options to try other power sources or to condition the power if that was the source of the noise in the system. In Figure 2, the electrical noise can be seen on the ATF waveform at 130 dB. In previous measurements in the NIOSH Taft laboratory with the same system, this noise was not evident. As mentioned previously, the limitations of time and weather precluded resolving the source of the noise. For the occluded measurements, the Stanford Research Systems SR-560 low- noise voltage amplifier was used to boost the ATF's signal to the DAQ system. One channel of the DAQ system sampled the ATF without gain and another channel sampled the ATF with gain of 20 dB. When the NIOSH Sound Power VI samples the voltage data of the microphone, it converts the voltages to pressure using the calibration information and measured microphone sensitivities. The data for the channel with gain were used to conduct the analyses for all impulse levels. However, at 170 dB, the channel with the 20-dB gain clipped the input signal when the fixture was unoccluded, so the 170-dB transfer functions were determined using the channel sampled without gain.

Second, the CompactRIO modules exhibit some DC bias when sampling. The modules are not as well isolated as other National Instruments cards used in the PXI or MXI chassis. The 16-bit resolution and 100 kHz sampling rate were compliant with the recommendations of the ANSI S12.42 standard. However, in subsequent measurements with other National Instruments equipment, the improved isolation, higher resolution, and sampling rate (24-bit, 200 kHz) yielded better recordings not plagued by the electrical noise and DC bias. DC bias was estimated by averaging the pre-trigger portion of the signal and then the bias for each channel was subtracted from the time analysis window. The sampling rate is important for capturing the peak impulse level, but once the impulse wave enters the ear canal of the test fixture, the signal is acoustically filtered and exhibits the resonance characteristics seen in Figure 2.

Environmental effects

Detailed history of the wind and temperature were not recorded during the course of data collection. The wind histories were retrieved from the Chippewa County International Airport online data for the days during data collection. The location of the hunting camp was approximately 2 miles from the airport. The temperature was between 50–60°F during the majority of the testing. Barometric pressure fluctuated little during the course of the measurements. The barometric adjustments were a few tenths of a decibel. The area where the measurements were conducted was covered with a short grass and dirt. Two trees were near to the measurement system. Because the trees did not present a large flat surface, reflections from the trees were diffuse and small in amplitude. The ground however produced strong reflections at each distance. In Figure 2, the reflections were at 1, 3, and 5 milliseconds following the primary impulse in the field measurement for the 130, 150, and 170 dB impulses, respectively. The reflections fell outside of the primary impulse at 150 and 170 dB impulse levels. At 130 dB, the ground reflection was near the primary impulse and was not significantly attenuated. In the analysis, the ground-reflected wave could interact with the test fixture response to produce a larger response than the initial test fixture response. In the laboratory environment, reflections can be attenuated by placing absorptive materials on the ground and by testing in a hemi-anechoic or anechoic environment.

Acoustic test fixture effects

When the ANSI S12.42 standard was developed, the standard described the requirements for an acoustic test fixture that included longer ear canals than a typical IEC 60711 coupler, a heated head to improve the compliance of foam earplugs, and simulated flesh for the ear canals and area surrounding the pinna. A test fixture meeting these specifications did not exist when the study was conducted and NIOSH's one-eared ISL fixture was used for the data collection. The standard specifies that two-ear simulators should be used. Consequently, the measurements reported in this paper are not in strict compliance with the standard. ISL and G.R.A.S. Sound and Vibration have both developed fixtures with heated, longer ear canals to meet the specifications in the ANSI S12.42-2010 standard. A future series of studies will compare performance of the various fixtures both outdoors and in the laboratory.

Computation of the IPIL

Triggering for the impulses at 150 and 170 dB was achieved by the field probe microphone. At 130 dB, another microphone was positioned near the impulse source to serve as a reliable trigger. In spite of the high amplitudes of the trigger microphone, the NIOSH Sound Power VI had sporadic instances where the system failed to capture the impulse waveform with a 100 msec pre-trigger interval. In some cases the pre-trigger interval was on the order of 300 ms due to the necessity to process the previous signal and reset the data acquisition system for the next impulse. The median value of the trigger times was 0.10006 seconds and 97.5% of the peaks fell within $\pm$ 0.0006 seconds of the median. The impulses were time-aligned before determining the transfer function between the unoccluded fixture and the field probe microphone.

Initial analysis of the data suggested that time-alignment would yield a more accurate estimate. The time-alignment does not yield any difference in the estimate if the signal is not contaminated by any noise. At the highest impulse level, the effect of time-alignment yielded negligible changes. For the 130-dB impulse levels, the signal to noise ratio was less and yielded effects of the order of a few tenths of a decibel to about one decibel. Similarly, the DC-shift correction can result in errors of a few tenths of a decibel. While the ANSI S12.42-2010 standard does not require the alignment of the impulses in the time analysis window, systematic errors could affect the results at lower impulse levels if the calibration impulses are not aligned.

The field-to-fixture transfer function can be computed from the calibration waveforms in two ways: first separately average the field waveforms and the fixture waveforms in the time domain and then compute the spectral transfer function; or compute the spectral transfer function of each pair of field and fixture waveforms then average the transfer functions in the frequency domain. If the signal-to-noise ratio is high, then there should be little difference between the two methods. In the ANSI S12.42-2010 standard, the latter method is prescribed for determining the transfer function. The latter method will be immune to the time-alignment issue with sufficient signal to noise ratio. The former method would require the impulses to be aligned precisely to reduce the effects of noise and to enhance the signal.

Number of samples to test

The authors of the ANSI S12.42-2010 standard did not have a comprehensive data set upon which to base several requirements of the standard for impulse tests. The requirement for the number of samples to be tested was based on experiences with REAT measurements. In Murphy et al (2004) and Murphy et al (2009), the sample size for REAT tests were established as 10 subjects for earmuffs and 20 subjects for ear plugs. For four earplugs tested according to ANSI S12.6 and rated with the noise reduction statistic for A-weighting (NRSA) defined in ANSI S12.68 (2007), the 95% confidence intervals were between 3 and 6 decibels using 20 subjects in a test group. Because the ANSI S12.42 method was to be performed using a test fixture, the variability was expected to be lower than what is commonly observed for REAT data. Clearly, this study demonstrates that the performance of one sample can be dramatically different from the others. Future work will be required to evaluate whether or not five samples are adequate to characterize a protector's impulse noise reduction. The EPA proposal to have the five samples selected from different manufacturing lots is a reasonable choice (EPA, 2009). If the ANSI S12.42 standard were to increase the required samples to 10 or 20, then the time to conduct a single product test would be significantly increased. If the standard deviations of the IPIL values increased or decreased with additional samples, then the protection percentiles would be similarly changed. Therefore, the required sample size should be investigated along with the number of fittings of the product. The ANSI S12.42 standard requires two fittings of each sample, but additional fittings may identify interactions of the protector with the acoustic test fixture. Although a comprehensive component analysis of the variance has not been published yet, preliminary analysis has shown that the interaction of level, sample, and fit accounts for about 30% of the variance.

Implications for rating performance

The EPA's proposed impulse noise reduction rating was designed to be used to aid the consumer in understanding the performance of a particular protector. Since the principal risk factors for hearing loss due to impulse noise are level, impulse duration, number of impulses, and frequency content, this rating addresses the most significant factor, peak sound pressure level. The range of IPIL values can be represented like the shaded range in Figure 8. The consumer will not be immediately aware that the limits of protection result from both the impulse peak sound pressure levels and variability of the products and their fit on the ATF. Supplementary information from the manufacturer can highlight the performance across the impulse test levels. Also, the manufacturers can provide additional guidance to inform the consumer about potential noise levels of common exposures.

The EPA proposed determining the maximum and minimum IPIL values across the range of impulse levels as the source of the protection percentiles (EPA, 2009). As demonstrated in Figure 8, the minimum and maximum of the 90th and 10th percentiles provide good coverage of the range of IPIL values at each impulse level. Clearly from Figure 8, the prediction interval computed from testing at a single impulse level (e.g. 150 dB) would both under- and over-report the potential performance of the product. The earmuff and the nonlinear orifice earplug exhibited significant growth in the attenuation with peak external pressure. Also, the reader should note that every product exhibited an increase in the IPIL with level. Research conducted by the U.S. Army in the early 1990s demonstrated that at levels on the order of 185 to 195 dB SPL, the rarefaction phase of the blast can actually lift the earmuffs off the head of a subject or an acoustic test fixture (Johnson, 1994). Shockwaves of 170 dB SPL produced by commonly available impulse noise sources are unlikely to exert sufficient force to move the hearing protectors. Furthermore when impulses are reflected by a surface, the reflected wave can interact with the decaying pressure envelope to produce higher peak pressure levels that vary dramatically with position relative to a single or multiple surfaces. The simplest model should assume that the subject will experience both the direct and ground reflected shock wave.

This study was not intended to evaluate the potential exposures of bystanders in situations where a small caliber weapon is being fired. The measurements confirm the results for impulse levels that bystanders might experience (Rasmussen et al, 2009). At 0.92 metres to the side of the muzzle, the peak levels were about 170 dB, 2.2 metres back and 1.5 metres to the right of the muzzle yielded 150 dB peak levels. If one were observing or training a shooter at a firing range, peak impulse levels could easily exceed 140 dB and hearing protection should always be worn. Poorly fit protectors have low REAT attenuations and may provide only a few decibels of protection against high-level impulses (Royster et al, 1996; Murphy & Tubbs, 2007; Murphy et al, 2009). Berger and Hamery (2008) demonstrated that several earplugs provided a small amount of protection. A slit leak may provide little or no attenuation in continuous noise environments of 80 to 120 dB SPL. As sound pressure levels increase, the nonlinear effects of fluid viscosity would increase the acoustic resistance and possibly yield more protection than expected.

Finally, protection from occupationally-related impulse noise exposures must be considered. Earplugs and earmuffs can reduce the peak levels of exposures significantly and provide adequate protection against these exposures. At the 150 dB peak exposure, all of the products evaluated provided at least 25 dB of peak reduction and could yield upwards of 35 dB peak reduction measured at the diaphragm of the test fixture microphone. Similar peak reductions were measured for a variety of electronic earmuffs and a double protection condition exhibited 50 dB peak reduction (Murphy & Tubbs, 2007; Murphy et al, 2007). Assuming maximum reduction for double protection of

50 dB, the 130 to 170 dB peak SPL occupational exposures could be reduced to 80 to 120 dB peak SPL at the eardrum. Current OSHA, MSHA, and NIOSH damage risk criteria suggest ceiling limits of 140 dB SPL peak for the unprotected ear in adults. These findings give support to the idea that workers do not need to lose hearing as a result of their jobs. Future damage risk criteria must account for the performance of hearing protection, the exposure level, numbers of impulses, and probably even the timing between impulses.

Conclusions

The primary purpose of this study was to test the methods developed in the ANSI S12.42-2010 standard with a range of hearing protection devices. Valuable experience was gained from this study and has laid the basis for future efforts. In particular, data have been collected comparing the performance of three acoustic test fixtures. Laboratory studies have been conducted although the results have yet to be completely analysed. The standard specifies a mannequin with a longer ear canal with a simulated flesh lining and that the fixture is heated. These requirements can be evaluated with future field and laboratory studies. The data collected in this study can be used to evaluate the performance of various damage risk criteria, albeit for a single type of impulse noise. Preliminary investigations of the change in damage risk criteria assessments have demonstrated a strong correlation with the protected peak sound pressure level. The opportunities for understanding hearing protection performance at higher sound pressure levels have been minimally explored.

The results from this study demonstrate the increase in impulse peak insertion loss as the peak sound pressure level increases. The sample size in this study may be too small to representatively assess the IPIL of a product design. Certainly, sampling of different lots would prove beneficial. Finally, the impulse NRR should be determined from the minimum and maximum of the 10th and 90th protection percentiles across the three ranges of impulse test levels. This choice of protection percentiles is determined from all of the data and will be able to capture any significant change in the variance that may occur across impulse levels.

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Notes

1. 170 dB: $0.92m = 0.92\boldsymbol{x} - 0.04\boldsymbol{y}$; 150 dB: $2.7m = 1.5\boldsymbol{x} - 2.2\boldsymbol{y}$; 130 dB: $19.2m = 1.4\boldsymbol{x} - 19.2\boldsymbol{y}$

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